INTELLIGENT & INFORMED

I & I

CAADRIA 2019

24TH ANNUAL CONFERENCE OF THE ASSOCIATION FOR COMPUTER-AIDED ARCHITECTURAL DESIGN RESEARCH IN ASIA

VOLUME 2

EDITED BY:
Matthias Hank Haeusler
Marc Aurel Schnabel
Tomohiro Fukuda

INTELLIGENT & INFORMED

Proceedings of the 24th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2019)

Volume 2

Edited by

Matthias Hank Haeusler
University of New South Wales

Marc Aurel Schnabel
Victoria University of Wellington

Tomohiro Fukuda
Osaka University

Intelligent & Informed

24th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2019)

15 – 18 April 2019
Faculty of Architecture & Design
Victoria University of Wellington

©2019 All rights reserved and published by
The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong

ISBN: 978-988-78917-2-7

Cover design and cover image 'Inhabiting Omni-Architecture' by Jessie Rogers
Printed in New Zealand

Foreword

The annual CAADRIA (Association for Computer-Aided Architectural Design Research in Asia) conference provides an international community of researchers and practitioners with a venue to exchange, to discuss and to publish their latest ideas and accomplishments. The proceeding has two volumes containing the research papers that were accepted for presentation at the Intelligent & Informed – 24th International CAADRIA Conference, hosted and organised by the Faculty of Architecture & Design at the Victoria University of Wellington, New Zealand. The papers are also available online at the open access cumulative database *CumInCAD* {http://papers.cumincad.org}.

The proceedings are the outcome of an extensive collaborative effort of a team of volunteers and our international Academic Review Committee. It marks another year of growing quality and strength in the history of CAADRIA. Calls for papers in July of 2018 resulted in the submission of 668 abstracts. These were blind reviewed by the Paper Selection Committee, which invited 395 abstracts for further development. Of these, 320 full papers were submitted to the full paper review stage. A team of 172 international reviewers assisted us in the full review stage. Two international reviewers carried out a double-blind review of each submitted paper. Following the reviewers' recommendations, 183 papers were accepted and finally 162 papers were accepted for the inclusion in these proceedings as the CAADRIA2019 Conference papers.

We congratulate the authors for their accomplishment. Next to the authors, the reviewers, who volunteered valuable time and effort, deserve our sincere thanks and acknowledgements. We thank the Organising Team and Hosts at the Victoria University of Wellington for hosting the 24th International CAADRIA Conference. We extend absolute special thanks the *ProceeDings* team, namely Gabriel Wurzer, for his relentless support with customizing the submission and review system to the needs of CAADRIA from the abstract submission stage all the way to production. Daniel Yu supported us in managing the submissions, while Manny Sayah developed an instrument {dataismore.com} that data-mined all papers to group them intelligently into chapters based on their content.

On the following pages, we acknowledge and thank those who contributed to the production of this volume. In closing, we sincerely thank the CAADRIA community for offering us the honour to serve as members of the paper selection committee for *Intelligent & Informed, the 24th International CAADRIA Conference 2019.*

Matthias Hank Haeusler (Chair), University of New South Wales
Marc Aurel Schnabel, Victoria University of Wellington
Tomohiro Fukuda, Osaka University
April 2019

Conference Theme: *Intelligent & Informed*

Intelligent

Human . Artificial . City . Heritage . Indigenous

&

Security . Sharing . Reliability . Additionality

Informed

Contextual . Cultural . Historical . Computational

The territories of computational design are ever-changing and represent a substantial region that remains uncharted; one with expanding and permeable boundaries that continue to be fully breached. This ocean of opportunity implores researchers to embark on ambitious journeys of exploration. Undulating and temporal, computational design needs research that engages explicitly with the innovative, intelligent and informed exploitation of computational design, and with the array of computational technologies that the discipline may engage with.

Human intelligence and creativity deliver the hegemonic direction for the field of computer-mediated architectural design research; an area where the computational component is a core aspect of the investigation. The actors in this are both witness to, and instigators of, the exciting, consequent, well-founded research that continues to deliver new knowledge, insights and information. This, then, explains the specific overarching theme of the conference: 'Intelligent and Informed'.

The scope of this theme is driven by the intention to take in aspects of machine intelligence, and a wide range of potential research that engages with the intelligent exploitation of computer-mediated techniques in Architecture.

Within the coverage of the call lies a broad spectrum of approaches ranging from speculative, informal investigations to conventional scientific research, including but not limited to the following research and praxis topics that focus around the conference theme 'Informed & Intelligent'.

We are welcoming researchers and practitioners to the Faculty of Architecture & Design at the Victoria University of Wellington in New Zealand to engage in discussion and research via paper & poster sessions, round table discussions, workshops, postgraduate student consortium and a digital art exhibition.

Conference Organisers & Hosts, Victoria University of Wellington
Marc Aurel Schnabel
Andre Brown
Tane Moleta

About CAADRIA

The *Association for Computer-Aided Architectural Design Research in Asia* (CAADRIA) promotes teaching and research in CAAD in the larger Austral-Asian and Pacific region supported by a global membership.

CAADRIA was founded in 1996 with the following objectives:

- To facilitate the dissemination of information about CAAD among Asian schools of architecture, planning, engineering, and building sciences.
- To encourage the exchange of staff, students, experience, courseware, and software among schools.
- To identify research and develop needs in CAAD education and to initiate collaboration to satisfy them.
- To promote research and teaching in CAAD that enhances creativity rather than production.

CAADRIA organizes among others an annual conference, the first of which was held in 1996 in Hong Kong. Since then, 23 conferences have been held in Australia, China, Hong Kong, India, Japan, Korea, Malaysia, Singapore, Taiwan, and Thailand. The 24th conference, in 2019, is held at Victoria University of Wellington in Wellington - for the first time New Zealand to include researchers, practitioners and schools of the pacific region. The conferences provide an opportunity to meet, to learn about the latest research, and to continue the discourse in the field. The proceedings of the conferences are available online at the open access cumulative database *CumInCAD* (http://papers.cumincad.org).

CAADRIA is one of the four founding organizations of the *International Journal of Architectural Computing* (IJAC), and co-edits one issue each year. IJAC is published by SAGE in both paper and electronic versions.

Christiane M. Herr
President, CAADRIA

CAADRIA Officers

President: Christiane M Herr
Xi'an Jiaotong-Liverpool University, China

Secretary: Walaiporn Nakapan
Rangsit University, Thailand

Treasurer: Wei Xin Huang
Tsinghua University, China

Membership Officer: Tian Tian Lo
Harbin Institute of Technology (ShenZhen), China

Web Master: Kyung Hoon Hyun
Hanyang University, Korea

Chief Administrative Officer: Marc Aurel Schnabel
Victoria University of Wellington, New Zealand

CAADRIA 2019 Conference Committees

Organisers & Hosts *Victoria University of Wellington, New Zealand*
Andre Brown (Sasada Awardee, Patron)
Marc Aurel Schnabel (Chair)
Tane Moleta (Curator),
Jessie Rogers (Chief Administrator)
Thuy Tien Le Phan (Support)
David Silcock (Scheduling Coordinator),
Austin D'Souza (Creative Project Assistant)
Chiara Shim (Promoter)
Hannah Rushton (Writer)
Iman Sayah (Data Miner)

Award/Scholarship Committee:
Rudi Stouffs (Chair) and Christiane M Herr

Paper Selection Committee:
Matthias Hank Haeusler (Chair), Marc Aurel Schnabel and Tomohiro Fukuda

PG Students Consortium:
Christiane M Herr (Chair), Rudi Stouffs and Dagmar Reinhardt

Sasada Prize Committee:
Tom Kvan (Chair), Christiane Herr, Atsuko Karga

Young CAADRIA Award Committee:
Christiane M Herr (Chair), Andre Brown and Matthias Hank Haeusler

International Review Committee

Asterios Agkathidis
Czech Technical Uni Prague
Chandler AhrensWashington
University in St. Louis
Masoud Akbarzadeh
The University of Pennsylvania
Suleiman Alhadidi
University of New South Wales
Fernando García Amen
University of the Republic
André L. Araujo
University of Campinas
Matthew Austin
University of Technology Sydney
Phil Ayres
Royal Danish Acad. of Fine Arts
Daniel Baerlecken
Georgia Institute of Technology
José Nuno Beirão
Technical University of Lisbon
Johannes Braumann
Uni for Arts and Design Linz
Andre Brown
Victoria University of Wellington
Michael Budig
SUTD
Peter Bus
University of Kent
Ines Caetano
Technical University of Lisbon
Timo Carl
University of Kassel
Erik Champion
Curtin University
Tilanka Chandrasekera
Oklahoma State University
Yuan Chao
National University of Singapore
Jia-Yih Chen
Taoyuan Innovation Inst of Tech.
Sheng-Fen Chien
National Cheng Kung University
Angelos Chronis
IAAC
Birgul Colakoglu
Istanbul Technical University
Kristof Crolla
Chinese University of Hong Kong
Jan Cudzik
Gdansk University of Technology
Pierre Cutellic
ETHZ
Mahesh Daas
University of Kansas
Bauke de Vries
Eindhoven Uni. of Technology
Matias del Campo
University of Michigan
Danilo Di Mascio
University of Huddersfield
Antonino Di Raimo
University of Portsmouth
Wolfgang Dokonal
Graz University of Technology
Mark Donohue
California College of the Arts
Theodoros Dounas
Robert Gordon University
Stylianos Dritsas
SUTD
Halil Erhan
Simon Fraser University
Alberto T. Estévez
Univ. Internacional de Catalunya
Alessandra Fabbri
University of New South Wales
Ruwan Fernando
Griffith University
Paolo Fiamma
Pisa University
Thomas Fischer
Xi'an Jiaotong-Liverpool Uni.
Pia Fricker
ETHZ Aalto University
Takeshi FUJII
Ritsumeikan University
Tomohiro Fukuda
Osaka University
Nicole Gardner
University of New South Wales
John Gero
Uni. of North Carolina Charlotte

Ning Gu
University of South Australia
Matthias Hank Haeusler
University of New South Wales
Jeremy Ham
RMIT University
Oliver Heckmann
SUTD
Christiane M. Herr
Xi'an Jiaotong-Liverpool Uni.
Pablo C. Herrera
Uni. Peruana Ciencias Aplicadas
Urs Hirschberg
Graz University of Technology
Weixin Huang
Tsinghua University
Yinghsiu Huang
National Kaohsiung Normal Uni.
Yasushi Ikeda
Keio University
Aswin Indraprastha
Institut Teknologi Bandung
Tim Ireland
University of Kent
Patrick Janssen
National University of Singapore
Michael Jefferson
University of Michigan
Taysheng Jeng
National Cheng Kung University
Guohua Ji
Nanjing University
Nathaniel Jones
Arup
Iestyn Jowers
The Open University
Sam Joyce
SUTD
Han-Jong Jun
Hanyang University
Anja Jutraz
University of Ljubljana
Gabriel Kaprielian
Temple University
Aysegul Akcay Kavakoglu
Istanbul Kemerburgaz University
James Kerestes
Ball State University
Chin Koi Khoo
Deakin University
Joachim B. Kieferle
Hochschule RheinMain
Sung-Ah Kim
Sungkyunkwan University
Michael Carlos Barrios Kleiss
Clemson University
Christoph Klemmt
University of Applied Arts Vienna
Robert Klinc
University of Ljubljana
Yoshihiro Kobayashi
Arizona State University
Tuba Kocaturk
Deakin University
Volker Koch
Karlsruhe Institute of Technology
Odysseas Kontovourkis
University of Cyprus
Toni Kotnik
Aalto University
Matthias Kulcke
Technische Universität Hamburg
Dennis Lagemann
ETHZ
Ih-Cheng Lai
Tamkang University
Ji-Hyun Lee
KAIST
Carla Leitao
Rensselaer Polytechnic Institute
Antonio Leitao
Technical University of Lisbon
Surapong Lertsithichai
Mahidol University
Biao Li
Southeast University
Andrew Li
Kyoto Institute of Technology
Chieh-Jen Lin
Tainan University of Technology
Yuezhong Liu
National University of Singapore
Tian Tian Sky Lo
Harbin Institute of Technology
Paul Loh
University of Melbourne

Thorsten Lomker
Zayed University Dubai
Russell Loveridge
ETHZ
Elisa Lublasser
RWTH
Sandra Manninger
University of Michigan
Adam Marcus
California College of the Arts
Bob Martens
Technical University of Vienna
Michio Matsubayashi
National Inst. of Technology
Iain Maxwell
University of Technology Sydney
Benachir Medjdoub
Nottingham Trent University
Annalisa Meyboom
Uni. of British Columbia
Tane Moleta
Victoria University of Wellington
Sina Mostafavi
TU Delft
Volker Mueller
Bentley Systems
Hugo Mulder
IT University of Copenhagen
Michael Mullins
Aalborg University
Rizal Muslimin
University of Sydney
Walaiporn Nakapan
Rangsit University
David Newton
University of Nebraska-Lincoln
Tsz Yan Ng
University of Michigan
Konstantinos-Alketas Oungrinis
Technical University of Crete
Mine Özkar
Istanbul Technical University
Burak Pak
KU Leuven
Dimitris Papanikolaou
Uni of North Carolina Charlotte
Hyoung-June Park
University of Hawaii
Panagiotis Parthenios
Technical University of Crete
Chengzhi Peng
University of Sheffield
Frank Petzold
Technical University Munich
Nick Pisca
0001D LLC
Ebrahim Poustinchi
Kent State University
Marshall Prado
University of Tennessee
Clemens Preisinger
University of Applied Arts Vienna
Alberto Pugnale
University of Melbourne
Ahmad Rafi
Multimedia Univeristy
Dagmar Reinhardt
The University of Sydney
Luis Romao
Technical University of Lisbon
Yasushi Sakai
MIT
Marc Aurel Schnabel
Victoria University of Wellington
Gerhard Schubert
Technical University of Munich
Mathew Schwartz
New Jersey Institute of Tech.
Jane Scott
The University of Leeds
Davide Simeone
Sapienza Università di Roma
Rudi Stouffs
National University of Singapore
Abel Tablada
National University of Singapore
Joshua Taron
University of Calgary
Kostas Terzidis
Tongi University
Oliver Tessmann
Technische Uni. Darmstadt
Ziyu Tong
Nanjing University
Bianca Toth
Woods Bagot

Armando Trento
Sapienza Università di Roma
Carmen Trudell
Rensselaer Polytechnic Institute
Cetin Tuker
Mimar Sinan Fine Arts University
Bige Tuncer
SUTD
Ziga Turk
University of Ljubljana
Pedro de Azambuja
Varela University of Porto
Kathy Velikov
University of Michigan
Joshua Vermillion
University of Nevada Las Vegas
Maria Vogiatzaki
Aristotle Uni. of Thessaloniki
James Walker
Royal Danish Acad. of Fine Arts
Tsung-Hsien Wang
University of Sheffield
Glen Wash
Xi'an Jiaotong-Liverpool University
Renate Weissenböck
Graz University of Technology
Liss Werner
Technische Universität Berlin
Claudia Westermann
Xi'an Jiaotong-Liverpool Uni.
Emily White
OCAD University
Nicholas Williams
Aurecon Melbourne
Albert Wiltsche
Graz University of Technology
Andrew John Wit
Temple University
Thomas Wortmann
SUTD
Ding Wowo
Nanjing University
Yen-Liang Aw Wu
NTUST
Yiqiang Xiao
South China Uni. of Technology
Satoshi Yamada
Ritsumeikan University
Christine Yogiaman
SUTD
Rongrong Yu
Griffith University
Philip F. Yuan
Tongji University
Andrzej Zarzycki
New Jersey Institute of Tech.
Yannis Zavoleas
University of New South Wales
Marciej Zawidzki
Polish Academy of Sciences

Keynote Speakers

Diffusive Architecture: Pluripotency and Entropy
Philip Beesley

Designing New Socio-Economic Imaginaries
Chris Speed

Design is Real, Complex, Inclusive, Emergent and Evil
Justyna Karakiewicz

TABLE OF CONTENTS

Foreword v

Conference Theme: Intelligent & Informed vi

About CAADRIA vii

CAADRIA Officers viii

CAADRIA 2019 Conference Committees viii

International Review Committee ix

Keynote Speakers xii

Smart Buildings/Cities/Regions 9

A Spatial Decision Support Framework For Planning 11
Pradeep Alva, Patrick Janssen, Rudi Stouffs

Method for Finding Elements Similar to Those Causing Building Component Failure Based on Building Information Models 21
Michio Matsubayashi

Planting Design by Simulated Competition 31
Michael White, M. Hank Haeusler, Yannis Zavoleas

Village Heritage Conservation in the New Data Age 41
Nan Bai, Lu Wang

Master Planning with Urban Algorithms 51
Bianca Ilha Pereira

Algorithms, AI and Architecture 61
Dermott McMeel

Synthesizing 360-Degree Live Streaming for an Erased Background to Study Renovation using Mixed Reality 71
Yuehan Zhu, Tomohiro Fukuda, Nobuyoshi Yabuki

Development of Generating System for Architectural Color Icons Using Google Map Platform and Tensorflow-Segmentation 81
Yuri Kato, Shohei Matsukawa

Communication Framework AND Emojis-Danmaku Applied To Cooperation Workshops 91
Yi-Sin Wu, Teng-Wen Chang

Context-Aware Mass Customization Construction System 101
Filipe JS Brandao, Alexandra Paio

Bespoke Tools Providing Solutions for Contemporary Problems 111
Will Wang, Ralph Spencer Steenblik

Developing Algorithmic Methodology to Visualize & Evaluate the Dynamics of Urban Form in the Early Design Phase 121
Shao-Yu Cha, Tay-Sheng Jeng

PixelGreen 131
Chin Koi Khoo, H. Koon Wee

Co-Designing in Social VR 141
Tomás Dorta, Stéphane Safin, Sana Boudhraâ, Emmanuel Beaudry Marchand

Intelligent Informed Landscapes 151
Marie Davidová

Informed Walkable City Model 161
Aswin Indraprastha, Bima Dwi Pranata Putra

Human-Building Collaboration 171
Daniel Rosenberg, Alexandros Tsamis

An Urban Form-Finding Parametric Model Based on the Study of Spontaneous Urban Tissues 181
Mohammed Aqil Cheddadi, Kensuke Hotta, Yasushi Ikeda

BIM-based Live Sensor Data Visualization using Virtual Reality for Monitoring Indoor Conditions 191
Worawan Natephra, Ali Motamedi

Enhanced Building Services 201
Andrzej Zarzycki

Classification and Review of Software Applications in the Context of Urban Design Processes 211
Hossein Behmanesh, André G.P. Brown

Collaborative Large-Scale Urban Design with the Focus on the Agent-Based Traffic Simulation 221
Kateryna Konieva, Katja Knecht, Reinhard Koenig

A Generative Design Method for the Functional Layout of Town Planning based on Multi-Agent System 231
Ruocheng Zhang, Hanshuang Tong, Weixin Huang, Runzhou Zhang

Non-Standard Housing 241
Jeroen van Ameijde

Design Cognition **251**

Caterpillar 253
Hao Zheng, Barrak Darweesh, Heewon Lee, Li Yang

Additive Manufacturing with Natural Composites 263
Stylianos Dritsas, Yadunund Vijay, Ryan Teo, Samuel Halim, Naresh Sanandiya, Javier G. Fernandez

Programming Intelligent Architecture to be Responsive to Real-Time Data 273
Hyunjae Nam

Optimization of Clay Mould for Concrete Casting Using Design of Experiments 283
Sihan Wang, Zack Xuereb Conti, Felix Raspall

Blockchain Grammars - Designing with DAOs 293
Theodoros Dounas, Davide Lombardi

Reflection in Action 303
Alice Sandstrom, Hyoung-June Park

Computational Measurement of Prospect-Refuge Perception in Two-Dimensional Built Space 313
Wenzhi Huangfu, Wang Leung Thomas Chung

Stereolithography with Randomized Aggregates 323
Elizabeth Teo, Yun Jie Pang, Yu Xie, Pheeraphat Ratchakitprakarn, Rebekah Low, Stylianos Dritsas

Robotic Free-Oriented Additive Manufacturing Technique for Thermoplastic Lattice and Cellular Structures 333
Manuel Ladron de Guevara, Luis Borunda, Jeremy Ficca, Daragh Byrne, Ramesh Krishnamurti

The Nature of Data in Early Modern Architectural Practice. 343
Chris Bamborough

Augemented Architecture 353
Surapong Lertsithichai

Adaptive Modular Spatial Structures for Shotcrete 3D Printing 363
Norman Hack, Hendrik Lindemann, Harald Kloft

Influences of a New Digital Cultural Layer on Design at Varying Scales 373
James Holth, Scott Meekings, Marc Aurel Schnabel, Tane Jacob Moleta

Agency of Interactive Space in Social Relationship 381
Kristina Boychenko

Designing for Shape Change 391
Elena Vazquez, Benay Gursoy, Jose Duarte

Data Informed Branch Typologies for Structurally Optimised Curvilinear Surfaces 401
Maryam Houda, Daniel Dias-da-Costa

A Blockchain Approach to Supply Chain Management in a BIM-Enabled Environment 411
Adam Fitriawijaya, Tsai Hsin-Hsuan, jeng Taysheng

Machinic Design Inference: from Pokémon to Architecture 421
Immanuel Koh, Pedro Amorim, Jeffrey Huang

Space Semantics 431
Sarah Yap, Gloria Ha, Rizal Muslimin

Prototyping of Chitosan-Based Shape-Changing Structures 441
Sachin Sean Gupta, Dhileep Kumar Jayashankar, Naresh D Sanandiya, Javier G. Fernandez, Kenneth Tracy

Innovative Design Approach to Optimized Performance on Large-Scale Robotic 3D-Printed Spatial Structure 451
Zhewen Chen, Liming Zhang, Philip F. Yuan

Theory, Philosophy & Methodology **461**

Digital Fabrication - From Tool to a Way of Thinking 463
Daniela Silva

Architectural Form Generation Based on the DNA Algorithm 471
Chuanwen Luo, Mingyu Jin, Lu Yin

Design Practice Complexity in the Post-Digital Age 481
Sining Wang, Kristof Crolla

Capturing Parametric Design Exploration Process 491
Verina Cristie, Sam Condrad Joyce

Three-Dimensional Model and Network-Based Representation of Traditional Japanese Wooden Building System 501
Keita Kado, Gakuhito Hirasawa

Architectural Computing 511
Dimitris Papanikolaou

Robotic Fabrication of Doubly Curved Façade System 521
Paul Loh, David Leggett, Daniel Prohasky

Oriole 531
Ebrahim Poustinchi

Design Cybernetics and CAAD Research 541
Christiane M. Herr, Thomas Fischer

Triangulated Shell Foam Structures based on Robotic Hot-Wire-Cutting 551
Thomas Fischer, Christiane M. Herr, Michael Grau

Towards to a Hybrid Model-Making Method based on Translations between Physical and Digital Models 561
Dongchen Han, Hong Zhang, Weiwen Cui, Jie Huang

Intelligent Territory 571
Alina Hramyka, Neil Grewal, Mohammad Makki, Brittney Dillon

Towards an History of Computational Tools in Automated Architectural Design 581
Nadja Gaudilliere

Practice & Interdisciplinary **591**

Diversity and Efficiency 593
Likai Wang, Patrick Janssen, Guohua Ji

Designing Out Urban Heat Islands 603
Stephen Green, Geoff King, Alessandra Fabbri, Nicole Gardner, M. Hank Haeusler, Yannis Zavoleas

Use of UAV Photogrammetry to Estimate the Solar Energy Potential of Residential Buildings in Severe Cold Region 613
Yunsong Han, Yongjie Pan, Tianyu Zhao, Chunxing Wang, Cheng Sun

Quantifying Visual Environment by Semantic Segmentation Using Deep Learning 623
Rui Cao, Tomohiro Fukuda, Nobuyoshi Yabuki

The Future of Environmental Performance Architectural Design Based on Human-Computer Interaction 633
Yuqiong Lin, Jiawei Yao, Chenyu Huang, Philip F. Yuan

Face-to-Face with People in Spaces 643
Tiara Dobbs

Discoverable Desks 653
Sophie Scott, Ben Doherty, Alessandra Fabbri, Nicole Gardner, M. Hank Haeusler

Computational Design Education/Conversation 663

Visual Programming for Geo-COmputation 665
Patrick Janssen, Derek Pung, Kian Wee Chen

Redefining Mixed Reality: User-Reality-Virtuality and Virtual Heritage Perspectives 675
Mafkereseb Kassahun Bekele, Erik Champion

A Critical Framework of Smart Cities Development 685
Victor Calixto, Ning Gu, Gabriela Celani

The Scholarly Rewards and Tragic Irony of 3D Models in Virtual Heritage Discourse 695
Hafizur Rahaman, Erik Champion

Intelligent Systems and Mass Production of Form 705
James Forren

Teaching Computational Design and BIM in the Age of (Semi)flipped Classrooms 715
Dominik Holzer

Human-Computer Interaction; Collaborative & Collective Design **725**

Reimagining Relativity 727
Jessie Rogers, Marc Aurel Schnabel, Tane Jacob Moleta

Sensory Urbanism and Placemaking 737
Anastasia Globa, Rui Wang, Beau B. Beza

Using an Online Participation Tool to Collect Relevant Data for Urban Design 747
Ludovica Tomarchio, Stephanie Hasler, Pieter Herthogs, Johannes Müller, Bige Tunçer, Peijun He

'Harmonielehre' for Architects 757
Urs Hirschberg

The Church of AI 767
Matias del Campo, Sandra Manninger, Marianne Sanche, Leetee Wang

Amplifying Citizens' Voices in Smart Cities 773
Iman Sayah, Marc Aurel Schnabel

Artificial Intelligence & Machine Learning **783**

Approach to Auto-recognition of Design Elements for the Intelligent Management of Interior Pictures 785
Jinsung Kim, Jaeyeol Song, Jin-Kook Lee

Optimising Image Classification 795
Jennifer Mei Yee Ng, Nariddh Khean, David Madden, Alessandra Fabbri, Nicole Gardner, M. Hank Haeusler, Yannis Zavoleas

Identifying Highly Dense Areas from Raw Location Data 805
Elias Jakobus Willemse, Bige Tuncer, Roland Bouffanais

Identifying the Landscape of Machine Learning-Aided Architectural Design 815
Tania Papasotiriou

Smart Buildings/Cities/Regions

A SPATIAL DECISION SUPPORT FRAMEWORK FOR PLANNING

Creating Tool-Chains for Organisational Teams

PRADEEP ALVA[1], PATRICK JANSSEN[2] and RUDI STOUFFS[3]
[1,2,3]*School of Design & Environment, National University of Singapore*
[1]*pradeepattavaralva@gmail.com* [2]*patrick@janssen.name*
[3]*stouffs@nus.edu.sg*

Abstract. In practice, most planners do not make significant use of planning support systems. Although significant research has been conducted, the focus tends to be on supporting individual tasks, and the outcomes are often the development of new stand-alone tools that are difficult to integrate into existing workflows. The knowledge contribution in this paper focuses on developing a novel spatial decision support framework focusing on the workflows and tool-chains that span across different teams within an organisation, with varying skill sets and objectives. In the proposed framework, the core decision-making process uses set decision parameters that are combined using a weighted decision tree. The framework is evaluated by developing and testing tool-chains for a real-world land suitability case study. The tool-chain was implemented on top of a GIS platform.

Keywords. GIS SDSS PSS; Planning Automation; Geoprocessing; Data Analytics; Geoinformatics.

1. Overview

Although many Spatial Decision Support Systems (SDSS) and Planning Support Systems (PSS) exist, most planners do not make significant use of such systems in practice (Geertman & Stillwell 2003, 2009; Vonk 2006, Schilder 2016). The aim of the research is to explore an alternative approach to the effective use of PSS and SDSS, evaluated through a land suitability case study. The focus is on developing systems for large organisations with teams of diverse professionals with different expertise.

In order to improve the support function of PSS, a better conceptual and empirical understanding is required of the relation between planning tasks and PSS. Pelzer et al. (2015) discuss the concept of task-technology fit and PSS. They believe this concept can lead to a better understanding of the usefulness that is reachable by different planning support capabilities of a PSS for different tasks. However, PSS research typically focuses on supporting individual tasks, and the outcomes are often the development of new stand-alone tools that are difficult to integrate into existing workflows.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 11-20. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

In our research, we focus on workflows rather than individual tasks. Rather than developing stand-alone tools, we aim to support specific workflows by developing tool-chains on top of existing GIS frameworks. These workflows and tool-chains will typically span across different teams within the organisation, with varying skill sets and objectives. For example, a key challenge is a typical workflow in which planning decisions need to be made based on geoprocessed data (Zhu and Ferreira 2015). In such a workflow, the task for the GIS team involves analyzing large amounts of geospatial data, which is typically slow and requires a high level of technical knowledge. The task for planners focuses on decision making using that processed data, which must be interactive and requires domain knowledge. Finally, the results of the decisions need to be communicated by the managerial team.

This paper discusses how such planning tasks within an organisation can be linked into seamless workflows, supported by geospatial tool-chains. In order to demonstrate the proposed framework, a case-study on land suitability assessment and resource management is presented. The case study is based on workflows being developed by NUS in partnership with JTC Corporation, the lead agency in Singapore spearheading the planning, promotion and development of the industrial landscape.

The next section proposes geospatial tool-chains, and section 3 presents a case study focusing on land suitability assessment and resource management. Finally, section 4 draws conclusions and discusses directions for future research.

2. Geospatial Tool-Chains

In the proposed framework, the core decision-making process uses a set of decision parameters that are combined into a single metric. The parameters are first calculated based on the latest geospatial data. Once each parameter is calculated, overall fitness is then derived by using a weighted decision tree (Klosterman et al. 2018). These weights may vary depending on any kind of development for an assessment of land suitability. As a result, the weights must be user-defined.

For example, for supporting decisions related to land suitability, the parameters may include Land Area, Plot Ratio, Shape and Location. When making queries, a user can set the desired weightages for each of these parameters. This decision tree is then used to calculate assessments for all of the available plots (see Figure 1). Each plot is then given a percentage score, 100% being the maximum score for the specific query.

Such a decision-making process will be embedded within a broader workflow. The research proposed a workflow consisting of three main stages, with customized tools targeting different types of users with varying expertise. A definite workflow is proposed, consisting of three main stages: 1) Geoprocessing performed by the GIS team, 2) Interactive decision making performed by the planners, and 3) Communications performed by the managerial team (see Figure 2).

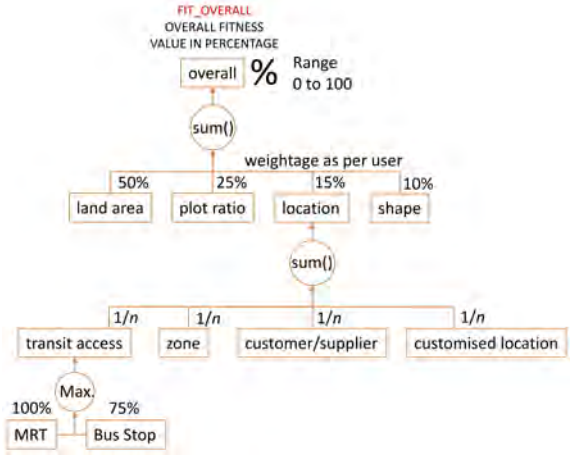


Figure 1. Decision tree.

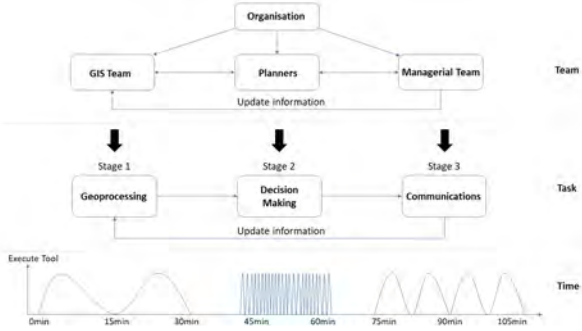


Figure 2. Tool-chain workflow.

2.1. THREE STAGES

Such planning workflows will typically involve different teams from varying departments in an organisation. In the proposed framework, a series of tools are developed for performing specific tasks in the workflow. In addition, an important issue is also the flow of data between specific tasks performed by different teams.

- Stage 1 - The *geoprocessing task* is performed by the GIS team, as this stage deals with compiling the latest data for the decision tree. The decision tree will need to be defined before this stage can be carried out.
- Stage 2 - The *decision making task* is performed by planners with specific domain skills in an organisation. This process may include extensive customisation and exploration of the decision-tree weights.
- Stage 3 - The *communications task* is performed by the managerial team, creating reports to be presented and deployed to a land developer. If the requirements cannot be met, the process will usually go back to stage 2.

The geoprocessing task handled by the GIS Team is the slowest task to execute, but is executed infrequently and does not need to be interactive. This task results in data sets that are then consumed by the decision making task. This task must be fast and interactive so that the planners are able to iteratively explore many alternative parcels. Finally, the communications task will consume the data sets created by the decision making task, and produce a set of final reports for presentation to the land developer.

In this division of labour, the geoprocessing task is only executed when new input data is added to the GIS database, such as changes to the masterplans and new land use information. The decision making-task, on the other hand, can be executed multiple times without having to re-execute the time-consuming geoprocessing task. If the requirements cannot be met, then the communications task can loop back to the decision-making task to consider alternative plots. The formalisation of these three stages makes the overall decision-making logic more transparent and evidence-based.

3. Land Suitability Case Study

The case study focuses on a land suitability assessment process for different land use developments using open-data available (see Figure 3). This process involves land developers looking for real estate developments.

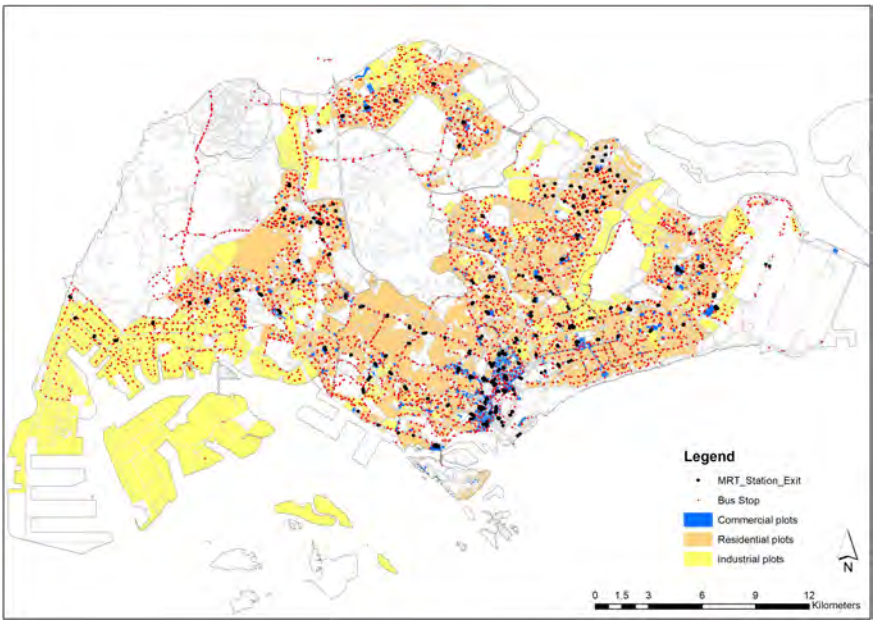


Figure 3. Plots with different land uses and public transit access in Singapore (open data source: data.gov.sg & mytransport.sg).

These land developers will approach organisations and will submit a request

for available land parcels that meet specified requirements. Through the land suitability assessment process, the organisation will select appropriate land parcels to present to the land developers. The land parcels are selected based on the requirements, taking into account planning regulations and other long term strategic planning goals. The process iterates back and forth filtering land parcels for different requirements and constraints in parallel.

A tool-chain has been developed and tested to semi-automate the land suitability assessment process (see Figure 4). The tool-chain combines various requirements and constraints into a single integrated query and helps planners to select land parcels based on geospatial data analysis

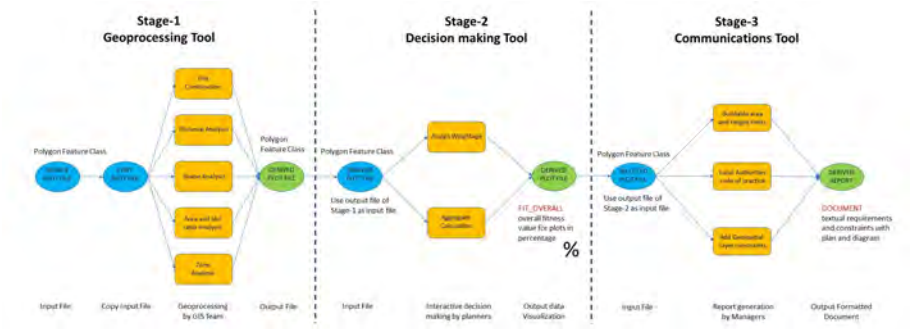


Figure 4. The land suitability assessment tool-chain with three stages. .

The Land Suitability tool-chain allows the planners to interactively query and interrogate an integrated database of land parcel information. The decision-making tool also provides the ability to customise the land query based on specific land developer requests.

The tools chains operate on GIS datasets called *feature classes*. Feature classes are homogeneous collections of common features, each having the same spatial representation, such as points, lines, or polygons, and a common set of attribute columns. Feature classes are stored in geodatabase files (.gdb). Geodatabase files were used due to their compact and efficient nature.

3.1. STAGE 1: GEOPROCESSING TOOL

The Geoprocessing Tool calculates spatial data required for the analysis performed with the Decision-Making Tool.

The main input to the Geoprocessing Tool consists of a feature class containing a set of land parcel polygons, referred to as *plots*. The results of the Geoprocessing Tool are added to this feature class as additional attributes. Other feature classes required by the tool include the masterplan with Gross Plot Ratio (GPR) information and public transit information (for buses and Mass Rapid Transit -MRT).

The types of analysis include shape analysis, regional or zone analysis, next to a specific customer/supplier, and additionally customised location preferences.

Additional feature classes may also be required depending on the types of analysis being performed.

3.2. STAGE 2: DECISION-MAKING TOOL

The Decision-Making Tool allows planners to interactively and iteratively assess available plots by setting the requirements and defining parameter weightages (see Figure 5).

The planners use the tool to enter the requirements from the land request and the weightages for the decision tree parameters. The tool then assesses the plot, and assigns an overall fitness value to each plot, normalised to the range of 0 to 100%. The fitness value is added as an additional attribute to the feature class. Plots are then ranked, with the plots with higher fitness being more suitable. In order to visualise this data, a heatmap of the plot fitness values is automatically generated. The planner can then review the plots with high fitness values and either select a preferred plot make, or adjust the parameter weightages and run a new query.

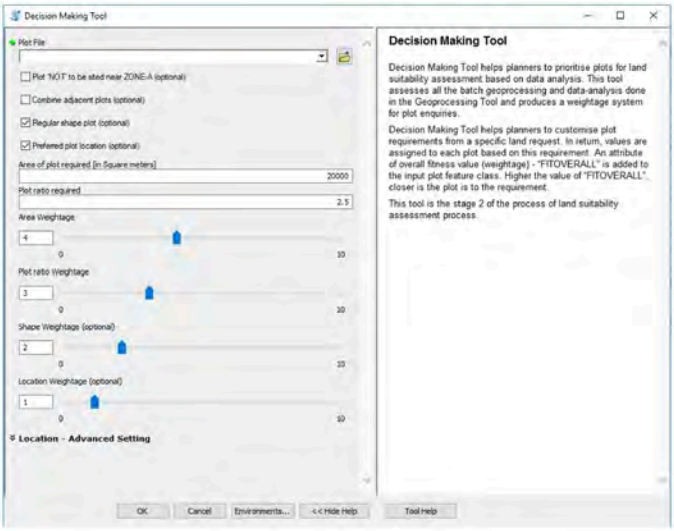


Figure 5. User interface of the Decision-Making Tool in ArcGIS.

3.3. STAGE 3: COMMUNICATIONS TOOL

The Communications Tool helps the managerial team to check various additional requirements and constraints based on the local authorities code of practices for a selected plot.

The tool checks two key constraints. The first constraint to be checked is the effective buildable area of the selected plot. The buildable area is calculated taking into account various no-build zones. These include no-build zones imposed by adjacent roads, with different road categories having different offsets. The second

constraint to be checked is the permissible building height of the selected plot. The building height is constrained by limits imposed by various government agencies. The maximum floor area for the development is first calculated based on the plot area and Gross Plot Ratio (GPR), which is derived from the Masterplan (2014). The building height is then calculated by applying a set of predefined rules for the selected building typology for the development of the buildable area of the plot. This building height is then checked against the height limits for the plot.

The tool also automatically generates a formatted report (in .docx format) that summarises all relevant information about the selected plot. The information in the report includes text and tables describing the key data for the selected plot, as well as all the regulations and codes of practice that are applicable. The report also includes a formatted plan diagram of the selected plot, showing graphical representations of some of the key constraints (see Figure 6). This report can be used for effective communication to the land developers or to officially register the chosen plot for tenure.



Figure 6. Result of Communications tool: plot plan showing calculated buildable area.

3.4. IMPLEMENTATION

The tool-chain has been implemented within the ArcGIS platform. This platform was chosen due to the fact that it is already commonly used within planning organisations, making tool adaptation and utilization easier. Our initial attempts to create tool-chains were developed using the ModelBuilder visual programming environment within ArcGIS. However, the programming paradigm lacked scalability and as a result, models quickly became very complex and difficult to understand. In the final version, all tools were implemented as Python tool scripts.

The three tools all include graphical user interfaces (GUIs) to allow users to enter the parameters, with built-in validation and error checking. The tools can be easily shared and deployed, becoming an integral part of the everyday working

environment. Documentation for each tool has also been developed, which can be accessed in the same way as the documentation for system tools (Zandbergen 2013). All three tools automatically filter out invalid data types and field names and will flag errors for the user, giving feedback and warnings.

In addition, all the output data of the three tools are saved inside geodatabase files (.gdb) located in a shared workspace in a network drive. This allows teams in the organisation to easily work together, linking and sharing data in a seamless way.

3.5. RESULTS

The tool-chain has been tested with a wide variety of queries using open data collected for plots in Singapore. As an example, a query for an industrial plot is presented. The query specifies the required plot area, GPR, plot shape, location, together with a set of decision tree weights. The results of the query are described below (see Figure 7 & 8).

Input Parameters	
Plot Area	20000 sq.m
Gross Plot Ratio (GPR)	2.5
Combine plots	Yes
Regular shape plot	Yes
Location preferred - Transit Access	Yes
Weightage Plot Area	3
Weightage Gross Plot Ratio	3
Weightage Shape	3
Weightage Location	1
Number of plots input	7484

=

Query Output	
Total number of plots combined	11555
Total number of plots output	19039
Available Plots	413

Figure 7. Plot query table.

The stage-1 Geoprocessing Tool was tested with a feature class containing 111,525 plot polygons. The time taken to execute the Tool was around 30 minutes. Stage-1 found 7484 industrial plots and created 11,555 second-order plot combinations. This resulted in a total of 19,039 plots available for query. The stage-2 Decision-Making Tool then filters these plots based on a set of specified weights and other requirements, resulting in a total of 413 available plots. The decision maker can then select the most suitable plot. Finally, the stage-3 Communications Tool can then be used to check additional requirements and constraints, and to generate a report.

At the end of stage-3, the registration of the selected plot is fed back into the database. This becomes a part of an organisational process, as the managerial team informs the GIS Team of these updates, thereby closing the geospatial data loop. Within the framework, the system, organisation, and its members go hand-in-hand in maintaining and manipulating geospatial data.

The tool-chain is currently limited to a specific number of input parameters. If additional parameters need to be added, then these can be added. This would require both the geospatial data schema and the Python script to be updated. However, such modifications may be difficult for users who are not familiar with Python programming and who do not have knowledge of the various tool templates defined within ArcGIS. Approaches are being investigated that are more flexible and modular, allowing additional parameters to be defined without requiring

programming.

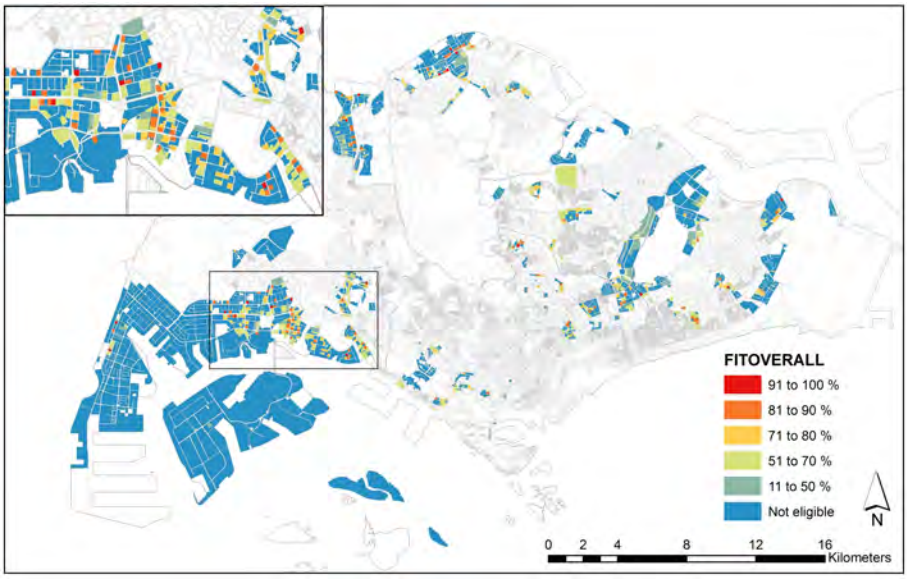


Figure 8. The result of land suitability assessment query using tool-chains.

4. Discussion

The paper has presented a spatial decision support framework focusing on the workflows that span across different teams within the organisation, with varying skill sets and objectives. A tool-chain was implemented on top of ArcGIS, supporting decision making for planners. In the proposed framework, the core decision-making process requires set decision parameters that need to be combined using a weighted decision tree (Klosterman et al. 2018).

A case-study demonstration is presented on land suitability assessment and resource management. In the decision-making stage, the planners assign priorities to different types of spatial analysis and filter land parcels. This tool-chain helps planners to select plots based on geospatial data analysis. The demonstration shows how planning tasks within an organisation can be linked to seamless workflows.

The broader aim of this research is to develop a practice-orientated approach to creating Planning Support Systems. A key problem with existing SPSS and PSS systems is that they are developed in isolation of the workflows within organisations. This results in a lack of synergy between the tools and the workflows in practice. This research started by first mapping out end-to-end workflows that existed within the organisation. Based on these workflows, a set of modular and flexible tool-chains were then developed on top of the existing GIS infrastructure already being used within the organisation. This approach ensures that these tools and system are well aligned with the workflows, result in effective

usage. Future research will apply the same overall approach to other planning workflows, including long-term planning projections taking into account various dynamic urban and city-scale constraints.

Acknowledgements

This research received funding support from NUS-JTC i3Centre. We would like to thank the JTC Corporation, under the Deputy Directorship of Aloysius Iwan Handono, for their support in providing information and technical data to facilitate the development of the workflows and tool-chains.

References

Ching, T.Y. and Ferreira, J. (2015), Smart Cities: Concepts, Perceptions and Lessons for Planners., *in* S. Geertman, J.r. J. Ferreira, R. Goodspeed and J. Stillwell (eds.), *Planning Support Systems and Smart Cities. Lecture Notes in Geoinformation and Cartography.*, Springer, Cham, 145-168.

Geertman, S., Allan, A., Pettit, C. and Stillwell, J. (2017), Introduction to 'Planning Support Science for Smarter Urban Futures', *in* S. Geertman, A. Allan, C. Pettit and J. Stillwell (eds.), *Planning Support Science for Smarter Urban Futures. CUPUM 2017. Lecture Notes in Geoinformation and Cartography.*, Springer, Cham, 1-19.

S. Geertman and J. Stillwell (eds.): (2003), *Planning Support Systems in Practice*, Springer-Verlag Berlin Heidelberg.

S. Geertman and J. Stillwell (eds.): (2009), *Planning support systems: Best practices and new methods*, Springer, Dordrecht.

Klosterman, R.E., Brooks, K., Drucker, J., Feser, E. and Renski, H.: 2018, *Planning Support Methods: Urban and Regional Analysis and Projection*, Rowman & Littlefield.

Pelzer, P., Arciniegas, G., Geertman, S. and Lenferink, S.: (2015), Planning Support Systems and Task-Technology Fit: A Comparative Case Study, *Applied Spatial Analysis and Policy*, **8(2)**, 155–175.

Schilder, M.C.: (2016), *Planning support systems in urban development in the Netherlands*, Master's Thesis, Delft University of Technology.

Stouffs, R. and Janssen, P. (2017), A Rule-Based Generative Analysis Approach for Urban Planning., *in* J.H. Lee (ed.), *Morphological Analysis of Cultural DNA. KAIST Research Series.*, Springer, Singapore, 125-136.

S. Toms and D. O'Beirne (eds.): (2017), *ArcPy and ArcGIS - Second Edition: Automating ArcGIS for Desktop and ArcGIS Online with Python*, Packt Publishing.

Vonk, G.: (2006), *Improving planning support; The use of planning support systems forspatial planning*, Ph.D. Thesis, Utrecht: Nederlandse Geografische Studies.

Vonk, G. and Geertman, S.: (2008), "Appl. Spatial Analysis" . Available from Open Access Article<https://doi.org/10.1007/s12061-008-9011-7> (accessed 11th June 2008).

P.A. Zandbergen (ed.): (2015), *Python Scripting for ArcGIS*, ESRI Press.

Zhu, Y. and Ferreira, J. (2015), Data Integration to Create Large-Scale Spatially Detailed Synthetic Populations., *in* S. Geertman, J.r. J. Ferreira, R. Goodspeed and J. Stillwell (eds.), *Planning Support Systems and Smart Cities. Lecture Notes in Geoinformation and Cartography.*, Springer, Cham, 121-141.

METHOD FOR FINDING ELEMENTS SIMILAR TO THOSE CAUSING BUILDING COMPONENT FAILURE BASED ON BUILDING INFORMATION MODELS

MICHIO MATSUBAYASHI
[1]*National Institute of Technology, Kushiro College*
[1]*matsubayashi@archi.kushiro-ct.ac.jp*

Abstract. In this study, we propose a method for finding elements similar to those that cause failure based on the spatial information and properties of the building component network in building information models (BIMs). As an example of failure, we selected the degradation of fittings such as doors. The developed process was performed using a BIM software package. First, we identified elements that had experienced failure based on past repair records. Then, similar elements were found based on information for a door class obtained from the selected element. Finally, the elements were filtered using either spatial or attribute information, and the results were exported as a comma-separated values file. An operation that adds other information to the attribute information of the elements extracted from the BIM is also proposed. After a sufficient number of items were identified, elements similar to the failed elements are identified by sorting.

Keywords. Building Information Model; Existing Buildings; Preventive Maintenance; Spatial Information; Attribute Information.

1. Introduction

The conservation of the building stock constructed during Japan's period of high economic growth, from the mid-1950s to the early 1970s, is now an urgent problem in Japan. Many buildings were constructed during this period. Sudden failures frequently occur in these buildings because of their age. For example, it has been reported that a window frame fell out and a handrail collapsed in buildings belonging to educational institutions. Thus, the maintenance of buildings and lifelines in educational institutions in Japan should be improved immediately. Our group develops facilities management technology using building information models (BIMs). In a previous case study, we converted old drawings for buildings at a university into BIMs for use in conservation (Matsubayashi, 2014). Our study focused on the utility value of the shape and attribute information that was acquired from existing design documents.

The engineering teams responsible for maintenance are understaffed because of Japan's declining population. At the same time, it has been reported that the total area of national university's buildings is increasing annually (MEXT, 2018a). Thus, it is necessary to effectively maintain these facilities with fewer engineers.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 21-30. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Solutions include shorting the time required to repair failures. Building failures are easier to deal with if the various types of information related to a building are utilized effectively and the failure causes can be predicted.

All building components can be integrated into a single database, such as a BIM. Such virtual models make it possible to discern elements with characteristics similar to those of other elements by using the spatial information and properties of the building component network. These associations cannot be determined using traditional tools, such as paper drawings and computer-aided drafting data. Because traditional tools classify drawings in terms of the cutting plane and viewpoint, drawings are unrelated. For facility management, a method for retrieving elements based on the information of a selected element would enhance the utility value of a BIM.

BIMs are useful throughout the life cycle of buildings. Eastman et al. (2008) showed the merit of employing a BIM for various users concerned with the life cycle of buildings. A BIM created during construction enabled owners and facility managers to efficiently manage and renovate facilities. The International Facility Management Association (2013) showed the merit of employing a BIM for facility managers. They discussed the legal issues associated with creating and handling a BIM for various users, and described an international data format for managed asset information. Motamedi et al. (2014) proposed a system called the FM Visual Analytics System that provides knowledge-assisted, BIM-based, and customized visualizations for finding the root causes of failure. This system employs fault tree analysis developed by facility management experts, manufacturers, or researchers to show the possible causes of a certain failure. Nakama et al. (2015) developed a system called the Building Information Management System that displays a BIM generated using BIM software on a website. Matsubayashi et al. (2016a) developed a process for converting a BIM into a two-dimensional schematic diagram for air conditioning systems considering that many engineers who maintain facilities are more familiar with such diagrams. Matsubayashi et al. (2016b) proposed a method for calculating the failure interval of a building component using information obtained from a BIM.

Few studies have focused on using the spatial information and properties of the building component network in a BIM for facility management, and few have focused on using a BIM for the preventive maintenance of existing buildings.

In this paper, we propose a method for more efficiently manage facilities using a BIM. Elements with characteristics similar to those of failed elements are found using the spatial information and properties of the building component network. The degradation of fittings such as doors is used as an example of failure.

2. Preparation for development of proposed process

2.1. BUILDINGS AT UNIVERSITY OF TSUKUBA

As a case study, we used a BIM created from old drawings and specifications for buildings at the University of Tsukuba. The Tokyo University of Education moved from Tokyo to Tsukuba Science City and reopened as the University of Tsukuba in October, 1973. Because most of the buildings were built during this period, their

deterioration is similar.

A serious accident, the collapse of the roof of a passage connecting buildings, occurred at the Tsukuba campus in December, 2017. After this accident, all connecting passages assumed to be in similar condition were urgently examined at the campus. When we interviewed members of the university's Department of Facilities to determine the criteria of selecting connecting passages for examination, they stated that they had identified connecting passages by confirming the shapes of those drawn on a site map of the campus and added them to the list of examination targets. This accident highlights that efficiently identifying elements with risks similar to those of failed elements using limited information is important in conservation.

2.2. CREATION OF BUILDING INFORMATION MODELS USING EXISTING DESIGN DOCUMENTS

Building 5C, designed by the well-known Japanese architect Fumihiko Maki, has been in use since the opening of the University of Tsukuba over forty years ago. Table 1 gives an overview of Building 5C. It is a six-story, multi-purpose building, with laboratories and rooms for offices, meetings, and classes. Seismic reinforcement work on the building was carried out from 2006 to 2008; the air conditioning, plumbing, and electrical systems in the entire building were renovated during this period. This study used Revit building design software to create the BIM, shown in Figure 1, and model building components based on design documents from these most recent renovation projects.

After elements were located in the BIM, the attribute information for each element was entered. Before inputting information, we compared the attribute information of a door in existing design documents with those of a door in the BIM. Except for door type (single or double doors), there were no common items. Since entering all attribute information would be extremely time-consuming, we decided to enter the minimum number of items into the BIM. When confirming the fittings table and the layout of doors in the design documents, we found that the doors in the fittings table were classified by the item "mark". Therefore, the mark of a door was selected among the items listed in the fitting table. The marks were entered into the item "comments" for a door. In addition, in order to manage the values listed in a fittings table as digital data, the information was entered into a Microsoft Excel spreadsheet. In this way, we can confirm the attribute information of a door written in existing design documents by using the marks.

Table 1. Overview of Building 5C.

Item	Description
Location	Tsukuba campus (University of Tsukuba)
Structure	Steel (partly steel-encased reinforced concrete)
Floors	B1F–6F
Total floor area	18,027 m^2
Major building projects	1973: Initial construction 2006-2008: Renovation

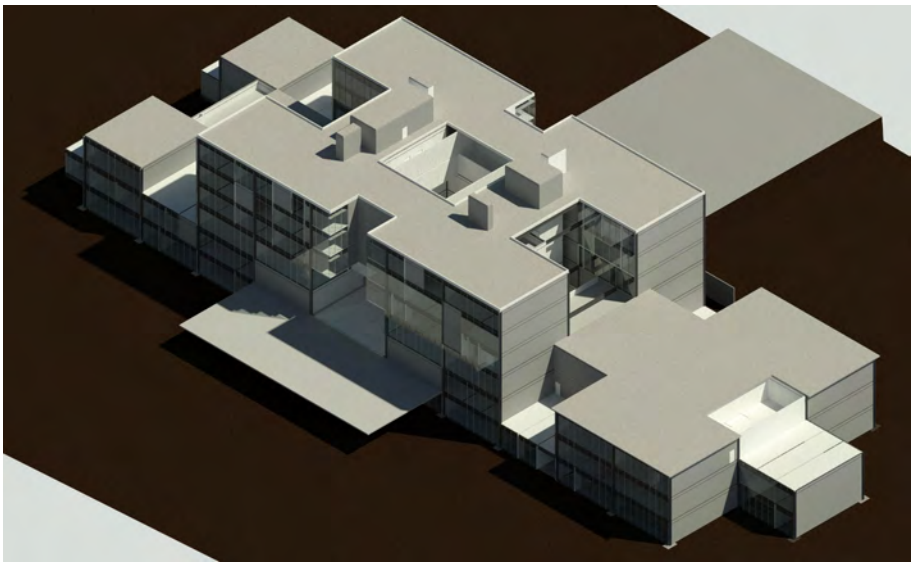


Figure 1. Building information model of Building 5C.

2.3. SELECTION OF BUILDING COMPONENT FAILURE TYPE

There are various types of building failure. As an example of failure, we selected the degradation of fittings such as doors. Although such failures are not serious, they consume a significant portion of engineering time because they are numerous. The failure example was selected by mainly referring to the repair request documents used at the University of Tsukuba. Table 2 shows an overview of such documents. When a building failure is found, documents are filled out with the details of the failure and sent to the university's Department of Facilities via e-mail or fax. The documents for a period of one year were analyzed. The most common item for repair was "others". After the items "electrical facilities" and "air conditioning" were removed, "door failure" was the most common item. In addition, the results of a questionnaire by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) showed that fittings had high repair demand (MEXT, 2018b).

Table 2. Overview of repair request documents used in our analysis.

Item	Description
Document type	Documents used for contacting Facilities Department when building problems occur.
Period	April 1, 2014 – March 31, 2015
Coverage	Tsukuba campus (391 buildings)
Number of documents	3,407
Repair request items	Water leak, Rain leak, Power failure, Water failure, Telephone problem, Gas leak, Others
Terms often seen in "others"	Light bulb, Fluorescent bulb, Air conditioner, Door, Lighting fixture, Drainage of toilet, Plumbing fixture, Window

The procedure for finding elements similar to those that caused failure was

decided by analyzing the repair request documents and by using the results of the interviews with members of the university's Department of Facilities. Table 3 shows items related to door failure in Building 5C. In Building 5C, most door failures involved door components such as a door closer. The detachment of a door is another repair request item. In the interviews, we were told that it would be effective to find candidate elements by using a common item after all elements had been obtained. Thus, we decided to use the information of the element that had caused failure (i.e., it was selected in the BIM). Based on the attribute information of the selected element, we found elements that had the same class and filtering those that had a common table item. For attribute information not provided in the BIM, tables acquired from additional resources were coupled with those of extracted elements by using a spreadsheet program. Sorting was then conducted using the item most related to the failure. As shown in Table 4, we decided each method corresponding to the contents of each failure. The locations of the obtained elements were confirmed by using the IDs of candidate elements. Figure 2 shows a flow chart of the developed process.

Table 3. Number of repair requests and details of door failures in Building 5C.

Total number of repair requests	**Number of repair requests related to doors**
94	15
Item	**Example**
Door component	Door closer, Door stopper, Door knob, Door lock
Door detachment	-
Others	Positional displacement of panel in bathroom stall, Door does not shut properly

Table 4. Assumed failures used for developing the proposed process.

Assumed failure	**Method**	**Description**
Door component (door closer, door stopper, door knob)	Sorting using most related item	Search for elements that have the same parts
Common	Sorting using a mark	Search for elements that have the same mark
	Designation of a range using the coordinates of the failed element	Search for elements located near the failed element
	Filtering of elements using the wall that includes the failed element	Search for elements that are included in the same wall

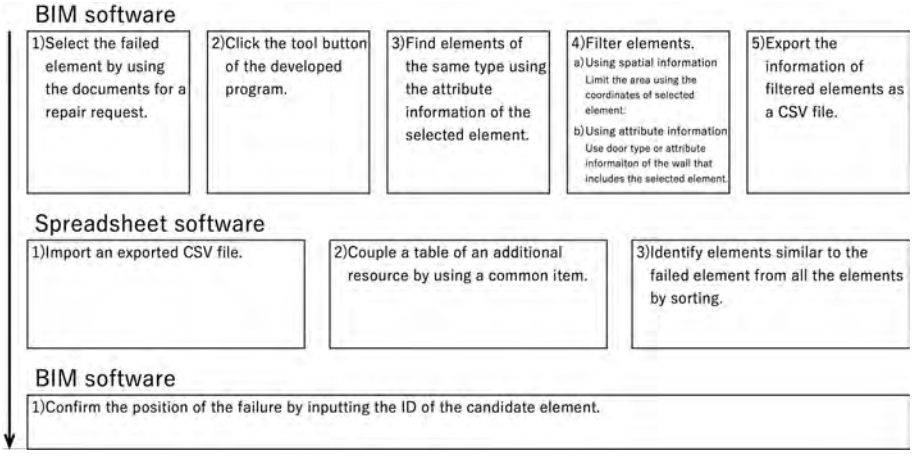


Figure 2. Procedure for searching for elements similar to those that caused failure.

3. Development of proposed process

3.1. FINDING ELEMENTS FROM BUILDING INFORMATION MODEL

The process was performed within the Revit platform, and implemented using the Revit application programming interface (API) in C Sharp. After the program collects other doors by using the attribute information of the selected door, it exports spatial and attribute information of them. A screenshot of the program is shown in Figure 3.

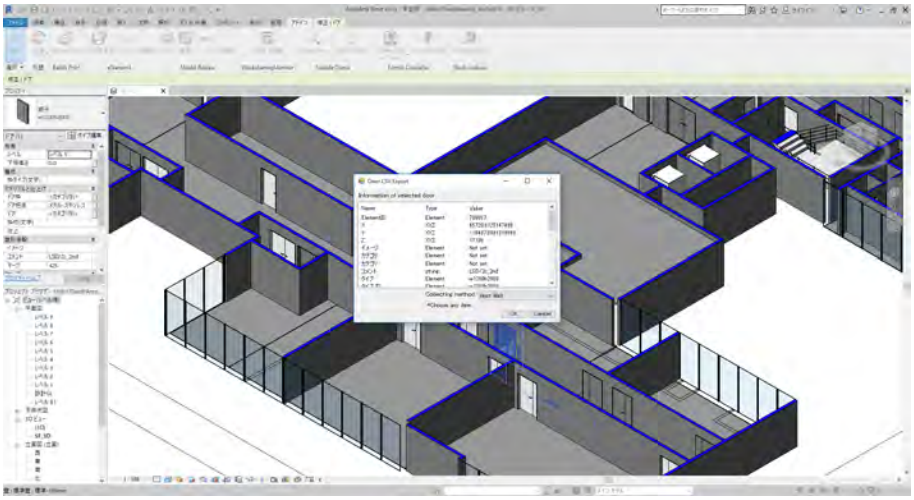


Figure 3. Screenshot of the execution of add-in command in Autodesk Revit and the generated dialog.

After we confirmed the spot where the failure occurred using repair request documents, we identified the element. We selected the element that had experienced failures to start the program. The program was executed when the tool icon in the upper ribbon was selected. The list of attributes obtained from the selected element was confirmed using the generated dialog. Doors were found based on the door class obtained from the selected element. Next, the elements were filtered using spatial and attribute information as needed. The range of spatial information was based on the coordinates of the selected element. The elements were limited to a range of 10 m in width and 10 m in depth from the position of the selected element, and were limited to the same floor.[1] The door type and the ID of the wall that includes the selected door were also used for filtering elements.

Finally, the elements were filtered using either spatial or attribute information, and the results were exported as a comma-separated values (CSV) file, which included the ID, name, class name, coordinates, host wall's ID, host wall type, and comments. Additional items were recorded for table coupling in a spreadsheet when needed.

3.2. JOINING TABLES OUTSIDE BIM SOFTWARE

A technique for adding other information to the attribute information of the elements extracted from the BIM is proposed as an additional operation. Additional resources included specifications and past repair records. Information from these resources was added to the database elements based on common features. Microsoft Excel was used to create the spreadsheets. In this study, the information recorded in the fittings table of the design documents was added to a CSV file. Table coupling was executed using the marks entered in the item "comments". These marks corresponded to those in the fittings table created using spreadsheet software. Figure 4 shows a screenshot of a spreadsheet after table coupling. The yellow column shows items added from an additional resource. After a sufficient number of items were identified, elements similar to the failed element were identified by sorting. After sorting, the locations of the obtained elements were confirmed in BIM software by inputting the IDs of candidate elements.

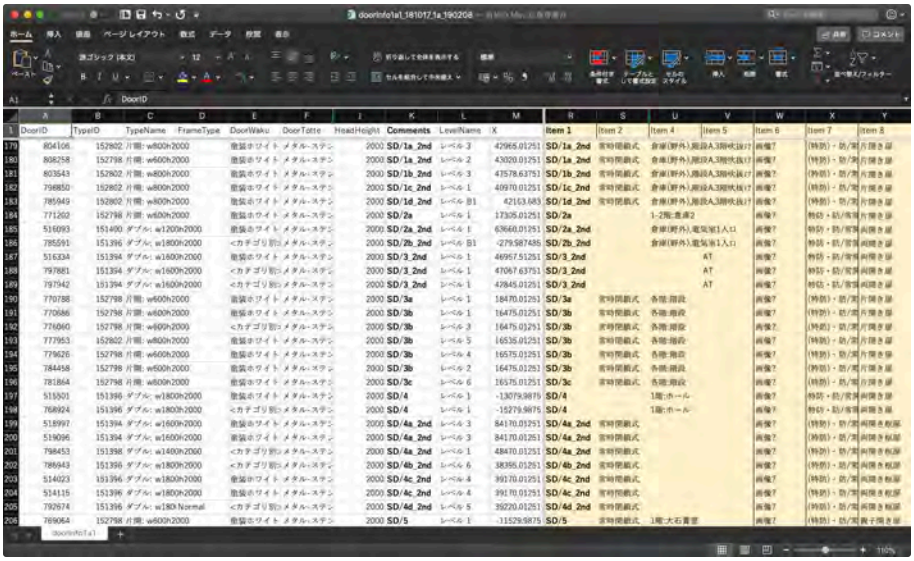


Figure 4. Screenshot of spreadsheet after table coupling based on the item "mark".

4. Case study

For the door failures in Building 5C, the number of candidates was counted after doors were filtered using the developed process. Door failures classified using the item "others" were found. 11 failures and 24 doors were use in the analysis.[2] In the repair request documents, each request was classified according to a location. Multiple doors were found for most rooms (confirmed using the BIM). Thus, the doors in each room were distinguished one by one. According to the contents of each failure, each filtering method was determined. The numbers of candidates

obtained after each filtering process are shown in Table 5. For door component failure, the elements were filtered mainly using the item of the door component most related to the failure. The items of door components were included in the fittings table, and coupled using spreadsheet software. For other types of failure, the elements were filtered by door type. Filtering using coordinates and the ID of the wall that includes the door were also conducted for each door.

Table 5. Numbers of candidates obtained after filtering using the developed process.

No.	Date	Floor	Location	Item used for sorting	# of candidates after filtering using "mark"	# of candidates after filtering using item for sorting	# of candidates after filtering using coordinates	# of candidates after filtering using host wall ID
1a	April 1, 2014	2	Room No. 212	Door closer	5	213	0	0
1b	April 1, 2014	2	Room No. 212	Door closer	8	213	2	3
1c	April 1, 2014	2	Room No. 212	Door closer	8	213	3	3
2	May 26, 2014	6	East emergency staircase	Mark	8	-	1	0
3a	May 28, 2014	3	Room No. 307	Mark	14	-	2	3
3b	May 28, 2014	3	Room No. 307	Mark	14	-	4	3
4a	June 4, 2014	6	Room No. 617	Door closer	10	213	4	5
4b	June 4, 2014	6	Room No. 617	Door closer	10	213	4	5
5a	June 19, 2014	1	Room No. 315	Door closer	4	213	1	3
5b	June 19, 2014	1	Room No. 315	Door closer	1	213	1	3
6a	July 22, 2014	1	Stair hall	Flush bolt	5	-	5	2
6b	July 22, 2014	1	Stair hall	Flush bolt	8	236	5	0
7a	August 8, 2014	3	Room No. 317	Door closer	14	213	2	3
7b	August 8, 2014	3	Room No. 317	Door closer	14	213	4	3
8a	October 3, 2014	4	Room No. 406	Mark	23	-	2	1
8b	October 3, 2014	4	Room No. 406	Mark	23	-	2	1
8c	October 3, 2014	4	Room No. 406	Mark	59	-	0	1
8d	October 3, 2014	4	Room No. 406	Mark	59	-	4	1
9a	October 20, 2014	3	Room No. 307	Door closer	10	213	2	3
9b	October 20, 2014	3	Room No. 307	Door closer	10	213	4	3
10a	December 15, 2014	1	Room No. 108	Arm or door stopper	12	324	4	1
10b	December 15, 2014	1	Room No. 108	Arm or door stopper	12	324	8	0
10c	December 15, 2014	1	Room No. 108	Arm or door stopper	2	324	8	0
11	February 12, 2015	1	Room No. 128	Door closer	10	213	1	0

Many elements remained when the elements were filtered using the item of a door component because many doors used the same components, as confirmed using the fittings table. In this case, it is necessary to further filter the elements using other items, such as the floor number. To find elements located near the selected element, the ID of the wall that includes the door and the door coordinates were used. The number of candidates became small when this information was used.

The repair request documents specified the rooms with door failure, but not which door failed, which affected the results. Nevertheless, the proposed method provides candidates based on actual data, making maintenance more efficient. In the future, facility engineers could go to the location of reported failure and confirm the failure using the acquired list.

5. Conclusion

We developed a method for finding building elements similar to those that caused failures based on the spatial information and properties of the building component network in a BIM. The proposed method uses the door coordinates and the ID of the wall that includes the selected door, which cannot be obtained using traditional tools, such as paper drawings and computer-aided drafting data. A case study of Building 5C showed that we could generate lists that included elements with characteristics similar to those of failed elements by using items acquired from a BIM and those from the fittings table in design documents. These lists are useful for preventive maintenance. The proposed method enables the association of more information than that possible using previous management systems.

The validity of the lists produced by the proposed method should be confirmed

with inspections. In addition, it is necessary to evaluate the generated lists using interviews with facility engineers.

Regarding added attribute information, it is necessary to find information that is closely related to the failure. In the proposed method, the item used for sorting greatly influences the results. If we expand the scope of information, and if we can use the information of not only a door but also the element that involves it (e.g., a wall that includes the failed door), the choices for the sorting increase. It is important to create new items for data coupling by acquiring information for other elements from a selected element. For example, it is assumed that the number of users of a room is closely related to the frequency of door use in the room. To obtain the number of users of a room, room information is necessary. We thus need to extend the program so that we can obtain room information from the door element in the BIM.

To further develop the program, the types of failure should be increased. This would make the program applicable to more types of failure.

Endnotes

1. To confirm only elements near the element that had experienced failures, these functions were added. A range of 10 m in width and 10 m in depth was decided after the surface area of a building floor was considered in this paper.
2. Only the repair requests regarding doors were found from those that included the item "others". The number of door failures in Building 5C was 15, but some were excluded. Some excluded failures were those related to doors of bathroom stalls. These doors are not listed in the fittings table in the design documents. In addition, doors not listed in the design documents for the renovation work were excluded.

Acknowledgements

This work was supported by JSPS (Japan Society for the Promotion of Science) KAKENHI Grant Numbers JP18K13906.

References

Eastman, C., Teicholz, P., Sacks, R. and Liston, K.: 2008, *BIM Handbook*, John Wiley & Sons, New Jersey (USA).

IFMA, F.o.u.n.d.a.t.i.o.n.: 2013, *BIM for facility managers*, John Wiley & Sons, New Jersey (USA).

Matsubayashi, M. and Watanabe, S.: 2014, Converting drawings and specifications of building stock to BIM model, *Proceedings of the 19th international conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2014*, Kyoto (Japan), 929-930.

Matsubayashi, M. and Watanabe, S.: 2016a, Generating two-dimensional schematic diagrams of mechanical, electrical, and plumbing systems from three-dimensional building information models, *International Journal of Architectural Computing*, **14(3)**, 219-232.

Matsubayashi, M. and Watanabe, S.: 2016b, Forecasting time between problems of building components by using BIM, *Proceedings of CAADence in Architecture*, Budapest (Hungary), 107-112.

Motamedi, A., Hammad, A. and Asen, Y.: 2014, Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management, *Automation in Construction*, **43**, 73–83.

Nakama, Y., Onishi, Y. and Iki, K.: 2015, Development of building information management system using BIM toward strategic building operation and maintenance, *Proceedings of the 20th international conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2015*, Daegu (Korea), 397–406.

Ministry of Education, Culture, Sports, Science and Technology, initials missing: 2018a, "Annual report on actual state of facilities of Incorporated National University" . Available from (in Japanese)<http://www.mext.go.jp/a_menu/shisetu/kokuritu/__icsFiles/afieldfile/2018/08/31/1297929_1.pdf> (accessed 18th November 2018).

Ministry of Education, Culture, Sports, Science and Technology, initials missing: 2018b, "Questionnaire result about aging facilities of Incorporated National University" . Available from (in Japanese)<http://www.mext.go.jp/b_menu/shingi/chousa/shisetu/047/shiryo/__icsFiles/afieldfile/2018/02/05/1400948_01.pdf> (accessed 18th October 2018).

PLANTING DESIGN BY SIMULATED COMPETITION

A computational-ecological model for the selection and distribution of plant species on urban roof terraces

MICHAEL WHITE[1], M. HANK HAEUSLER[2] and
YANNIS ZAVOLEAS[3]
[1,3] *UNSW*
[1,3] *{M.G.White|Y.Zavoleas}@unsw.edu.au*
[2] *UNSW & CAFA Visual Innovation Institute Beijing*
[2] *M.Haeusler@unsw.edu.au*

Abstract. This paper investigates ecologically-inspired computational strategies for the intelligent performance based landscape design of urban rooftop gardens. Plant communities in nature form resilient layouts that maximise use of available resources through a process of competitive pressure. Simulating these processes could allow us to design vegetation systems for the built environment that are adapted to variables on site, while meeting our design goals. This paper uses an agent-based model to ask if simulated ecological competition can be used as a computational method for producing effective planting layouts for urban roof terraces. A case study will be conducted to review the performance of the simulation. Through further research we will examine whether these strategies can also optimise for benefits including increased biodiversity, favourable microclimate, and reduced energy and water use.

Keywords. Computational Landscape Architecture / Ecology; Urban Heat Island; Rooftop Terrace Gardens; Emergence; Climate Change.

1. Introduction

This paper presents the potential for digital methods of competitive ecological plant community simulation in landscape architecture as an intelligent and informed way to address climate change challenges. Through research in performative landscape architecture it has been demonstrated that benefits of vegetation include mitigation of urban heat-island effect, pollution filtration, increase in thermal comfort, noise attenuation, and decrease in surface runoff (White 2018). To fully capture and quantify these benefits requires a model of soft-vegetative landscape that can predict and maximise design performance.

This research is motivated by a call from Ecologists and others for a greater consideration of ecological principles in the design and planning of built

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 31-40. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

landscapes in literature including the approach of 'Designer Ecosystems' (Ross 2015). A number of landscape architects and planting designers have proposed 'Designed Plant Communities' that incorporate ecological principles into urban landscape design (Rainer 2015, Lovell 2009). One can observe that this movement towards Designed Ecologies is linked to the theory of performative landscape architecture in which quantitative metrics such as water and air quality, infiltration, biodiversity and others are key drivers of the design process.

We take this as a starting point to explore and deepen the use and understanding of computational-ecological models for the selection and distribution of plant species and positioning our research, its background and literature review, methodology and case studies through this paper.

2. Literature Review

2.1. ECOLOGICAL PLANTING DESIGN

One of the recurring themes in the field of landscape architecture, from the 'picturesque controversy' to landscape ecology today, asks what the aims of planting design actually are. It is often unclear, for example, whether the goal is to create a facsimile of natural systems, or an explicitly anthropocentric environment. This has relevance to this papers development of planting designs by simulation of natural processes. Marc Treib (1999) in *Nature Recalled* argues that the modernist movement in architecture led to the decline of formalist 'designed landscapes' and that this was contributed to by the naturalist influence of McHarg's Design with Nature and his reverence for ecological systems as a model. While this paper draws upon the tools of simulated ecology to inform design, it seeks to expand the use of these tools to make more informed decisions regardless of conceptual approach.

Thomas Rainer and Claudia West (2015) discuss the concept of Designed Plant Communities, in which planting designs are generated with an understanding of ecological principles at work in natural environments. Both scholars draw upon these principles in an effort to develop planting schemes that are resilient, and sustainable, and ones requiring minimal maintenance while also capturing some of the aesthetic qualities of a 'wild' landscape. Examples of this can be found in the work of the German landscape architect Heiner Luz and Dutch planting designer Piet Oudolf.

Recent research by Ross (2015) in ecology suggests that incorporating simulation and ecological principles in landscape design can lead to more sustainable and resilient outcomes. Ross distinguishes Designer Ecosystems from other forms of human intervention as sites that are *"designed as ecosystems, taking advantage of internal ecosystem feedbacks to provide a suite of ecosystem services beyond a single primary goal"*.

In ecological plant modelling, the development of Universal Adaptive Strategy and CSR (Competitors, Stress Tolerators and Ruderals) Theories by Grime (1974) provide some insight into the processes by which plant species interact. Each plant species optimises for survival and propagation under particular conditions. A common example would be a forest in which two species of trees dominate. The first species is fast growing and suited to full sunlight, while the second is slower

growing but prefers low-light, moist conditions. With the starting conditions of a grassland, the first species will rapidly grow to dominate the canopy, however once this canopy is established future conditions favour the growth of the second species which will eventually come to dominate until some interruption to the equilibrium. The application of this theory to digital ecosystem models has been aided by the use of Functional-Structural Plant Models (Godin 2015, Bornhofen 2008).

In natural ecosystems plants are distributed by biological methods of dispersal including wind-blown seeds, spreading rhizomes and animal vector dispersal. These plants are subjected to survival pressure and competition resulting in a pattern of 'best fit' in which the plants are suited to their location and conditions by selection. In contrast traditional models of planting design plants may be arranged geometrically or randomly according to matrices and seed mixes. Although some effort is made to locate plants in suitable positions, competition is suppressed by horticultural practice and location and selection is fixed by design. Simulated competition as a means of distribution may provide superior planting performance.

2.2. REVIEW OF EXISTING METHODS OF THE DIGITAL REPRESENTATION OF PLANTS

"We might call the form of an organism an event in space-time, and not merely a configuration in space" (Thompson 1917).

Methods of digital representation of plants can be broadly divided into two categories: The first, described here as Geometric representations describe the fully developed form of the plant at a particular point in its life cycle. These include early Lindenmayer-systems, interactive procedural modellers developed by Deussen et al, models utilising a Space Colonization algorithm and simple two-dimensional representations (Lindenmayer 1997, Deussen 1998, Lane 2002). The second, described here as Functional models describe how individual plants change and grow over time in response to stimulus and available resources. These include Functional-Structural Plant Models or FSPMs, later extended L-system methods and particle-based models tracing the flow of resources (Godin 2005). It is important to note that although these models represent broad approaches, further developments have extended each to new applications.

Lindenmayer and Prusinkiewicz's 'The Algorithmic Beauty of Plants' popularised the field of algorithmic botany describing the use of L-systems or Lindenmayer-systems (Lindenmayer & Prusinkiewicz 1997). L-systems are a grammar-based method in which strings of characters are iteratively rewritten according to procedural rules. This string of characters is used to represent instructions to draw the plant structure in 2D and 3D space. L-systems allow for the expression of plants as both physical objects in space and processes existing across time using a grammars that capture the hierarchical growth process (Kurth 2007). The later development of multi-level systems allows the modelling of both individual plant and groups of plants by adding a higher level L-system to control the spatial distribution of plants (Lane 2002).

The advantages of L-Systems are:

- They allow for procedural generation of species models rather than relying on

a fixed library of static models.
- They allow some visualisation and analysis of growth over time with later additions.
- Instances can be generated at render time from a compact dataset of parameters.

Deussen developed a graph-based modelling system using an interactive system of rule-nodes that can be connected to form a procedural method for generating a particular species (Deussen 2008). This method eventually became the basis for the commercial software XFrog. This software and related approaches are used to develop the majority of photo-realistic digital models for the entertainment industry including films and videogames due to the high level of realism, and the degree of control over the outcome by artists (Vos, Struik & Evers 2002).

Functional-Structural Plant Models were developed for the study of factors affecting plant growth, competition and environmental dynamics (Godin 2005). Particularly these models are used to simulate light, water and energy as they are captured by the plant and lead to physical change and growth. Further development in the agricultural and forestry industries has led to 'virtual experiments' in which simulations of plant communities drive commercial and conservation decision-making. FSPMs integrate the 3D structure of plants with their underlying biological processes. It is this capability that makes FSPMs a candidate for further application in performative landscape design.

Following is a preliminary summary table of the characteristics of the approaches to digital plant modelling discussed.

Table 1. Comparison of Methods for Digital Plant Modelling.

Generative Method	Interaction with environment	Complexity	Open Source	Physical Forces	Biological Processes
0L-Systems	No	Low	Yes	No	No
Extended L-Systems	Yes	High	Yes	Yes	Yes
Space Colonisation	No	Low	Yes	No	No
Resource particle systems	Yes	High	Yes	Yes	Yes
XFrog (Deussen et al)	Yes	High	No	Yes	No

2.3. ARTIFICIAL LIFE AND VIRTUAL PLANT ECOSYSTEMS

A number of methods have been developed to distribute individual digital plants in a way that resembles real ecological communities. Artificial Life systems simulate the life and growth cycles of plants over time. Multi-level L-systems integrate the mechanism of distribution with the structure of individual plants.

One method simulates competition between adjacent plants based on their ecological neighborhoods of effect (Deussen 1998). These techniques of simulated competitive pressure demonstrate an ability to create planting layouts that are intelligently adapted to their base environment. Deussen's example below shows plants with high water tolerance out-competing less suitable plants in wet areas. Although this method has practical applications to the built environment, Deussen's primary goal was superficial realism to create synthetic images of ecosystems for use in visual media.

In response to work by Deussen and others Benes noted that the degree of 'clustering' or the tendency of plants to be distributed near closely related neighbors was not as pronounced as in images of real world landscapes. Benes developed a method of distribution in which plants have a tendency to reproduce within regions defined by bezier curves. These regions compete against each other in aggregate, exchanging territory with other clusters while maintaining relative monocultures within.

Following earlier work in the development of L-systems, Lane developed a model of multi-level L-systems in which the distribution of individual plants could be controlled by a replacement grammar (Lane 2002). This allowed a process of two-way feedback in which the form and growth of an individual plant was affected by the structure of the community.

The primary goal of the virtual plant communities created by the computer graphics community is 'visual plausibility' (Deussen 1998, Benes 2002). While some of the models developed are relevant to the practice of landscape architecture, successful application will require validation of the simulations against real environments.

3. Methodology

3.1. OVERVIEW

The computational method used for the ecological simulation is an agent-based model of competitive growth as utilized by Deussen (1998), taken there from the ecological model of plant interference & self-thinning by Firbank & Watson (1985).

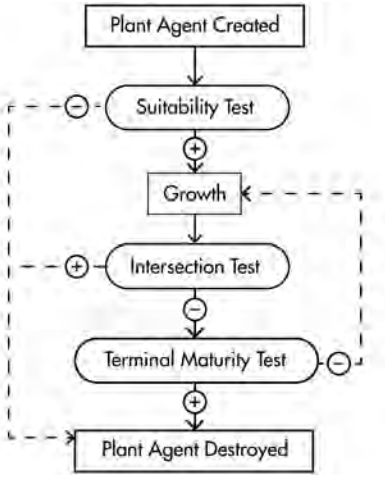


Figure 1. Diagrammatic methodology.

Individual plant agents are subjected to a competitive ecological simulation in which their chance of survival and expansion at each stage is determined by the suitability of local conditions for the growth of their given species. As

individuals intersect, a suitability factor determines which plant will out-compete and dominate a given area. Plants will also die out after surviving for a given number of generations based on that species longevity.

The computational method includes the following steps:

1. Planting Agents are created and assigned variables from the botanical data table in Fig 2.
2. Microclimate matrices are calculated including soil depth and hours of sunlight
3. A survival-suitability metric is calculated for each plant by comparing conditions at its position to the botanical data.
4. A growth process is initiated for successful plants according to their growth rate.
5. As plants intersect, those that are outcompeted or do not have the resources required for survival are eliminated.
6. Successful plants are retained and new plants introduced in the next generation. New plants are introduced as immature specimens.

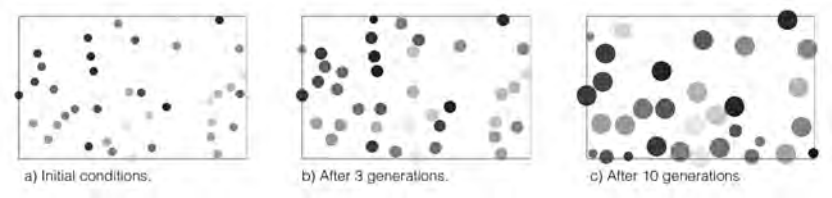


Figure 2. Agent-based ecological simulation.

3.2. BOTANICAL DATA

Plant species were selected from species present across eastern New South Wales, Australia, in the area local to the subject site.

Table 2. Botanical Input Data - characteristics of plant species.

Botanical Name	minSoil	Sun	Water	growthRate	matureSize	lifeSpan
Themeda triandra[1]	300	4-10	100-2700	0.075	0.4	60
Lomandra longifolia[1]	300	4-10	600-2000	0.125	0.5	60
Eremophila glabra[1]	450	4-10	150-550	0.15	1	60
Liriope muscari[1]	300	2-8	700-2300	0.075	0.5	48
Viola hederacea[1]	300	0-6	900-2700	0.075	1	40

[1] Species data from Florabank (Florabank 2018)

Botanical data was collated from a number of sources to predict viable conditions for growth. These conditions were compared to conditions in locations across the case-study site to generate a survivability score. See table 2.

- Species: Abbreviated botanical name.
- minSoil: minimum required soil depth for healthy plant development.

- minSun: minimum average hours of sunlight for healthy plant development.
- maxSun: maximum average hours of sunlight for healthy plant development.
- minWater: minimum annual rainfall in mm.
- maxWater: maximum annual rainfall in mm.
- growthRate: rate of radial growth per year measured in metres.
- lifeSpan: maximum longevity measured in years.

4. Case Study

4.1. URBAN ROOF TERRACES

With the increase of urbanization and apartment living a reduction in available recreational space has occurred and more urban residents are relying on shared roof terraces for their recreational needs. Kennedy et al (2015) found that in new multi-residential developments "the availability of natural ventilation and outdoor private living spaces play important roles in resident perceptions of liveability. ... Many domestic activities are conducted in exterior private spaces such as verandas, balconies and terraces". These terraces face challenges to providing amenity including solar exposure due to lack of large trees and high winds due to elevation. Many of these spaces are under-utilised due to lack of comfort. Water is typically provided through irrigation, and planting may fail in times of drought.

With this new development comes a change in the lifestyle for new generations who live in dense urban areas. Meanwhile, such a change brings about significant challenges, as for example that residents occupying exterior private spaces in dwellings are potentially exposed to noise discomfort (Ibid. 2015) as well as other environmental concerns such as inadequate shade and exposure to high winds. The design of these spaces is required to balance diverse goals and challenges including thermal comfort, energy use and increased social interactions among residents (Huang 2006).

4.2. DATA COLLECTION

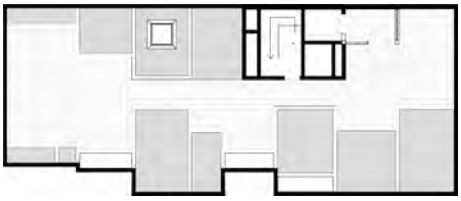


Figure 3. Case study roof terrace architectural layout.

Environmental data collection was conducted to predict conditions on an existing roof terrace. Solar information was calculated using DeltaCodes Shadow Analysis software. Available soil depth was recorded based on structural constraints.

This data was composed into bitmap files and input into the ecological simulation in Grasshopper. Future development will include the automation of this process using existing plugins.

4.3. RESULTS

An ecological simulation was conducted to generate a proposed planting layout for the roof terrace landscape. See Figure 5 for the progression of the plant community over time as it adapts to conditions on site.

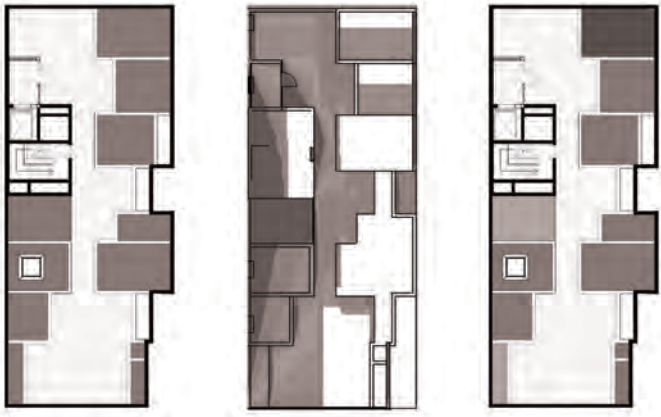


Figure 4. Environmental condition metrics for case study roof terrace (from left to right: Area available for planting, hours of direct sunlight per day, maximum soil depth over structure).



Figure 5. Progression of ecological simulation on case study roof terrace (from left to right: initial seed conditions, results after 5 iterations, results after 50 iterations).

Plant species in these images have been assigned a colour-value according to their tolerance for shade conditions. See Figure 5 for a time series illustrating the

colonisation of shaded areas by shade tolerant plants as they out-compete species less suited to the local environment.

5. Conclusion

This proposal views a functional computational model of plants as a cornerstone in the future capacity of landscape architects to meet performative goals at all scales. The simulation of plant groups as functional systems both contributing to and affected by the conditions of their local environment is key to understanding how designers can improve these conditions through plant selection and design. Closer integration of the fields of landscape architecture and ecology has been proposed by proponents of the theories of landscape urbanism and landscape ecology (Ross 2015). This work will contribute to the ongoing development of a computational, simulation based approach to planting design and visualisation in landscape architecture, continuing the work of Belesky, Deussen, White and others (Belesky 2018, Deussen 2015, White 2018) . These new tools will empower landscape architects to explore new possibilities of complex quantitative planting schemes whether naturalistic or formal in expression. The findings of this research may contribute to policy and planning regulations regarding best practices for planting design. Current challenges include access and availability of accurate botanical data for the range of species in cultivation. The accuracy of simulation needs to be further verified through real world tests. As a profession landscape architecture is rapidly moving into the digital realm, including integration with BIM models, and increased capabilities in computational and generative design. Ultimately this proposal aims to contribute to the broader development of a simulation-based approach to designing living systems that incorporates the latest evidence-based research. Simulation and testing of outcomes are profoundly employed in the design process by merging qualitative with quantitative data to propose more ecologically sustainable outcomes. Further research is required to develop the data appropriate sets as evidence to performative based landscape design. Without a significant increase in available data on the characteristics of individual plant species and cultivars there is a limit to the accuracy and applicability of the models discussed. Ongoing efforts in digital scanning and archiving and the development and continuous updating of open-access plant datasets are rapidly improving the availability of this information. Future investigation will explore the integration of this simulation model into documentation practices including an interactive planting generator using Dynamo and Revit.

References

Belesky, P.: 2015, A field in flux: Exploring the application of computational design techniques to landscape architectural design problems, *ACADIA 2015 - Computational Ecologies: Design in the Anthropocene*.

Belesky, P.: 2018, “Plants” . Available from <http://groundhog.la/documentation/plants/>.

Bornhofen, S. and Lattaud, C.: 2008, Evolving CSR strategies in virtual plant communities, *Artificial Life XI: Proceedings of the 11th International Conference on the Simulation and Synthesis of Living Systems, ALIFE 2008*, 72-79.

Deussen, O.: 1998, Realistic modeling and rendering of plant ecosystems, *Proceedings of the 25th annual conference on Computer graphics and interactive techniques - SIGGRAPH ’98*.

Deussen, O., Colditz, C., Stamminger, M., Drettakis, G., Deussen, O., Colditz, C., Stamminger, M., Drettakis, G. and Deussen, O.: 2002, Interactive visualization of complex plant ecosystems, *Proceedings Sixth International Conference on Information Visualisation*, **1**, 219-226.

Firbank, L.G. and Watkinson, A.R.: 1985, A Model of Interference Within Plant Monocultures School of Biological Sciences , University of East Anglia , Norwich, *Journal of Theoretical Biology*, **116**, 291-311.

Godin, C. and Sinoquet, H.: 2005, Functional-Structural Plant Modelling, *The New Phytologist*, **166**(3), 705-708.

Grime, J.P.: 1974, Vegetation classification by reference to strategies, *Nature*, **250**(5482), 26-30.

Herrington, S.: 2017, *Landscape Theory in Design*, Routledge.

Huang, S. C. L.: 2006, A study of outdoor interactional spaces in high-rise housing, *Landscape and Urban Planning*, **78**(3), 193-204.

Kennedy, R. and Buys, L. 2015, The Impact of Private and Shared Open Space on Liveability in Subtropical Apartment Buildings, *in* A.M. Wood (ed.), *Global Interchanges: Resurgence of the Skyscraper City*, Council on Tall Buildings and Urban Habitat, 318-323.

Korner, S., Bellin-Harder, F. and Huxmann, N.: 2016, Richard Hansen and modern planting design, *Journal of Landscape Architecture*, **11**(1), 18-29.

Kurth, W.: 2007, Specification of Morphological Models with L-systems and Relational Growth Grammars, *Image - Journal of Interdisciplinary Image Science*, **5**, 50-74.

Lane, B.: 2002, *Models of Plant Communities for Image Synthesis*, Ph.D. Thesis, University of Calgary.

Lindenmayer, A. and Prusinkiewicz, P.: 1997, *The algorithmic beauty of plants*, Springer Verlag.

Lovell, S.T. and Johnston, D.M.: 2009, Creating multifunctional landscapes: How can the field of ecology inform the design of the landscape?, *Frontiers in Ecology and the Environment*, **7**(4), 212-220.

Rainer, T. and West, C.: 2015, *Planting in a Post-Wild World: Designing Plant Communities for Resilient Landscapes*, Timber Press.

Ross, M., Bernhardt, E.S., Doyle, M. and Heffernan, J.: 2015, Designer Ecosystems: Incorporating Design Approaches into Applied Ecology, *Annual Review of Environment and Resources*, **40**, 419-443.

Treib, M. 1999, Nature Recalled, *in* J. Corner (ed.), *Recovering landscape*, Princeton Architectural Press, 29-43.

Vos, J., Struik, P.C. and Evers, J.B.: 2002, 3D modelling of plants : a review, *Plant Research International*, **52**, 1-23.

White, M.R. and Langenheim, N.: 2018, A Spatio-Temporal Decision Support System for Designing With Street Trees, *International Journal of E-Planning Research*, **7**(4), 1-24.

VILLAGE HERITAGE CONSERVATION IN THE NEW DATA AGE

Rural Information Modelling in the Context of Rural Vitalization in China

NAN BAI[1] and LU WANG[2]
[1]*Tsinghua University, Technical University Berlin*
[1]*bn16@mails.tsinghua.edu.cn*
[2]*Tsinghua University*
[2]*wang_lu@tsinghua.edu.cn*

Abstract. Rural Vitalization being a nation-wide policy for China in the following five years, it is becoming even more important to preserve and conserve the village heritage, especially with the global background of Information and Communication Technology (ICT) involvement. This research reviews on the existing and potential methods which has been or could be used to better understand the rural built environment in the new data age, and proposes an interactive message platform named Rural Information Modelling (RIM) which could collect, storage, analyze and display the various message concerning the village heritage, especially the morphological, cognitive and behavioural information. With the help of RIM, stakeholders can better interact with the rural environment, and better negotiate with each other, leading to a more objective and rational construction process, which could express the willingness of both the outside architects, urban planners and visitors, and the in situ villagers and government.

Keywords. Rural vitalization; heritage conservation; ICT; Rural Information Modelling.

1. Background

The global urbanization process had accelerated in the past century, turning already most of the world's population into urban residents. It is argued that by the end of the 21st century, the world would be totally urbanized, with most part of the globe connected with each other (Batty, 2011). If we are to accept the argument, the situation in China is still asking for much efforts. While Fei et al. (1992) defined the foundation of Chinese society as a rural society in the 1940s, the rapid development in contemporary China has been reversing the leading position of rural society. The population in the urban area exceeded the rural one in 2010 for the first time. However, the percentage of rural population in China is still far higher than the western countries, which means that the rural area is still a significant part in China nowadays, both spatially and socially. On September 26th, 2018, the CPC Central Committee and the State Council of China released

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 41-50. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

The Five-Year Plan on Rural Vitalization Strategy, expressing the strong intention of the government to support the development and modernization of rural China in the next five years (CPC and State Council, 2018).

As proposed by BMBF (Bundesministerium für Bildung und Forschung), the modern society has approached the age of Industry 4.0 (BMBF, 2013 & 2017), making everything tend to connect with everything else as Information and Communication Technology gets more involved in the everyday life, forming a giant spatial and social data network. The new data age has been constantly changing the urban areas into smart cities and even conscious cities (Bunschoten, 2017), but how will it also change the rural vitalization process in China at the same time?

2. Context

2.1. THE DEVELOPMENT OF RURAL STUDIES IN CHINA

Since the early scientific study of the society in rural China in the 1940s (Fei, et al., 1992), several pieces of research have been conducted, focusing on the economic, spatial, social or political aspects of the rural areas. Rural geology looks at rural space as a complex three-fold model, combining its physical locations, commercial exchanges and human culture with qualitative and quantitative methods (Long and Zhang, 2012). The ecosystem sustainability and the human perception towards the environmental changes are also seen as parts of rural spatial complexity (Laterra, et al., 2012). Along with the urbanization process in China, researches on rural-urban duality conversion have been conducted through methods like governance policy analysis, on-site surveys and Cellular Automata (Wu, 2002, 2018; Shen et al., 2013).

However, the rural-urban duality has been somehow destroying the weaker rural social ecology. Many houses were left empty and the public space was greatly ignored since the major rural population went to cities for their careers. The Vacancy of Architecture was leading the spatial structure and local characteristics destroyed and lost (Wang, 2000). It is in this context that the academia and the government have realized the importance, necessity, and urgency of preserving rural heritage, finally leading to the nation-wide policy of rural vitalization. Within the context of rural vitalization, researchers see the development as a process of integrating policies, actors, technologies, and strategies into the process of optimizing the rural-urban organization structure, enhancing production-transportation efficiency and improving the living standard of the rural population (Long, 2014; Liu, 2018; Wang, 2018).

2.2. DIFFERENCE OF PERCEPTION ON RURAL HERITAGE

The Venice Charter published by International Council on Monuments and Sites (ICOMOS) in 1964 set the foundation of the principles for architectural heritage preservation and conservation, and the ICOMOS 1999 in Mexico published the first charter of preserving rural and vernacular heritage (Chen et al., 2008). However, it is not the case that only the buildings, space or villages on the conservation list can be regarded as valuable. Chen et al. further argued that the

heritage of a village must be perceived as integrity since the typical characteristics all over a traditional village should systematically express the vernacular society and lifestyle. Discussing the theory of rural renovation practice in Germany, Wang (1999) argued that there exists a substantial or spatial object without the label of monument or relics, yet being critical to some villagers or even the whole village, which could be called a memorial with abundant emotions.

Since the focus of view on heritage might be different, the perception of the environment where the heritage locates might also differ among various agents. It was pointed out by Luo (2018) that how much heritage could be preserved greatly depend on the popularity of the concept of heritage in public, rather than the knowledge of professionals. Some primitive but valuable stuff in the village might be regarded by the local villagers as the barrier standing in their way towards modernization. The situation should not be judged simply as stages of aesthetics. Fei et al (1992) have already argued that there is no superiority in the sense of intelligence (or the aesthetics) for rural and urban populations since it is all defined by the environment. Wang (2000) believed that the planning for villages and settlements must respond to the willing of local villagers, get their comprehension and accept their participation, otherwise, the construction would fail as the Tower of Babel.

2.3. THE CHANCE MADE POSSIBLE BY ICT IN THE NEW DATA AGE

As Information and Communication Technology (ICT) develops, various new methods have been approaching the practice in the field of heritage preservation, which may include computational simulation, digital diorama, interactive presentation based on Web 2.0 or even Web 3.0, Virtual Reality, Augmented Reality, Human-Computer Interaction, et al. The new technologies are helping the people better perceive and understand the physical environment in a virtual way that they are getting more and more familiar with, and they are helping the messages from different agents better transferred to each other. CASA in UCL has been generating a full-scale model on London to analyze and present various aspects of the city, including architecture, human being, transportation, and infrastructures, and perform the results in a VR platform (Batty, et al., 2005; Dawkins, et al., 2018). A research group from Ritsumeikan University has been conducting a spatiotemporal model of ancient Kyoto City to check the urban history in the different time period, simulate and evaluate the future development simultaneously (Nakaya et al., 2010). CHORA Conscious City Lab proposed a game-based toolkit named Urban Gallery to integrate the different stakeholders in the decision-making process through an interactive presentation, aiming to better popularize the participatory design methods, as well as educate the public and the government (Bunschoten, 2017).

With the engagement of ICT and the improving accessibility of various sorts of open data and big data, the research on rural issues could also see the chance to implement new analytic methods. By analyzing the 3 million village location points, Yang et al. (2016) detected the distribution mode of Chinese villages and provided several pathways for space optimization. Social network analysis could be conducted within the actors of rural development policy (De Rosa, et al., 2008).

As new technologies change the lives in rural areas, we should not only redefine cities but also give a new definition to the rural (Halfacree, 1993).

3. Concept

3.1. DEFINITION AND RANGES OF RIM

Building Information Modelling (BIM) has become a ripe concept in the field of architecture since first proposed in the late 1900s (Aish et al., 2017). It could be described as a tool with multiple layers of information embedded in it, letting different stakeholders share the message throughout the whole building process (Kepczynska-Walczak, 2018). Combining the collaborative concept of BIM and the analytical pursuit of Geographic Information Systems (GIS), a new tool for sharing and integrating the messages in cities popped up, namely the City Information Modelling (CIM). A spatial database and the correspondent spatial models are proposed to be conducted and instruct the urban design process (Gil et al., 2010). The same idea, however, could be implemented in the rural context, as we propose the concept of Rural Information Modelling (RIM) here.

As discussed in the previous sections, the range of village heritage preservation is not just a YES-or-NO judgment, which is neither simply preserving several houses and public spaces in the village, nor the one-sided argument from architects and professionals. It should be rather a complex, abundant, inclusive system which takes all stakeholders into account. In the new data age, all those information could be recorded and quantified as data in the proposed RIM, forming the sources and elements for future design and research.

In terms of the meanings of the data, the RIM should include the physical, historical, social, psychological and behavioral information. The physical information stands for the traditional messages that architects and urban planners get during their field trip on site, which may include the form of settlement, the boundary of the village, the structure of the streets, the organization of the public spaces, and the shape, type or status of the buildings. The historical information represents the messages which were valued by the cultural relic's preservation officials, which may include the development of history, the labeling for styles of shape, the change in time, the source of heritage, and the characteristics of the local culture. The social information is the messages which were gathered by the census, such as the economic structure, political ideology, population structure, property, and the social network which developed greatly in the new data age. The psychological information covers the part of messages studied by the social psychologists and environmental behaviorists, which may include the cognition and perception of the local residents on their own heritage environment, and the subjective evaluations for the conditions by specialists. Finally, the behavioral information falls in the field of sociologists and anthropologists, as well as the data engineers in the new data age, which may include the movement of human being in the built environment, the personal behavior patterns and the collective trends.

In terms of the characteristics of the data, the RIM could be distributed in four quadrants as shown in figure 1a. The horizontal axis describes the visibility of the

data, with one end standing for the substantial beings which could be seen, sensed, known and even touched; while the other end represents the virtual concepts supported by corresponding theories which is uncertain in shape and could only be sensed indirectly. The vertical axis, on the other hand, describes the affiliation of the data, with one end representing the objective properties which are about the village itself, independent from one specific person or generation, able to exist and circulate on their own; while the other end covers the personal properties that are embedded in the superficial or deep level of human being. Other than the two, there also exists a recessive axis which defines the possibility of operations on the element, which are based on interpretive or empirical analysis methods, respectively.

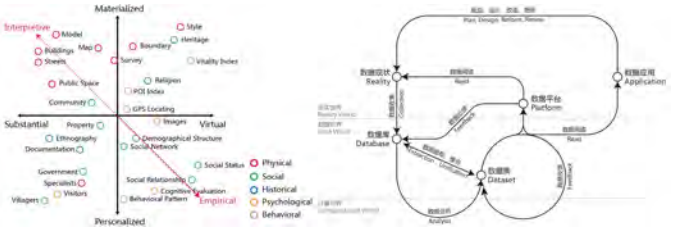


Figure 1. a) The distribution of data from RIM in quadrants and their meanings. b) The holocyclic system of the RIM.

The gathered data would be put into a holocyclic system concerning with the issue of village heritage, as is shown in figure 1b. The system of RIM would cover all the pathways from data collection, data analysis, to data visualization and data application, connecting the reality end, storage end and analysis end of the information. The system does not necessarily lead to the core act of design, but everything in the model would interact with the designing. From concept finding and element extracting, to principals of designing and selection from variations, and to the post-occupancy evaluation, all the process could be supported by the system through message sharing, feedback, and negotiation.

Following we would give examples of three most important layers of the RIM systems which would be used to evaluate the vitality and the heritage within a specific traditional village in Anyi County, Jiangxi Province in southern China.

3.2. A MORPHOLOGICAL LAYER IN RIM

The most intuitive information of a traditional village is its morphological dimension, in both scale of the whole village and specific object. The first step of recent village preservation practice in China starts with the documentation of the visible elements. A method proposed by Feng (2014) has become the official and complete guide to investigate, survey and document the traditional villages. By taking photos and filling forms in a structured requirement, every single person can participate in the information gathering process. The mass-participation of government, volunteers and citizens/villagers explains the rapid growth of verified traditional villages in China (from 646 in 2012 to 4153 in 2016). The village

of Luotian in Anyi, Jiangxi was also recognized through this process, leaving large numbers of photos connected with the original plan of the area. However, as the village has been involved in a critical vitalization project with the help of the local government, leading to changes onto the appearance of the houses and the streets, there must be some update simultaneously to the system, pairing with the original situation as the construction proceeds. In this sense, the traditional methods of Feng should also be adapted in a more instant digital way. Open Street Map, Weibo, and other social media could be considered to provide the source for message updating.

Other than the visual and textual descriptions, the deeper social logic of the space should be considered as a morphological issue (Hillier et al., 1989). The concept and method of Space Syntax were first adapted in a French village named Gassin, calculating and comparing the different degrees of connections within the streets and crossings, in order to distinguish the most important space in terms of availability among the others (Batty, 2013). The same logic could be adapted in Chinese rural areas, forming a vital dataset of spatial information in RIM. However, one critical issue must be solved before fully adapted - the complexity of the street system in a real village almost always exceeds the tracks perceived from a satellite or CAD map. There could also be roofed laneways, hidden closes or even some ever-open indoor areas that could change the concept of openness and availability greatly, which could only be discovered after fieldwork and 3D modeling.

3.3. A COGNITIVE LAYER IN RIM

When Lynch (1960) first proposed the concept of The Image of the City, he intended to assemble the information of where the most easily perceived space was in the cognitions of local residents through methods of deep interviews and map drawings. The most frequently mentioned elements in the form of words or drawings were considered the most typical image of the city since they could draw the attention of the public and get remembered. In a similar formulation but totally different content, Liu (1995, 1998) proposed the concept of The Image of the Village, naming the vital elements of the villages in a rather interpretive way. Later research in the context of the image of the village further developed the concept of Culture Landscape Gene, organizing the elements in a traditional village into a biological frame (Shen et al., 2006; Hu et al., 2012).

It should still be noted that the method suggested by Lynch was a combination of qualitative and quantitative studies, the value of which is greatly concealed by the famous concept of the five elements. We also conducted research in Luotian village in Anyi strictly following the experimental paradigm of Lynch. Totally 15 participants were involved in the deep interview, representing different power status concerning the rural vitalization process, which included the local villagers, the government, the developer, the designer, as well as the visitor. We found that though the general cognition pattern of different stakeholders may correlate with each other significantly, which was also proved by Lynch, still the completeness of cognition is strongly defined with the degree of involvement in the environment. Surprisingly, the local villagers showed the least involvement in the whole area,

expressing a fully localized pursuit in daily life, thus producing least details in the cognition map. This research based on grounded theory will be further discussed in another paper we are working on.

Further participation by a larger sample group for the cognitive layer could be conducted through a platform based on ArcGIS Online (Kunze et al., 2018), which would be easily accessed through mobile phone or laptop, possible for more villagers, visitors and even the potential visitors who have not yet been to the village to give their opinions based on the information they see, which is a collective outcome of all the participants before them (Bai et al., 2018).

3.4. A BEHAVIORAL LAYER IN RIM

Environmental Behaviour study has been focusing on the reaction of human being in various indoor or outdoor space, including staying, moving, relaxing, wandering et al. since the 1970s, discussing the impact of public space on human activities (Gehl, 1987). The study of human behavior in the environment based on physically trailing, observing, and counting is still widely used (Qi et al., 2018), yet could update with the help of ICT and big data. Together with GPS tracking, Bluetooth locating, Ultra Wideband technology and Radio Frequency Identification, Wi-Fi Positioning is a method widely used in the research field of Indoor Positioning Systems (Huang et al., 2017). Studies have been conducted in office blocks and touring resorts with the method, in order to gather the spatiotemporal information of the collective group and to analyze their purpose, interest, action pattern and social relationship, which is also promising in public places of the villages (Lin et al., 2018).

The Wi-Fi positioning can tract, storage and analyze the detailed spatiotemporal message around the predetermined points of interest as long as we suppose. However, it cannot provide the exact track of human movement spreading in the field with a limited number of devices. Trajectory recording based on mobile GPS signals with specific apps could then get involved as a supplementary method to provide the movement information of several individuals as relatively complete samples (Liu et al., 2018). By combining the two methods, the behavioral patterns of people in the Luotian village could be tracked and analyzed, making it possible to more objectively identify the most important, attractive and popular places in the village, giving support to the first two layers of RIM on evaluating the rural vitalization process in Anyi.

4. Discussion

Since the RIM proposed here greatly interacts with ICT the villages, one basic issue to state clear before popularizing is how indeed ICT is involved in rural China. To do so, we could at first make a general analysis based on census data on the economic issues and the possible extents of ICT involvement. Using the data from the Cities Year Book of 2002 and 2010, we could generate the rank-size Zipf Plot of mobile phones and internet ownership per capita within the overall population in the city-regions and their urban subgroups, as is shown in figure 2. It could be easily seen that the general usage of ICT for both urban and overall populations

has increased in that eight years, while the differences between the two get smaller on both ends of the ranking, which means that in the highly developed areas, the rural areas and the urban areas tend to have the same extent of ICT involvement.

To understand the ICT situation in rural counties more precisely, a more detailed analysis based on the data from Gansu Province (which is one of the least developed provinces of the country) in the year 2007 to 2017 could be conducted. Figure 3a shows the relationship of the disposable income per capita and the ownership of mobile phones and computers per hundred homes in rural areas, which suggests that the richness of the rural population strongly correlates with the ICT involvement. The shift in the rank of mobile phone ownership between 2007 and 2017 is shown in Figure 3b, which makes it possible to distinguish the counties that have gone through positive or negative development processes.

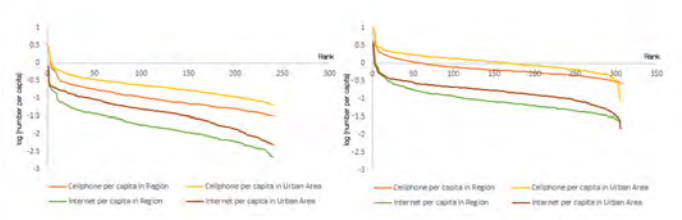


Figure 2. The ownership rank size of cellphone and internet per capita in all region and urban areas. Left: in year 2002; Right: in year 2010.

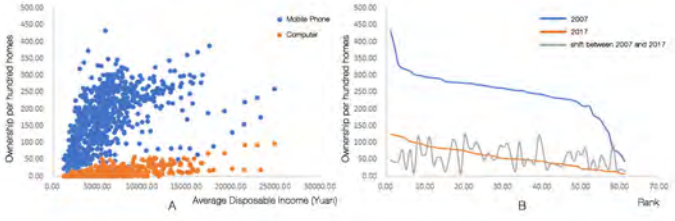


Figure 3. a) The Relationship of Average Disposable Income and the ownership of mobile phone and computer per hundred homes. b) The shift of ranking of mobile phone ownership from 2007 to 2017.

As soon as the RIM system is to be applied in real-world situation, it will have different meanings for different stakeholders in the rural vitalization process. For the villagers, participating the modeling process would give them chances to rediscover the value of the place they are living in, by asking themselves where the most meaningful space locates and trying to define their own genius loci. It would also be a chance for the villagers to fully express their willing and let the construction follow their own path. For the architects and urban planners, RIM could be a media to really read and interpret the village, rather than subjectively observe the site through their own glasses and tell their own stories, which would make the concept development more rational and understandable

for later viewers. For the government, RIM would be an easier decision-making tool since it combines various factors and has the chance to compare different variations. And for the visitors, sightseeing with a more vividly displayed database would facilitate them with much more specific aims, and would also give them chances to get their voice heard through a feedback option.

5. Conclusion

To more actively involve the stakeholders in the rural vitalization process and make them comprehend the village heritage more objectively, we propose here an interactive message platform, which is also named as RIM. The RIM system would collect, storage, analyze and display various dimensions of data concerning the village heritage, especially the information of the spatial morphology, the psychological perception and the behavioral patterns, helping the people, either deeply involved in the environment or totally as an outsider, better understand, interact with or negotiate on the heritage conservation issues.

References

Aish, R. and Bredella, N.: 2017, The evolution of architectural computing: from Building Modelling to Design Computation, *Architectural Research Quarterly*, **21**, 65-73.

Bai, N., Ye, W., Li, J., Ding, H., Pienaru, M.I. and Bunschoten, R.: 2018, Customised Collaborative Urban Design - A Collective User-based Urban Information System through Gaming, *Proceedings of eCAADe 2018*, Lodz, 419-428.

Batty, M.: 2011, Commentary: When All the World's a City, *Environment and Planning A*, **43**(4), 765-772.

Batty, M.: 2013, *The new science of cities*, MIT Press.

Batty, M. and Hudson□Smith, A.: 2005, Urban Simulacra: London, *Architectural Design*, **75**(6), 42-47.

Bunschoten, R.: 2017, From smart city to conscious city, *Urban Design*, **3**, 18-41.

Chen, Z. and Li, Q.: 2008, *Vernacular Architecture Heritage Preservation (in Chinese)*, Huangshan Publishing House.

CPC Central Committee, initials missing and State Council, initials missing: 2018, "The Five-Year Plan on Rural Vitalization Strategy (in Chinese)" . Available from <http://www.xinhuanet.com/politics/2018-09/26/c_1123487123.htm> (accessed 22nd October 2018).

Dawkins, O., Dennett, A. and Hudson-Smith, A.: 2018, Living with a Digital Twin: Operational management and engagement using IoT and Mixed Realities at UCL, *Proceedings of GISRUK*, Leicester.

Fei, H.T., Fei, X., Hamilton, G.G. and Zheng, W.: 1992, *From the soil: The foundations of Chinese society*, Univ of California Press.

Feng, J.: 2014, *Fieldwork Guidebook for Chinese Traditional Village Documentation (in Chinese)*, Culture and Art Publishing House.

Gehl, J.: 1987, *Life Between Buildings: Using Public Space*, The Danish Architectural Press.

Gil, J., Montenegro, N. and Duarte, J.: 2010, Assessing Computational Tools for Urban Design: Towards a "city information model", *Proceedings of eCAADe 2010*, Zurich, 361-369.

Halfacree, K.H.: 1993, Locality and social representation: space, discourse and alternative definitions of the rural, *Journal of rural studies*, **9**(1), 23-37.

Hillier, B. and Hanson, J.: 1989, *The social logic of space*, Cambridge university press.

Hu, Z., Liu, C., Deng, Y. and Yang, L.: 2012, Traditional Settlements Landscape's Gene and its Research Progress (in Chinese), *Progress in Geography*, **31**(12), 1620-1627.

Huang, W., Lin, Y. and Wu, M.: 2017, Spatial-Temporal Behavior Analysis Using Big Data Acquired by Wi-Fi Indoor Positioning System, *Proceedings of CAADRIA 2017*, Suzhou,

745-754.
Kepczynska-Walczak, A.: 2018, Building Information Modelling for 2020+ Realm: Contemporary practice and future perspectives, *Proceedings of eCAADe 2018*, Lodz, 271-280.
Kunze, A., Marz, M. and Wyka, E.: 2018, Smart Communities - Unleashing the Potential of Data for Smart Communities, *Proceedings of eCAADe 2018*, Lodz, 69-70.
Laterra, P., Orue, M.E. and Booman, G.C.: 2012, Spatial complexity and ecosystem services in rural landscapes, *Agriculture, Ecosystems & Environment*, **154**, 56-67.
Lin, Y. and Huang, W.: 2018, Social Behavior Analysis in Innovation Incubator Based on Wi-Fi Data - A Case Study on Yan Jing Lane Community, *Proceedings of CAADRIA 2018*, Beijing, 197-206.
Liu, P.: 1995, Research on Images for Site Selection of Traditional Villages (in Chinese), *Theses on Chinese Historical Geography*, **1**, 119-128.
Liu, P. and Dong, S.: 1998, Study of Landscape-Image of Chinese Ancient Village (in Chinese), *Geographical Research*, **17**(1), 31-38.
Liu, H. and Zhang, X.: 2018, Application of Time and Space Behavior Trajectory Analysis in Open Space, *Proceedings of International Symposium for Environment-Behavior Studies 2018*, Wuhan, 21-26.
Long, H.: 2014, Land consolidation: An indispensable way of spatial restructuring in rural China, *Journal of Geographical Sciences*, **24**(2), 211-225.
Long, H. and Zhang, X.: 2012, Progress in international rural geography research since the turn of the new millennium and some implications (in Chinese), *Economic Geography*, **32**(8), 1-7.
Lynch, K.: 1960, *The image of the city*, MIT Press.
Nakaya, T., Yano, K., Isoda, Y., Kawasumi, T., Takase, Y., Kirimura, T., Tsukamoto, A., Matsumoto, A., Seto, T. and Iizuka, T.: 2010, Virtual Kyoto project: Digital diorama of the past, present, and future of the historical city of Kyoto, *Culture and computing.*, **2010**, 173-187.
Qi, Y. and Saio, N.: 2018, The State of Resident Activities and Space in Chinese Traditional Village, Lingquan, Shaanxi Province, *Proceedings of International Symposium for Environment-Behavior Studies 2018*, Wuhan, 1342-1348.
De Rosa, M., Sabbatini, M. and Spigola, M.: 2008, Network analyses to catch rural complexity, *Journal on Chain and Network Science*, **8**(1), 75-82.
Shen, X., Liu, P. and Deng, Y.: 2006, Seeking the Landscape's Genes Atlas: One Kind of New Angle of View about Settlement's Cultural Landscape Districts Research (in Chinese), *Human Geography*, **90**(4), 109-112.
Wang, L.: 1999, Preservation and Revitalization for rural architectures in traditional villages: Revelation from rural revitalization planning in Germany (in Chinese), *Architectural Journal*, **11**, 16-21.
Wang, L.: 2000, The future image for villages: experiences from traditional villages and contemporary settlement planning (in Chinese), *Architectural Journal*, **11**, 16-22.
Wang, S.: 2018, A social analysis of rural revitalization and development from the perspective of social ecology: a discussion on the social infrastructure construction for rural revitalization (in Chinese), *Journal of Peking University: Philosophy and Social Sciences*, **55**(2), 5-12.
Wu, F.: 2002, Calibration of stochastic cellular automata: the application to rural-urban land conversions, *International Journal of Geographical Information Science*, **16**(8), 795-818.
Wu, F.: 2018, Planning centrality, market instruments: Governing Chinese urban transformation under state entrepreneurialism, *Urban Studies*, **55**(7), 1383-1399.
Yang, R., Xu, Q. and Long, H.: 2016, Spatial distribution characteristics and optimized reconstruction analysis of China's rural settlements during the process of rapid urbanization, *Journal of rural studies*, **47**, 413-424.

MASTER PLANNING WITH URBAN ALGORITHMS

Urban parameters, optimization and scenarios

BIANCA ILHA PEREIRA
[1] *University of Brasília*
[1] *biancailhap@gmail.com*

Abstract. The analogue definition of studies on urban planning can be very time consuming in the top-down process of designing. Keeping in mind the rapid urbanization we had in Brazil, and the continuous migration to the capital of the country located in Federal District, our aim is to use digital aid models that could be flexible and make quicker responses to urban issues. Algorithms as finite sequences of instructions have broad application. Designing cities demands the interpretation of variables linked to the territory and takes into account the current legislation in order to develop urban plans. This research creates an algorithmic basis using Grasshopper® to propose a mathematical solution for interpreting the existing space, and from it, to model urban scenes. The territorial analysis uses the user's perspective, with the interpretation of pre-existing characteristics, such as main roads, function and equipment distributions that make up the basic services. It is based on parameters extracted from theoretical repertoire and community facilities optimization through Galapagos evolutionary solver to deliver different proposed scenarios.

Keywords. Urban algorithms; master planning; Grasshopper; Galapagos; Federal District.

1. Introduction

With the advent of computing, the endless databases and the difficulty of processing data in an analogous way, we understand that it is necessary to take advantage of machines to comprehend and study the evolution of urban results. Considering the complexity inherent in cities, the use of algorithms tries to approximate some aspects to be worked on projects for the materialization and definition of project guideline.

Machines work to help and give us more strategic and intelligent responses for urban planning. This paper analyzes the behavior and human needs and the territorial context to generate reliable propositions to fulfill the urban fabric through computational algorithms. It is a review of a master's thesis research which has a more detailed approach (Pereira, 2016).

The discussion about the traditional development of urban projects considers that decision-making occurs from top-down process, with the designer making

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 51-60. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

decisions taking into account the knowledge obtained, while the use of generative, parametric and algorithmic computational tools leads to a bottom-up approach, in which, from the definition of basic parameters by the architect, the computer makes the big decisions. (Terzidis, 2006; Verebes, 2013). After creating the shape grammar based on algorithms that will define the study, using procedural modeling is possible to change different parameters, to manipulate features and get different scenarios in a fast exploration.

The contribution of algorithms and parameterization as a response to manage complex systems inherent to urbanism has been used in different contexts as promising tools for urban planning. The complexity and the dynamic of a liveable space is tough to predict without using computer-aided projects. Therefore, many algorithmic components have been build up to simplify the application of methods with the concern both in the creation of a dynamic project method and in the pre-analysis of the issues of urban insertion and integration of new occupations (Beirão, 2012; Beirão et. al., 2012; Aparicio, 2013; Koenig et. al., 2016).

Much more than creating new spaces, we need to integrate the existing ones, using the consolidated infrastructure to fill urban voids that have potential for urbanization, since the urban population in Federal District at Brazil is still increasing. Our goal is to deal with the aforementioned tools to elaborate urban planning and meet demand for residential areas, exploring variables and requirements that will make a vibrant urban neighborhood.

2. Methods

Regarding the propositions of the city, a theoretical repertoire was elaborated on urban vitality, elements, their distributions, the characteristics of living and active spaces. From authors such as Jacobs (1961), Rogers (2001), Gehl (2010), and a research about urban development in Vienna, Austria (Irschik et.al., 2013), we extracted the minimum parameters for dimensioning the blocks and to calculate the influence of public facilities for the algorithmic structure to generate master plans.

The methods for this research were divided in two stages: the parameterization, which permeates the whole study, and the elaboration of the algorithm that draws up instructions to be taken for urban design considering the aforementioned parameters. The algorithm creates the urban mesh from stipulated constraints - road system, public equipment and criteria for dimensioning blocks - and afterwards is articulated to elaborate the occupation plan integrated to the urban coefficients, in order to generate different scenarios with the variability of the parameters. The chosen urban area to evaluate the proposed method is a residential neighborhood in the capital of Brazil.

The input parameters selected for inclusion in the urban study are shown at *Table 1*.

Table 1. Parameters for the urban study.

Items	Dimensions
a) Standard blocks	100 to 150m length
b) Neighborhood Park	6.000m² with influence radius of 600m
c) Health care	360m² with influence radius of 1.000m
d) Child education	3.000m² with influence radius of 300m
e) Elementary School	8.000m² with influence radius of 1.500m

The base defined for the urban studies is, first, an algorithm that uses input parameters that were stipulated during the contextualization of the project and that are composed by the road axes (with spaces defined in '1') and by existing public facilities ('2', '3', '4', and '5'). It engenders the urban grid of the new installment, according to criteria molded in reference to the project objective.

2.1. FIRST STAGE: ALGORITHM TO CREATE THE URBAN MESH

1. Marking of the road axes that extending will reach or perpass the perimeter of the polygonal;
2. Launching of the roadways of the urban network from the interconnections of the roads adjacent to the new parceling, considering a regular mesh with variable dimensions by means of parameters, in order to allow the interconnection of the road systems (*see Figure 1*);
3. Categorization of existing public facilities in the urban grid and adjacent to the project perimeter;
4. Mapping of the radius of coverage of each equipment, by type, to enable the analysis that precedes the insertion of additional equipment in the project polygon;
5. Use of the evolutionary solver Galápagos to insert additional equipment in the project polygon, according to the distance of the existing ones in relation to the centers of the blocks, considering that all the blocks must be within the range of all types of equipment (*see Figure 2*);

The mapping of the existing or designed facilities in the project influence area was used as input for the Galápagos. This considered the maximum radii of influence for each type of equipment. The Galapagos' calculus pointed to the optimized location for the new facility, also calculating the minimum necessary equipment to contemplate every block. For the zoning of land functions, attraction curves were inserted. Therefore the manipulation of the curves allows flexibility in the distribution of uses and changing of the characteristics of the urban area.

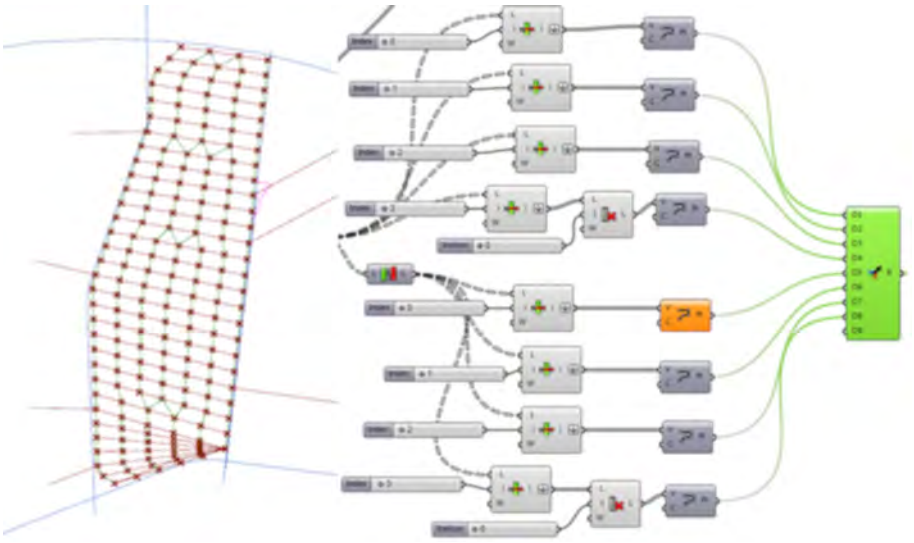


Figure 1. Mesh divided vertically and horizontally, as seen in Rhinoceros and Grasshopper, respectively.

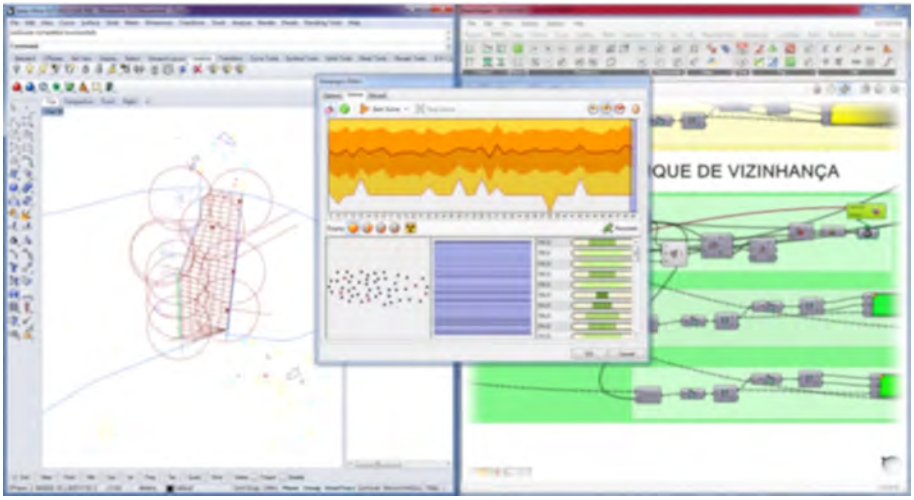


Figure 2. Views on Rhinoceros®, Grasshopper® and Galapagos performing the optimization on distribution of community facilities in the project area.

2.2. SECOND STAGE: ALGORITHM FOR THE OCCUPATION PLAN

The occupation plan was conceived considering the scenario development and consistent with current urban planning practices. The algorithmic basis formulated includes parameters whenever possible, so that, with the benefit of computational

support for the processing of multiple data, the quantitative can be reassessed and manipulated to obtain new urban calculations. The steps of the algorithm was as follows:

1. The surface of the polygon was trimmed by the road axes to generate the surfaces of the blocks;
2. The blocks suffered a decrease of area through the offset component according to the width stipulated for the road system, so that we obtain only the area of the mesh that will be parceled out;
3. An average area was used to split the blocks. When the court area is more than four times the stipulated area, the court is, by default, divided in half through the midpoint of the smallest length and his opposite, so the other dimension is later divided into more parts. This division also generated the split of the surface of the court, so each block that met the division criteria by area was subdivided into two parts.
4. After the subdivision of the surface, the distance criterion was used to select the blocks that will contain public facilities, whose point references was obtained in step 05 stage 1;
5. Then, the blocks that will contain the equipment were split according to the area demanded for each kind of facility. The lots for the facilities were selected through proximity criteria, using as input the points obtained from Galapagos;
6. The remaining areas, which will not be included in equipment, were redivided with a new area reference, average, for other uses (economic development area - ADE, mixed, residential and commercial)
7. Attraction curves were inserted to define the distribution of uses. This selection can be executed through an automated criteria, which were not used in this research because there are different ways of analyzing the territory, and the flexibility of the curves allows the manipulation of the characteristics of the area, needed in our politic context;
8. Then, the urbanization indexes ‘occupation rate’ and ‘feedback’ were added, composing the volume of urban planning and also allowing the calculation of the population density, the area constructed by destination and the coefficient of utilization of the polygon. Such indexes are important to obtain scenarios, considering the urban rules that define legal limits for the occupation, still allowing the manipulation of the quantitative in each destination, separately.

3. Urban design experiment

As a kick off for the macro spatial organization resulting from the analysis of the surroundings of the enterprise, we elaborated a map with information raised in the projects. The topography was ignored in the stage that this research fits. These data were the inputs for the urban study. The alternatives of articulation of the territory will be obtained from urban algorithms in light of the connection of the existing axes and the rays of coverage of the equipment.

Since the launching of the road axes, the subdivision of the polygonal area was made in order to separate the blocks, with the highlight of those that will contain the public equipment designed in the previous stages: offset; division squares; area of public facilities; proximity of the point launched by Galapagos with the square

division for the best location; division of the remainder after the insertion of public facilities, considering the area of new lots; distribution of uses through attraction lines - articulated polyline in Rhinoceros.

The generative method used for the urban mesh generated some triangular areas due to the compensation in the vertical divisions of the traverse. We understand that these blocks can function as visual landmarks in the subdivision.

Afterwards, we elaborate maps with the equipment layout according to the use, with the radius of equivalent coverage according to each destination. A simplified criterion for the insertion of new equipment in the study polygon was used measuring the distance of the equipment to the center of the new blocks, so that all the equipment was accessible according to the criteria of destination and range. It was reductionist because, as this is a basic launch of the preliminary plan, there are not the actual distances to be traveled, bearing in mind the road system and the direction conversions that a route requires.

The use of the Galapagos, called evolutionary solver, uses the variables inserted in the Grasshopper® to mathematically find the most adequate, best performing solution. The Galápagos was used to equate the insertion of new equipment, considering each of the types under study. By equalizing the number of equipment and an input index of possible arrangements - called seed -, the Galapagos returned as a result the option with the lowest possible number of equipment to met all the blocks inside the range of each equipment.

Once the grid already has the blocks delimited and the lots split, the urban parameters were adjusted to create occupation plans. The basic urban rules defined by the legislation for the polygon under study are:

- Permissible population density: mean = 50 to 150 person per hectare (local law)
- Population per household: 3.79 inhabitants / household (local law)
- Comfort rate per household unit: 86m².
- Maximum area of construction = 2 (two times the polygon area)

The urban parameters of ‘maximum lot coverage’ and ‘maximum building height’ were added for the elaboration of scenarios and three-dimensional models. With these parameters, it is possible to calculate the permeability rate and the plot ratio. As a result, we have the urban indexes of the scenarios, which are the ‘gross floor area - GFA’ for each land use, the area of lots by land use, the population density and the plot ratios. These results are automatically updated with the parameters manipulation, which allows the elaboration of comparative studies and different scenarios.

From the elaborated parametric algorithmic base, it is possible to change the parameters, from the dimensioning of the blocks to the urban parameters, to obtain the prospection of different scenarios and variabilities that allow the discussion of the results and the technical and political analysis of the best result.

It is possible to use the evolutionary solver Galapagos, and to obtain solution with better performance using, for example, the maximum housing density. However, keeping in mind that political decisions guide the preparation of projects and do not necessarily correspond to technical criteria, a structure was chosen that

generates a plan of occupation that allows manipulation both in the parameters and in the distribution of uses.

As a research, we use the same basis of the urban grid and change some parameters to elaborate the scenarios (*see Figure 3*).

Three scenarios show possibilities of urban settings using the proposed method and considering the density parameter as a limit. The first scenario is distributed throughout the polygonal. The second include green areas and thickens residential plots. The third is developed in high mixed-use buildings, occupying a smaller polygonal. The result demonstrates the method versatility and the possibility of tailoring data through editable curves and parameters from the parametric algorithm. It also shows the applicability of the method in both the academic and professional fields for building prospective scenarios.

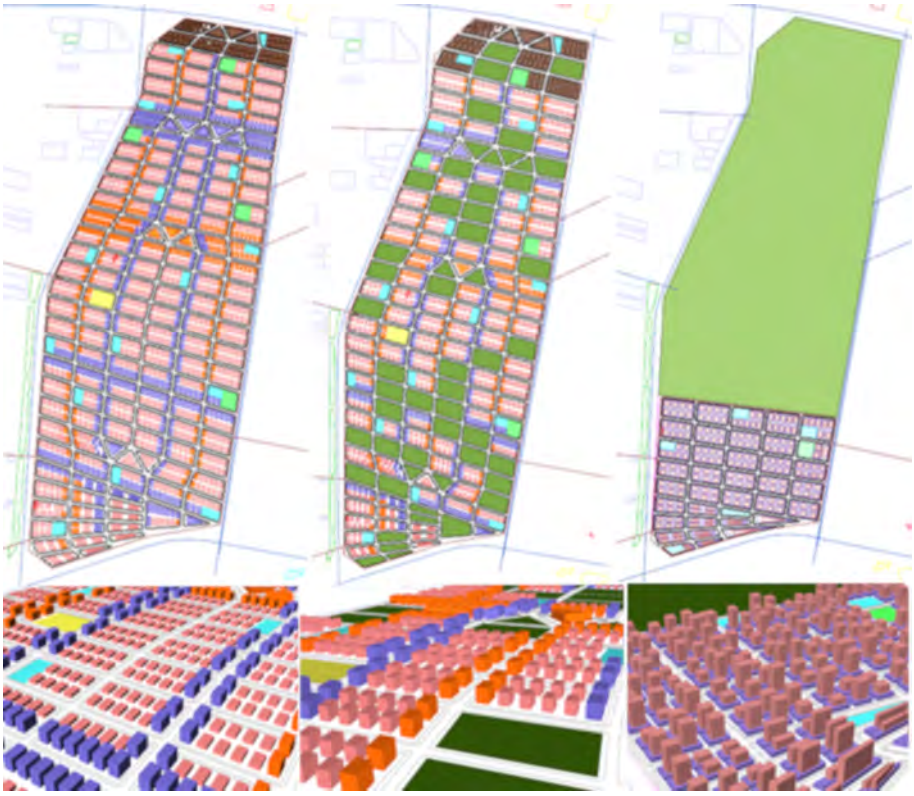


Figure 3. Masterplans and aerial views of the scenarios.

The experiment had the objective of reaching an end product to validate the proposed method. The answer of this research was to obtain an urban study based on the linear and punctual elements that were obtained by reading the territory and the parameters that were inserted to elaborate the occupation plan. Such an approach was simplified, considering the complexity of the present study, and aims

to guide more in-depth research and consider the insertion of more variables.

4. Discussion and conclusion

The explicit theory in this research, which considers the history of cities, the provisions on regular meshes and especially the content that projects urban vitality in the city do not together form the basis of the algorithm applied in this chapter. It must take into account the author's professional path, which is loaded with convictions and permeates the results of the study. Even if there is controversy about the learning, applications and attitudes taken, this methodology can serve as a generator for variabilities that contain other beliefs.

As a parameter of methodology with a focus on replicability, the launch of the urban mesh follows steps that allow the variability of parameters, but fixes the design of the mesh, since we understand that the regular urban mesh presents characteristics that adapt more easily to different situations besides favoring the integration with other areas and the expansion of the territory. Also, with the exception of the launching of public equipment, the division of lots took place based on a single area parameter for the various uses, which can be handled later in the occupation plan or developed within the algorithm using programming.

The generality, inherent to the possibility of replication of methods, and the synthesis necessary for the dimensioning of the research, can miss specifics important to the urban design, that must be worked in a step after the occupation plan, product of this study.

The choice of three different parties for occupancy plans leads to a discussion about the impact on the environment and the characteristics of urban vitality. What is the medium term the coexistence of permeable areas and dwellers, so as to allow the natural drainage of the soil, create areas of conviviality with nature without causing urban voids that cause the fear of circulating in the areas?

The use of the parametric algorithmic project is presented as a viable means of proposing an urban project because it allows the insertion of several elements present in the territory. It means that also allows the substitution of the original elements, admitting the application of the algorithmic model in several situations, and the manipulation of variables, to adapt the response options and generate design alternatives.

The study of characteristics of intelligent cities and spaces with urban vitality leads us to believe that, with the use of distances, radius of action, concepts of spatial distribution of uses and other parameterizable characteristics, we can obtain urbanistic designs with great possibilities of become active.

We understand that the results of this study compose occupancy plans that are, by definition, prospective launches that will drive urban development projects. We intend to take the discussion to the academy and to the field of work, since such methodology is based essentially on the reading of the existing territory, which sustains a coherent justification for the traces of the spaces complementary to the implanted mesh.

4.1. CONTRIBUTIONS

Thinking about the other solutions presented, on this research was decided to create a grammar based on the existent roads and public facilities. We realized that choosing one of those types without starting from the existent parts of the neighborhood would be a mistake. So, after define which one would be the variables to consider in square dimensioning and other vitality exponentials, we started the 'grammar' with the selection of existing roads.

The public facilities were put on the same archive, the ideal radius of coverage was defined and inserted as a variable - to be able to change the size - and the Galapagos tool was used to locate in an optimized way the new facilities over the territory under study. The calculus gave us the minimum amount of each public facility to cover the whole surface of squares. So, each one of the squares was inserted in the radius of one equipment, existent, projected or even prospected.

Regarding the algorithmic basis, the major contribution of this procedure is the ability to calculate and locate urban public equipment using predetermined and changeable factors, which, in this case, are the scope and scale of such equipment. The launch of the Galápagos positioning in the Grasshopper optimizes this distribution in order to distribute the minimum equipment required to attend the entire project traverse.

In addition, the study, through the guidelines that generated the parameterized urban grammar allows several different polygons to be studied with a very fast result. It is possible to generate different views, to change land uses, to dimension blocks, and to have results in a range of computational processing.

In times of dynamization of land use, flexibility of use, alteration, displacement, and decentralization of urban centers, such tool emerges as an auxiliary component in the launching of parties. The application is for urban studies, before the development of the project in a Building Information Modeling (BIM) system.

References

Aparicio, G.: 2013, "Parametric future cities" . Available from <http://blogs.aecom.com/connectedcities/parametric-future-cities/> (accessed 15th June 2015).

Beirão, J.N.: 2012, *CItyMaker - Designing Grammars for Urban Design*, Delft University of Technology, Faculty of Architecture, Department Urbanism.

Beirão, J.N., Arrobas, P. and Duarte, J.P.: 2012, Parametric Urban Design: Joining morphology and urban indicators in a single interactive model, *eCAADe*, **1 - City Modelling**(30), 167-175.

Gehl, J.: 2010, *Cities for people*, Island Press, London.

E. Irschik, E. Kail, A. Klimmer-Pölleritzer, A. Nuss, G. Puscher, M. Schönfeld and A. Winkler (eds.): 2013, *Manual for gender mainstreaming in urban planning and urban development*, Urban Development Vienna, MA 18, Vienna.

Jacobs, J.: 1961, *The death and life of great american cities*, Vintage books edition, New York.

Koenig, R. and Varoudis, T.: 2016, Spatial Optimisations: Merging depthmapX, spatial graph networks and evolutionary design in Grasshopper, *Design Tools - Exploration*, **2**, 249-254.

Pereira, B.I.: 2016, *Algoritmos urbanos: potencialidades e aplicação no Distrito Federal*, Master's Thesis, Universidade de Brasília.

Rogers, R.: 2001, *Cidades para um pequeno planeta*, Gustavo Gill, Barcelona.

Terzidis, K.: 2006, *Algorithmic Architecture*, Architectural Press, Oxford.

Verebes, T.: 2013, *Masterplanning the adaptive city: computational urbanism in the twenty-first century*, Routledge, Oxon.

ALGORITHMS, AI AND ARCHITECTURE

Notes on an extinction

DERMOTT MCMEEL
[1]*School of Architecture and Planning, University of Auckland*
[1]*d.mcmeel@auckland.ac.nz*

Abstract. This paper reports on ongoing research investigating applications and methodologies for algorithms and artificial intelligence within urban design. Although the research recognises not all design is numerically quantifiable, it posits that certain aspects are. It provides evidence of algorithmically derived solutions-in many cases-being as good as those developed by a design professional. I situate the research within a series of examples of design quantification and description. Before discussing practical implementations of algorithmic spatial planning by the co-work start-up WeWork. These projects demonstrate an ongoing narrative to establish spatial syntactical rules for building and urban design. Finally, the paper reports on original research that aims to apply algorithmic space planning to urban design. A work-in-progress, at this stage the finding report on our methodology, preliminary implementation of an algorithmic strategy. It finally presents emerging data pointing to what might happen if the sector does not embrace algorithms and AI.

Keywords. Algorithm; Artificial Intelligence; Architecture; Urban Design.

1. Introduction

This section will situate the research within a historical context of machine supported creativity, before outlining the paper structure.

Perhaps the obvious starting point for this contextualisation is the Industrial Revolution; recognised as an inflection point when machines began to supplant people as a source of making. However, prior to the Industrial Revolution, the Renaissance had-by the 1600's-already created "an unprecedented demand for desks, tables, sideboards, sets of hanging shelves and cupboards, all suited to the housing and display of new possessions" (Hale, 1994, p. 266). During this pre-industrial period, Sennet argues towns were already swelling with artisans to meet public demand for goods (Sennett, 2008, p. 82). He goes onto suggest the industrial revolution of the 1700's was actually a response to an imbalance of supply and demand that already existed. Objects once produced by people are instead reengineered to favour machine production. I would like to draw attention

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 61-70. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

to two aspects of this narrative. First, there was already an imbalance in the market and a demand for things to be made faster. The technology solution redressed that imbalance to satiate demand. Second, it was the artisans-the creative sector-who were significantly disrupted in this transformation. In his manifesto Capital, Karl Marx deepens our understanding of this phenomenon. He argues that the machines take the tools from the people, supplanting them as the instruments of making. People are then relegated to machine maintenance, work which is repetitive and creates nothing. This, argues Marx, undermines the sense of self and community.

More recently in the 1980's the emergence of Computer Aided Design (CAD) caused another disruption. No longer were large spaces required for teams of people to manually draw. Simultaneously smaller architectural practices investing in CAD systems could now compete with much larger and more established practices on speed, production and scale of project (Coyne et al., 1996). This caused dramatic change to the industry with large firms shrinking dramatically or going out of business.

Moving forward again to 2000's Building Information Modelling (BIM) was establishing itself as the next disruptive technology. Concurrently practitioners like Frank Gehry and Zaha Hadid were at the forefront of a new geometrically complex form of architecture. Innovation in building form was made possible by their appropriation of emerging parametric and procedural forms of computer modelling software such as CATIA, Rhino and Grasshopper. Even the introduction of the mobile phone had an impact of the dynamics of design and construction (McMeel, 2009).

This short contextualisation is to demonstrate that the creative industries are not insulated or protected from technological change. Indeed historically they have been significantly susceptible to disruption from less sophisticated technology that the current wave of robotics, algorithms and AI. It is useful to reflect on this historical narrative in light of current speculation on robotics and Artificial Intelligence. Most of which points to disruption of 'white-collar' and service sectors (Shewan, 2017; West, 2015). What this paper hopes to show by stepping through a series of examples is that significant aspects of design work can be clearly quantified and thus automated. In particular instances the algorithmically automated designs are as good at those derived by experts.

This paper starts by first reviewing the historical body of work that approaches spatial design systematically. It then looks at current research deploying algorithmic methods for office design. Second we unpack algorithmic methodology and speculate how it could be applied it to urban design. Finally we analyse our results to assess if an algorithmic methodology can be used successfully for urban design.

2. Background

This section will work through a series of computational methods that position fundamental aspects of design as explicit, numerically describable and verifiable. We will discuss them under the three themes of Space Syntax, Multi Objective Optimisation Problems and Algorithms. The aim is to recognise the historical

work that exists around establishing rules for spatial design and where this original research project will build upon it.

2.1. SPACE SYNTAX

The concept of Space Syntax emerged in the late 1970's and is largely credited to Bill Hillier (2007). It posits space can be described by being separated into discrete parts with explicit connections between these parts. We are perhaps most familiar with this concept through design guides like the RIBA Metric Handbook (Littlefield, 2008). Which contains derivations of space syntax diagrams outlining the spaces and connectivity required for a variety of building types such as hospitals, airports and TV studios. These complex buildings require people to move in explicit ways and particular functions to be proximate to each other. Thus, space syntax diagrams are useful to help design complex buildings that work. It has also been used as a key tool to determine walkability (Watts, Diaz Moore, Ferdous, & Burns, 2015). Importantly the idea of space syntax does not include form, it is explicitly about describing specific space and connectivity.

In parallel the architect and design theorist Christopher Alexander released the seminal work A Pattern Language (Alexander, Ishikawa, & Silverstein, 1977). This extended the proposition of Hillier to suggest different parts of our environment could be defined as specific patterns. Patterns existed at different scales and could be nested within each other. The concept of nesting patterns within each other allowed for a significant increase in the potential for complexity. While simultaneously the discrete pattern principles could continue to be understood. This is a concept that continues to be used in parametric schema and object-oriented computing (Burry, Burry, & Davis, 2011).

2.2. MULTI OBJECTIVE OPTIMISATION PROBLEMS

MOOP's are a strand of mathematics that posits in any sufficiently complex system multiple objectives need to be optimised simultaneously. In such a system no single solution exists that simultaneously optimises each objective. It has been used in various fields including finding solutions for traffic planning, radiation therapy and conceptual building design (Bitterman, 2011; Perederieieva, Ehrgott, Raith, & Wang, 2016; Raith, Wang, Ehrgott, & Mitchell, 2014). MOOP's build on Hillier and Alexander's concepts by acknowledging a significantly higher level of complexity. It also recognises the impossibility of optimising for all objectives.

2.3. ALGORITHMS

The widespread use of graphical software such as Revit and Rhinoceros have allowed for the inclusion of complex programming within the design domain. This space is dominated by the creation of complex building forms. However, there is a clear shift to apply these powerful computational tools to other problems; such as the complexities of building planning.

Several different approaches can be identified which we will discuss under the themes decision support and decision making. In the first category, 'decision support' algorithms are used to provide decision support this has been investigated

by Bitterman (2011) and Nagy et. Al. (2017) where algorithms are used to identify a solution space, a set of solutions that designers then interrogate and discuss with clients, before making a final selection. The New York based co-working provider WeWork is investigating the use of algorithms for office planning (Anderson, Bailey, Heumann, & Davis, 2018). Where algorithms provide a selection of layouts that meets their design requirements. WeWork operates thousands of co-working spaces, and have been able to compare their algorithmically derived solutions with architecturally derived ones. The second approach is 'decision making,' perhaps more contentious as it has less designer involvement. It involves describing complex spatial arrangements in an Excel spreadsheet. This extends to detailed and highly specific spatial relationship, zoning and spaces that require adjacency. The only geometric input required is the building boundary and the algorithm creates a spatial design (Das, Day, Hauck, Haymaker, & Davis, 2016).

In summary, we have reviewed some historical and current approaches to computation and design that seek to view aspects of design as a rule-based organisational and optimisation activity. With the exception of Bitterman's work the research is dominated by systems for two-dimensional spatial planning, rather than 'design.' Spatial planning in most cases is comprised of a large number of explicit factors that the designer or designers are attempting to optimise. For the purpose of this research, we are particularly interested in WeWork's methodology. It focuses on fitting repetitive and regular geometric shapes (desks) into a bigger space (an office). This has obvious parallels with suburban planning, which also involves fitting many rectangular shaped building plots into a larger site. The following section will unpack this method and explain how it will be used.

3. Research

The approach to the research project was to posit that office and urban design had a number of similar principles; fitting things efficiently into a space, or 'packing' as it is sometimes called. WeWork's designers have several tried and tested methods for fitting desks into a space. For example, one approach is to fit desks around the edge and then start filling in the rests of the space with back to back rows. Like office planners, urban planners have tried and tested approaches for efficiently subdividing large plots of land into sub-plots for selling. By automating these approaches it creates the potential for increasing efficiency and speed of the designing process, or it can allow designers to spend more time on higher-level, more complex design problems and less on mundane repetitive tasks.

3.1. METHOD

The project applies WeWorks methodology from office planning to urban planning. First, WeWork approach planning initially as two dimensional space planning exercises. The general aim is to strike a balance between maximum efficiency-which maximises financial return-and comfort. The planning is based on quantifiable values, for example, required dimensions and areas of a desk and a seat. In most cases, as previously discussed, tried and tested approaches are known and result in the most efficient arrangements. It is when unusual shapes

or boundary conditions exist that expert knowledge is required and higher level problem-solving is required.

Second, WeWork's algorithms return multiple solutions, WeWork theorises their occupancy data from thousands of offices can be used to train an Artificial Intelligence to identify which solutions would be most popular within the context of their business. This research project initially focuses on the development of algorithms that mimic typical urban space planning strategy.

This phase of the project focuses on mapping the first step of WeWork's work onto urban planning. We develop algorithms to subdivide a site into smaller blocks and populate those blocks with plots for housing.

3.2. THE PROJECT

The first stage of the project was to understand the 'base unit.' In this case we focused on the rules and regulations around detached suburban housing. One of the primary drivers for this research was investigating what processes with the planning, design and construction of housing could be improved with automation. There are significant housing issues within New Zealand, this is part of ongoing research to explore how it might be improved. With than in mind the project worked within the most common context of development; the planning of detached housing on green or brownfield sites.

The Auckland Unitary Plan has explicit rules regarding minimum distances required between a house and its plot boundary, and there are explicit height limitations (Figure 1).

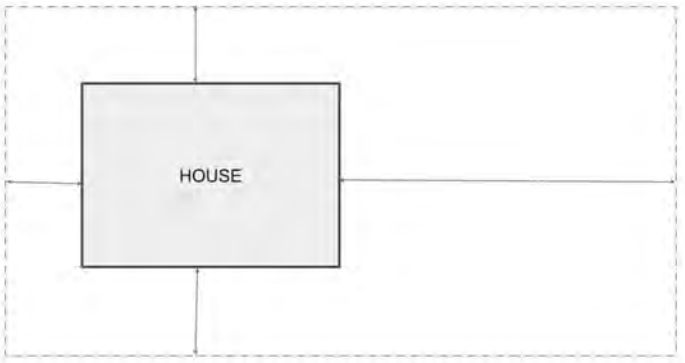


Figure 1. A building plot: a detached house footprint and minimum boundary requirements.

3.3. THE ALGORITHMS

The researchers began with the base unit of a typical detached house footprint and the minimum distance to front, back and side boundaries. This was created within a parametric design software that enables size of the house to be changed and the boundary dimensions would automatically update. The initial approach was to create blocks from these individual building plots. Then blocks would be built up to fill what we call a super-plot (Figure 2). In a similar strategy to WeWork we are starting with the smallest know base unit and working backwards.

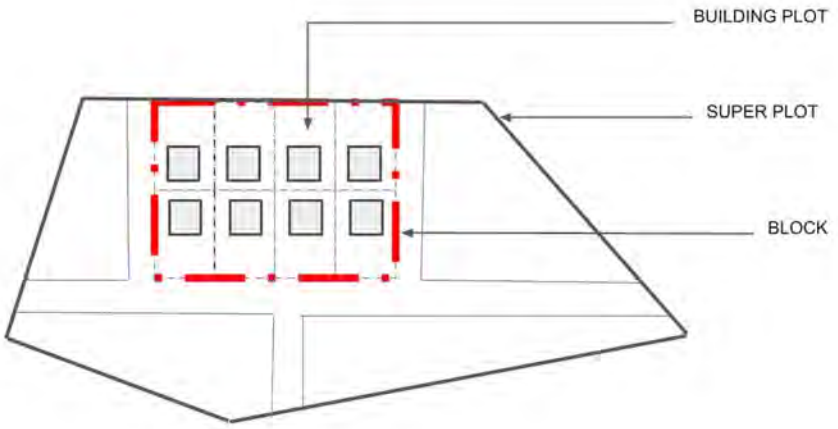


Figure 2. A building plot, block and super-plot.

The software chose was the Rhinoceros 3D modelling software with the parametric Grasshopper plug-in. This enabled us to apply Python scripted algorithm to simple geometries (Figure 3). As the work developed particular configurations were identified that were not desirable. For example where a block was rectilinear the subdivision was precise and accurate. Where it was not unusual overlaps or geometries were created. In these cases it was possible to identify the specific undesirable arrangements and build into the algorithm contingency to avoid them. At this stage of the research we have developed a proof-of-concept that enables simple subdivision based on the Auckland Unitary Plan (Figure 4).

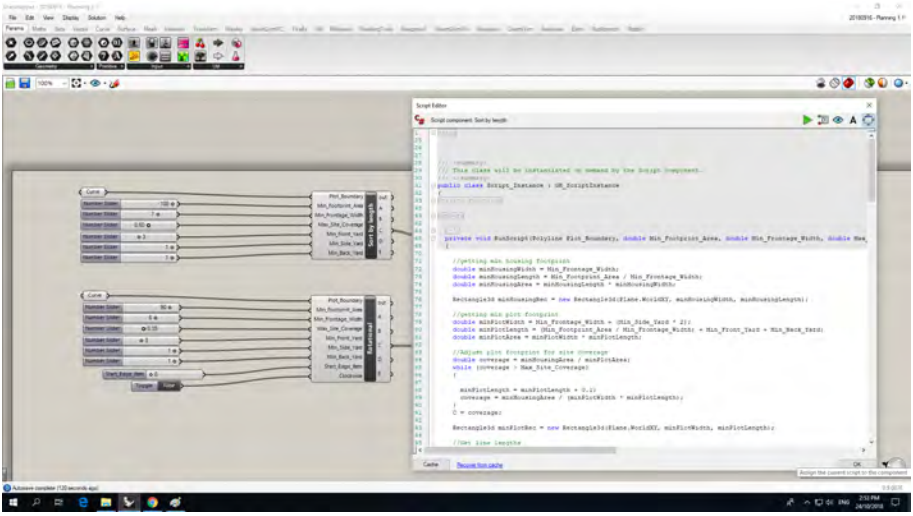


Figure 3. Grasshopper including Python script.

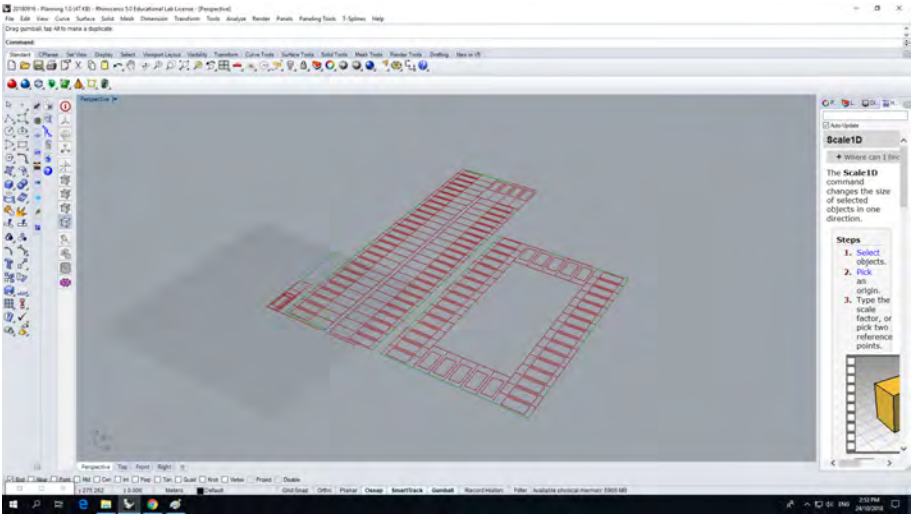


Figure 4. Super-plot algorithmically subdivided in blocks and house plots.

3.4. FUTURE

The next stage of research will create a simple working algorithm that can be applied to basic non-rectilinear shaped super-plots. Mapping WeWork's methodology the focus will be to compare how the algorithms perform against pre-existing developments subdivided by experts.

The rules and regulations for planning a suburban development are more

complex than an office space. Also, while WeWork's base unit of a desk and chair does not change, for a suburban subdivision there are various base units such as semi-detached housing, detached housing, duplex, terrace, apartments etc. It is common for subdivisions to have a combination of several of this typology. As a way of formally addressing this complexity we propose the implementation of a standard machine readable form of these regulations. Using a standard such as LegalXML we plan to encode specific aspects of the regulations such that the algorithm can create plots and blocks that conform to site specific regulations from region to region and country to country.

Finally, the research will eventually explore if it is possible to gather data to train an appropriate AI-similar to WeWork's hypothesis-to return assessments on desirability of different algorithmic solutions.

4. Analysis

Although the research is in an embryonic stage there are a several aspects to note. First, WeWork demonstrated in approximately 77% of cases their algorithms were as good as human designers. When humans were superior to algorithms it was in situations where the rules could-or needed-to be bent to gain advantage. We found we could implement our own algorithm for urban space planning. In addition-when applied to rectilinear shaped subdivisions-they were simple and could execute subdivision accurately and quickly.

The issues of desirability or quality is harder to determine. WeWork have design guidelines to help their designers maintain consistency across their office spaces. Their algorithms were developed to adhere to these guidelines so that-in principle at least-the algorithmic solutions were not a significant departure from the human derived result. Recalling that efficiency is key to WeWorks success, fitting as many desks into a space as possible is a high priority. Again this is a principle applicable to urban space planning. At the time of writing our research had not evolved to encode design principles into the subdivision logic.

Furthermore, efforts by WeWork to understand office design, occupancy and management have resulted in some important statistics. Started in 2010, by 2018 is has become the biggest private property occupier in London (Williams, 2018); a market they did not enter until 2014. Like many 21st Century companies, they are innovating and applying new methods to existing sectors. Underpinning WeWork's success is their use of data, something the average architectural or property developer does not engage with. The senior researcher at WeWork asserts if you are not designing with data you are not designing (Murrye Bernard, 2018).

Finally, WeWork is a new form of business, a hybrid of designers, property and facility managers, they design and manage the occupancy of office space. The occupancy data gathered informs future office design. Indeed the spin-off service 'Powered by We' offers to build and operate your office space for your business. They again are aggressively moving into new territories and disrupting traditional businesses and modes of practice. Their new mode of design/management practice has dominated London in less than 5 years.

5. Conclusions

In this paper we have outlined a methodology appropriated from WeWork and applied it to urban design. We have demonstrated that an algorithmic approach to the subdivision of suburban planning is possible. The focus has not been on form of complex geometry it has instead to apply powerful computational tool to the regular and repetitive aspects of this specific design space. Making planning faster and simultaneously allowing designers more time to concentrate on higher-level design problems. It has also drawn attention to new modes of practice for spatial design and management that challenges conventional business models. The paper began with a provocation, an exhortation on extinction. The hybrid operational services provided by WeWork is new, and it provides a single point of service that meets the needs of the market better than the current fragmented services design, construction and management services. It may mark the beginning of the transformation of architecture to a platform economy. If so, we are at the vanguard of a technological change that will have significant consequences for the sector.

Acknowledgments

The author would like to thank the following: Cameron Spicer, Research Assistant on this project and Dr Daniel Davis whose work inspired some of the themes in this paper.

References

Alexander, C., Ishikawa, S. and Silverstein, M.: 1977, *A pattern language : towns, buildings, construction*, Oxford University Press, New York.

Anderson, C., Bailey, C., Heumann, A. and Davis, D.: 2018, Augmented space planning: Using procedural generation to automate desk layouts, *International Journal of Architectural Computing*, **16**(2), 164-177.

Bernard, M.: 2018, "The Interloper: WeWork Upends the Conventional" . Available from <https://www.architectmagazine.com/practice/the-interloper-wework-upends-the-conventional-architecture-firm#xtbackslash_o?fbclid=IwAR19ty3ego0WBGe7N5Kb6vZRJCFqEJY69CImXGI4luYpJG6kh8esnUS3WWI>.

Bitterman, M.: 2011, Sustainable conceptual building design using a cognitive system, *Proceedings of the 14th international conference on Computer Aided Architectural Design*, Liege, 297-313.

Burry, M., Burry, J. and Davis, D.: 2011, Untangling Parametric Schemata: Enhancing Collaboration through Modular Programming, *CAAD Futures 2011: Designing together*, Li\'ege, Beligum.

Das, S., Day, C., Hauck, A., Haymaker, J. and Davis, D.: 2016, *Space Plan Generator*, ACADIA.

Hale, J.R.: 1994, *The Civilization of Europe in the Renaissance*, Fontana Press.

Hillier, B.: 2007, *Space is the machine: a configurational theory of architecture*, Space Syntax.

Littlefield, D.: 2008, *Metric handbook*, Routledge.

McMeel, D.: 2009, *The Artistry of Construction*, Ph.D. Thesis, Edinburgh University.

Nagy, D., Lau, D., Locke, J., Stoddart, J., Villaggi, L., Wang, R., Zhao, D. and Benjamin, D.: 2017, Project Discover: An application of generative design for architectural space planning, *SimAUD 2017 Conference proceedings: Symposium on Simulation for Architecture and Urban Design*.

Perederieieva, O., Ehrgott, M., Raith, A. and Wang, J.Y.T.: 2016, Numerical stability of path-based algorithms for traffic assignment, *Optimization Methods and Software*, **31**(1),

53-67.
Raith, A., Wang, J., Ehrgott, M. and Mitchell, S.: 2014, Solving multi-objective traffic assignment, *Annals of Operations Research*, **222**(1), 483-516.
Sennett, R.: 2008, *The Craftsman*, Yale University Press, New Haven.
Shewan, D.: 2017, "Robots will destroy our jobs – and we're not ready for it" . Available from <https://www.theguardian.com/technology/2017/jan/11/robots-jobs-employees-artificial-intelligence>.
Watts, A., Diaz Moore, K., Ferdous, F. and Burns, J.: 2015, Neighborhood integration and connectivity predict cognitive decline in older adults with and without Alzheimer, *Gerontology & Geriatric Medicine*, **1**, 1-9.
West, D.M.: 2015, "What happens if robots take the jobs? The impact of emerging technologies on employment and public policy" . Available from <https://www.brookings.edu/wp-content/uploads/2016/06/robotwork.pdf> (accessed 1st January 2019).
Williams, A.: 2018, "WeWork becomes central London's biggest office occupier" . Available from <https://www.ft.com/content/40a87044-ff97-11e7-9650-9c0ad2d7c5b5>.

SYNTHESIZING 360-DEGREE LIVE STREAMING FOR AN ERASED BACKGROUND TO STUDY RENOVATION USING MIXED REALITY

YUEHAN ZHU[1], TOMOHIRO FUKUDA[2] and NOBUYOSHI YABUKI[3]
[1,2,3]*Osaka University, Suita, Osaka, Japan*
[1]*zhu@it.see.eng.osaka-u.ac.jp* [2,3]*{fukuda|yabuki}@see.eng.osaka-u.ac.jp*

Abstract. In a modern society, people spend more time indoors. Indoor Environmental Quality (IEQ) and its effect on occupants' health and comfort has become an important area of study. Many existing building stocks still have huge social, economic, and environmental value. There is a high demand for stock renovation, which gives existing buildings new lives, rather than building new ones. In the early stage of the renovation design, it is essential to achieve a timely feedback process as bring together stakeholders. Introducing Mixed Reality (MR) with Diminished Reality (DR) provides users with an indirect view of the world where some objects have been made invisible which makes it easier to display indoor renovation plans. This paper describes the development of an MR system for architectural designers that integrates DR results into the MR system. Aiming to provide a stable, realistic and real-time DR results for enhancing feedback efficiency during renovation design which can help stakeholders better understand or evaluate the renovation plan.

Keywords. Building stock renovation; mixed reality (MR); diminished reality (DR); real-time background update.

1. Introduction

In an advanced society, the world is gradually interested in health and wellness inside buildings. It is said that people spend an average of 87% of their time indoors (Klepeis et al., 2001). Therefore, it is important to provide people with a comfortable and healthy indoor environment. Indoor Environmental Quality (IEQ) and its effect on occupants' health and comfort has always been considered in new buildings. However, the proportion of building stock is much larger than new buildings (Kovacic et al., 2015). Many existing building stocks still have huge social, economic, and environmental value. There is a high demand for stock renovation, which gives existing buildings new lives, rather than building new ones.

In order to reduce the cost and decrease environmental impacts during the renovation process, using Mixed Reality (MR) technology to display indoor renovation plans has been proposed (Zhu et al., 2018). MR is the one where real

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 71-80. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

world and virtual world objects coexist (Milgram and Kishino, 1994). Introducing MR technology into the renovation design steps enables the simultaneous design of the building plan and environment design which can reduce the construction period with less coordination, timely feedback and fewer variation orders. The MR experience makes non-professionals can also understand and participate in the design process. MR including augmented reality (AR), virtual reality (VR) and diminished reality (DR). In contrast to AR which superimpose virtual information on the real scene, DR is the process of removing, eliminating, or diminishing the number of objects from the real world (Nakajima et al., 2017). The introduction of DR technology provides users an indirect view of the world where some objects have been made invisible which makes it easier to display indoor renovation plans, as removing an existing wall is one of the basic steps in the building stock renovation.

There are many methods to achieve DR. In-painting is one of the methods that attempt to paint over objects using texture and patch information from the source image itself (Jan and Broll, 2014). New algorithms of the image in-painting methods are constantly being proposed. Such as combining Visual-SLAM into the algorithm, which is a method to segment the background surfaces uses some feature points of the background (Kawai et al., 2013). However, those method combining Visual-SLAM are not available on the solid-colored wall. And the more satisfied the DR results, the more computing resources are needed (Sasanuma et al., 2017). Then, the time required for calculations will increase, and real-time DR will be hard to realize. On the other hand, in-painting methods usually used to erase small and independent objects. Relative to this, building structure such as wall and column is a relatively large object and connects to the environment. Therefore, it is hard to use the in-painting methods to erase an entire wall. In this research, we propose a method that can achieve realistic large-scale DR in real-time.

Another set of methods utilizes pre-captured images or video of a background scene. Then, when new physical items are incorporated into space, the background images can be used as a reference for obtaining background information obstructed by the new objects. Those methods utilize pre-captured background cannot display the real-time background and observation angle provided to users is limited to the angle of the pre-captured background. Therefore, to achieve a realistic large-scale DR, reconstructing the background area virtually in real-time is necessary.

Previously, a system for DR with multiple handheld camera system has been proposed (Akihito et al., 2007). They used multiple cameras to capture the same scene from different directions, and used the AR marker to calibrate the multiple cameras, so that they can computing the occluded content, diminished the target object. However, its DR results are not stabilized because of its algorithm based on pixel-by-pixel comparison does not work if the occluding object has no color variation across its surface. Another advanced DR method utilizes an RGB-D camera to hide arbitrary trackable objects (Meerits and Saito, 2015a). They used RGB-D camera to reconstruct the missing parts then introduce color correction technique to merge image content originating from different cameras. In this method, because of the performance of RGB-D camera itself, reconstruction

results would have many missing parts which seem like black noise. Although they used in-painting way to repair those black noise, the quality of its DR results still has its limitations, and some black noise still exist.

This paper describes the development and application of a real-time MR system for architectural designers that includes DR function. The system proposes a method that erases a real wall virtually to connect two rooms. Introducing SLAM based MR technology to do the registration and display a stable background at the specified location. The background reconstruction is operated by a 360-degree camera, and the reconstruction results are sent to Head Mounted Display (HMD) through a Wi-Fi connection in real-time. Users can experience the MR system on the HMD and study renovation with a wall disappearing. This MR experience can help them better understand or evaluate the renovation plan flexibility.

2. The Proposed MR System

In accordance with Figure 1, this system consists of four well-defined steps, namely, real-time data collection, background reconstruction, renovation plan digitization, and system integration. The system includes one HMD (HoloLens) and one 360-degree camera. The HoloLens has four "environment understanding" cameras, one RGB camera and one Gyro sensor. This set of equipment can provide calibration information for registration and occlusion generation, as seen in Figure 2. The streaming data used to reconstruct the background is collected, via a 360-degree camera, which is placed in the central location of different rooms from the HMD. These two devices communicate via Wi-Fi connection. Wi-Fi signals can pass through walls, which makes it possible to collect background data behind the target wall. The renovation plan is to build a BIM model that can provide professional information by designers that will make it faster and easier for designers to modify the renovation plan. Synchronizing the BIM model with the 3D coordinates and occlusion information not only ensures the accuracy of the DR result but also allows the user to have a more realistic MR experience. The entire system operates on HMD, and so, users can watch the DR results from its see-through display. From the user's perspective view, the target wall will be diminished, the room behind the physical wall will be displayed in front of the user, and as the user can walk back and forth, the occlusion of the background room and the physical objects around the diminished wall will be correctly displayed.

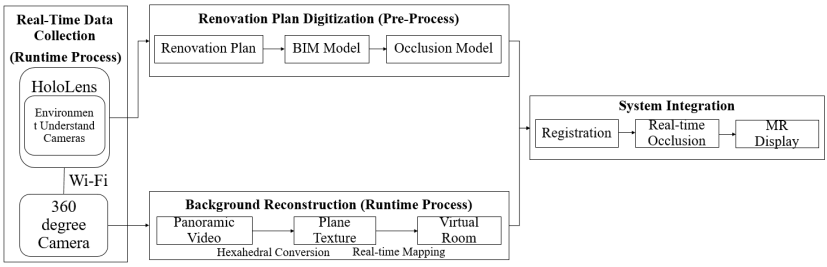


Figure 1. System workflow.



Figure 2. HoloLens side view (left); front view (right).

2.1. REAL-TIME DATA COLLECTION

The structure of the background scene is reconstructed in real-time. Many existing DR approaches that are based on in-painting methods have achieved real-time object elimination. One of the approaches realized an entire image completion pipeline without relying on pose tracking or 3D modelling (Herling and Broll, 2010). However, the DR results of this methods are static and the DR target is limited to simple objects without a complex pattern. This is because its background information is based on the characteristics of the surrounding environment. The more complex the target object is, the more unexpected the DR result comes out. Therefore, methods for generating background scenes using 3D reconstruction have been frequently used in recent years. PhotoAR+DR project proposed a reconstruction method using photogrammetry software which manufactures background 3D model by reconstructing the photographs of the surrounding environments (Inoue et al., 2018). The generated background is pretty realistic but it takes a long time to process for ten hours or even days. Another research team presented a general method of visualizing hidden areas using an RGB-D camera (Meerits and Saito, 2015b). This method can also reconstruct dynamic background scenes. However, the construction data captured from RGB-D camera is point cloud data. The point cloud data files are extremely large; thus, the real-time reconstruction can be delayed or part of the scene may be missing. Researchers have to reduce the density of point cloud data in order to correct the stability of DR results. Overall, in this paper, we will propose a method to collect background scene information using a 360-degree camera. In comparison to the general RGB camera and RGB-D camera, the 360-degree camera has a wider field of view, which can scan the entire background scene all at once. The file size of the resulting panorama is significantly smaller than the point cloud data, where a wired connection is mandatory in order to transfer data. In our research, 360-degree camera data size is small enough to use wireless transmission. First, we will need to create a plugin using the API provided by the camera manufacturer, and then, we need to build a Wi-Fi connection between the HMD and 360-degree camera. The connection method is based on the HttpWebRequest class, and the data is usually acquired and submitted through GET and POST. With this wireless network transmission connection, panoramic video can be transferred to the HMD in real-time.

2.2. BACKGROUND RECONSTRUCTION

2.2.1. Panorama Conversion

Our proposed system gets the original panoramic video data byte-by-byte from the 360-degree camera, and separates the image of each frame from the data stream. However, this original panoramic image cannot be directly used to rebuild the background. Because this will have a serious image distortion. Converting the panorama image into another form that fits the mask model is necessary to reduce the distortion. Mask model is a 3D virtual model of the diminished target, and it can determine which part of the virtual room for DR is exposed in front of the occlusion model. A 1:1 hexahedron room mask model to map the background image. Then, the panoramic photos are converted into six patches and attached to the hexahedron. The algorithm refers to a part of a VR study that discusses the transformation of a cubic environment map (90-degree perspective projections onto the face of a cube) into a cylindrical panoramic image (Paul Bourke, 2016). Basically, there are two solutions that can split the panoramic image. The first of which is based on OpenCV image processing and the other is based on OpenGL. The latter changes the direction of the LookAt camera, obtain six textures, and then, read and save the return data. In this study, we need to process the panoramic image from the data stream in real-time. The OpenGL methods would cost GPU computing resources, which is a weak point of HMD. Hence, the OpenCV methods are chosen.

2.2.2. The Dynamic Texture on the Mask Model

In this study, the background scene should not be a static image or a model, a dynamic virtual room is created to replace the diminished wall. The mask model is a hollow cube with one empty side. The system continually receives the converted images that are dynamically mapped to the mask model (except the diminished wall that is planned to be removed in the renovation design). After that, the real-time dynamic DR results are shown on the mask model.

2.3. OCCLUSION

Occlusion happens when one object in a 3D space is blocking another object from view. In order to convey a more realistic MR experience, the physical objects should interact with virtual objects. The occlusion of incorrect objects makes the DR result look somewhat unreal, which can be seen in Figure 3. In this study, our proposed system not only scans and generates the real-world objects occlusion in real-time, using four “environment understanding” cameras from HoloLens, which can perceive the depth of the scene like RGB-D camera; the system also deletes the real-time occlusion of the diminished wall. In order to prevent the occlusion of the DR target wall, which is scanned by the “environment understanding” cameras from covering the background scene, the range of real-time occlusion generation should be limited. The occlusion of the target wall is not generated by limiting the scan range of the “environment understanding camera”.



Figure 3. DR result without occlusion.

2.4. SYSTEM INTEGRATION

Every module is integrated into a game engine, Unity, which supports Universal Windows Platform (UWP) development. Moreover, programs developed using UWP can operate on all Windows 10 devices including the HMD-HoloLens. The panorama conversion function is based on OpenCV (2.2.1) and its library needs to be imported into the Unity Asset as optional attachment packages.

3. System Evaluation

To validate the advantages of the proposed method, an evaluation test was carried out in room 411 and room 410, M3 building, Suita Campus, Osaka University. The DR target wall was between the two rooms and the length and height of the target wall are 6.5 m and 2.6 m respectively. The observational positions were set at A, B, and C in the room 411 (Figure 4). The 360-degree camera, THETA V, was placed in the center location of the room 410. The overall layout is shown in Figure 4. The system data flow of the DR part was shown in Figure 5. The captured panoramic video was streamed from THETA V to HoloLens via Wi-Fi connection. We used the method refer to THETA developers' API 2.1 (THETA developers) to build the transfer protocol. In this method, we first used HttpWebRequest class and set the POST-request; then, parsed motion-jpeg HTTP stream from the camera and generated each frame from streaming data. After that, we used OpenCV-based methods to convert the panoramic images into a Hexahedral map. This can be seen in Figure 6. At last, we mapped each frame onto a mask model as a texture and waited for it to finish processing. After all the steps were complete, the integrated results were projected on a translucent screen (HoloLens). This is so that people could "perspective" through the DR target wall. The real-world perspective of the user experiencing the MR system was shown in Figure 7. In the Figure 7, the part

that is wrapped in the red frame was the target wall. A part of the target wall that is close to the entrance is not taken as a target of elimination. This is simply because it was a bearing part.

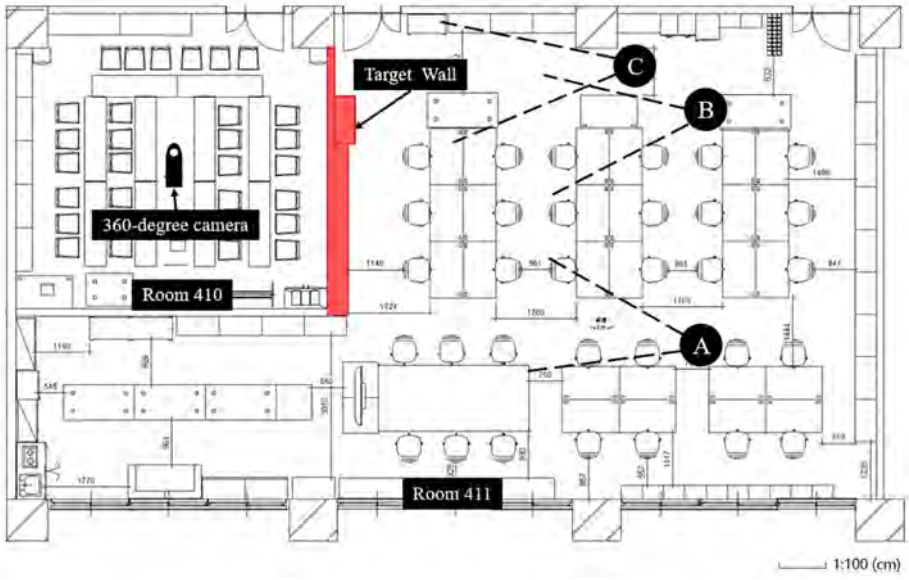


Figure 4. Room floor plan.



Figure 5. System data flow.

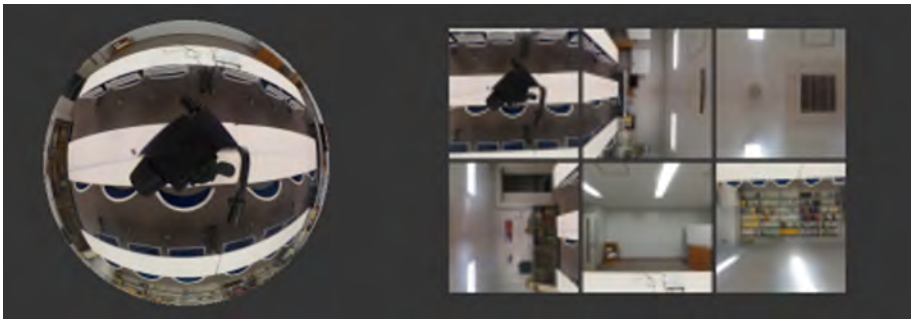


Figure 6. Panorama Image Conversion.

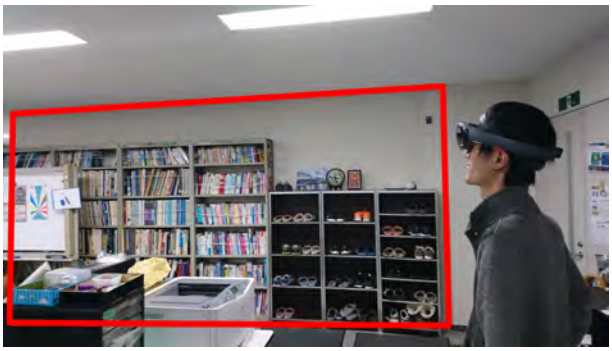


Figure 7. Reality view (red frame: DR target wall and shelves).

3.1. RESULTS

The original condition of the target wall is shown in Figure 7. The experimental results using the proposed MR system are shown in Figure 8, which contains 2D segmentation maps. In the segmentation maps, the grey parts are real-world objects while the blue parts belong to the background scene. The five planes of the mask model and the walls, the ceiling and the floor of room 410 are coordinated to coincident in the real-world position. Therefore, when the user walks around, they can experience the correct sense of space within the virtual room 410. The DR results which are observed through HMD made users feel that the target wall has disappeared. In room 410, the movements behind the target wall are also displayed in the virtual room 411 immediately. The registration function is stabilized while the virtual object shows no drift and disappearance.

However, the occlusion is not fully displayed correctly. From the segmentation map, we can conclude out that a part of the occlusion edge was shown incorrectly, and several virtual parts that should not appear in the DR results are scattered in the results. The reason for this result is that the occlusion result generated by real-time scanning is not accurate. The lack of scanning accuracy is the main cause of this problem. In addition, due to the performance limitation of the HoloLens performance, the results itself do contain systematic errors. Besides the irregular edge, the whiteboard, which should be in front of the virtual room, is covered by the virtual part. Although the range of real-time occlusion generation is set between the whiteboard and the target wall, the distance between the whiteboard and the wall is too close, and because of this, occasional errors occur.

Furthermore, the DR results are dynamic, and the refresh rate is still low. When testing this MR system on a PC platform, the entire process is fast enough to run in real-time. However, the image transmission speed is limited by HoloLens' bandwidth, which, in turn, lowers the frame rates.

3.2. DISCUSSION

If we only rely on algorithms to guess the background, generating correct content for complex backgrounds is quite difficult, and probably impossible since there are

no repeating patterns. As a result, we proposed the method of using 360-degree camera data to reconstruct the background. This method is not only suitable for complex backgrounds but also works on large, diminished targets.

Latency issues are common problems in streaming media transmission. In this study, the video quality cannot be declined because the virtual room will become blurred, which, in turn, affects the entire MR experience. Therefore, we chose to reduce the refresh rate. The program is changed manually in order to refresh the background. We set a button on the user interface, the background will be refreshed each time when the button is pressed.



Figure 8. MR result and its segmentation map in position A (above), B (middle), C (bottom); left: (MR Result) right (segmentation map).

4. Conclusions and Future Work

In this paper, we demonstrated a novel MR system that diminishes a wall and shows that details the movement of the background scene in real-time. The correct occlusion mixes the virtual world and the physical world which makes the MR experience appear more realistic. For designers, they can change the renovation plan in a short period of time and observe the effect in the MR system. For occupants, the MR experience helps them to fully understand the designer's

intentions and have a clear concept of the renovation results.

Currently, the system is operated in LAN. As for future work, if we create a relay server, the system would be operated on WAN and it can rebuild a remote room in front of the user. During image conversion processing, in order to ensure the edge of each wall is accurately assigned to each surface of the mask model, segment parameters are set manually. However, with the rise of artificial intelligence in recent years, we believe the best approach to assign the correct parts is by using machine learning to train and figure out correct room parts, and to segment the panorama.

Acknowledgement

This research has been partly supported by JSPS KAKENHI Grant Number JP16K00707.

References

"Converting to/from cubemaps" : 2018. Available from Paul Bourke<http://paulbourke.net/miscellaneous/cubemaps/> (accessed 10th December 2018).

"THETA developers' API" : 2018. Available from <https://developers.theta360.com/en/docs/> (accessed 10th December 2018).

Akihito, E. and Hideo, S.: 2007, Diminished reality using multiple handheld cameras, *Proceedings of ICDSC-07*, Vienna, 251-258.

Herling, J. and Broll, W.: 2012, PixMix: A real-time approach to high-quality diminished reality, *Proceedings of IEEE ISMAR 2012*, 141-150.

Inoue, K., Fukuda, T., Cao, R., and Yabuki, N.: 2018, Tracking Robustness and Green View Index Estimation of Augmented and Diminished Reality for Environmental Design, *Proceedings of CAADRIA 2018*, Beijing, 339-348.

Jan, H. and Broll, W.: 2010, Advanced Self-Contained Object Removal for Realizing Real-Time Diminished Reality in Unconstrained Environments, *Proceedings of IEEE ISMAR 2010*, 207-212.

Neil E. Klepeis, K.l.e.p.e.i.s., William C., N.e.l.s.o.n., Wayne R., O.t.t., John P., R.o.b.i.n.s.o.n., Andy M., T.s.a.n.g. and Paul, S.w.i.t.z.e.r.: 2001, The national human activity pattern survey, *J. Expo. Anal. Environ. Epidemiol.*, **11**, 231-252.

Kovacic, I., Summer, M. and Achammer, C.: 2015, Strategies of building stock renovation for ageing society, *Journal of Cleaner Production*, **88**, 349-357.

Meerits, S. and Saito, H.: 2015a, Real-time diminished reality for dynamic scenes, *Proceedings of IEEE ISMAR-W 2015*, Fukuoka, 53-59.

Meerits, S. and Saito, H.: 2015b, Visualization of Dynamic Hidden Areas by Real- Time 3D Structure Acquistion Using RGB-D Camera, *Proceedings of 3D Systems and Applications Conference*, 2-5.

Milgram, P. and Kishino, A. F.: 1994, "Taxonomy of Mixed Reality Visual Displays, *IEICE Transactions on Information and Systems*, **E77-D**, 1321-1329.

Nakajima, Y., Mori, S. and Saito, H.: 2017, Semantic Object Selection and Detection for Diminished Reality based on SLAM with Viewpoint Class, *Proceedings of IEEE ISMAR-A 2017*, Natnes, 338-343.

Norihiko, K., Sato, T. and Yokoya, N.: 2013, Diminished Reality Considering Background Structures, *Proceedings of ISMAR 2013*, 259-260.

Sasanuma, H., Yoshitsugu, M. and Noriko, Y.: 2017, Diminishing Real Objects and Adding Virtual Objects Using a RGB-D Camera, *Proceedings of IEEE ISMAR-A 2016*, 117-120.

Zhu, Y., Fukuda, T. and Yabuki, N.: 2018, SLAM-Based MR with Animated CFD for Building Design Simulation, *Proceedings of CAADRIA 2018*, Beijing, 409-418.

DEVELOPMENT OF GENERATING SYSTEM FOR ARCHITECTURAL COLOR ICONS USING GOOGLE MAP PLATFORM AND TENSORFLOW-SEGMENTATION

YURI KATO[1] and SHOHEI MATSUKAWA[2]
[1,2]*Keio University*
[1,2]*{yuri5712|sho000}@sfc.keio.ac.jp*

Abstract. In this research, the goal is to develop a generating system for architectural color icons using Google Map Platform and Tensorflow-Segmentation. There has been no case of developing a system that allows users to visualize the color tendency of buildings as architectural color icons for each building element from images of various regions. It is considered meaningful to be able to create criteria for decision making in architecture and the urban design by developing a system to clarify the current state of the architectural colors. It will contribute a rise in the consciousness of landscape conservation and be essential for the design of architectures and public objects. This paper includes the explanation of development method, use experiments, and consideration of five problems among architectural color icons creation. It is assumed that the accuracy of the present system will be better as the technology improves.

Keywords. Google street view; machine learning; image segmentation; color palette; color analysis.

1. Introduction

1.1. RESEARCH BACKGROUND

1.1.1. Architectural color icons and color palette

The info-graphic of the color of the abstracted building presented in "Geography of the Color" [1] is called architectural color icons. A color palette is information defining a combination of colors. These are significant design tools that shares an image of design with others.

1.1.2. Noisy-color pollution

In order to decide colors in architecture and urban design, consideration must be given to the surrounding environment and existing buildings in order to improve the landscape as well as the taste of the owner. In the 1980 's, noise pollution causing discomfort to people by public color is a problem in Japan. The 2004 landscape law was enacted. With this, each municipality reads the history, culture and environment of the land, creates color pallets and guidelines, and limits the range of colors that can be used for buildings.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 81-90. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

1.1.3. Japanese "Color Guidelines"

Request for establishment of legal system concerning landscape from local government, underwritten by Ministry of Land, Infrastructure and Transport, landscape law was enacted in 2004 in Japan . (3) There is a color guideline that complements the intention of this landscape law, concrete recommended colors and usage with diagrams and photographs, etc., and the resolution of the guideline differs for each municipality created.

1.2. 2.3 FIVE PROBLEMS AMONG ARCHITECTURAL COLOR ICONS CREATION

From 1.1, it is necessary to construct a platform that can prepare architectural color icons as color guidelines equally provided for any area in addition to existing regulations. Five problems to be solved are conceivable in generating architectural color icons.

1. Color features of the target area; The architectural color design which does not consider the color features of the target area becomes a noise problem.
2. Labor and time saving; In the existing method, since the measuring person actually visits the site and measures the color with eyes, a lot of labor and time are required.
3. Non-experts can also create; Color Guidelines Visual sense color measurement requires expert knowledge, and color icon creation is high for non-experts.
4. Dynamic framework; In response to diversified demand, it is difficult to construct a dynamic framework that changes the scale of the target area not only as a single point but also as a line as a sequence, as a wide area.
5. Visual image; Opportunities for sharing concrete visual images closer to reality are uneven.

1.3. PREVIOUS RESEARCHES

1.3.1. J.P. Lenclos" Geography of Color"

A French colorist J.P. Lenclos actually visited various countries and regions and generated "architectural color patterns" representing the color palette adapted to the area from the architectures of the land, allowing users to readily imagine the application of the design.

1.3.2. Automatic analysis of interior colors of secondhand cars by Recruit Co., Ltd.

Using the image analysis API "Image Paradise", automatic interpretation of interior colors of secondhand cars by machine learning was developed. It is analyzed that plurality of photographic images is registered by dealers, discriminates objects in the images, and determines the color. As a result, time and labor for color determination are saved and the part of the working process is designed automated.

1.3.3. "Automatic color palette"

J. Delon, A. Desolneux, J. L. Lisani, A. B. Petro. developed a system that generates color palettes of major colors from input images, using Automatic Color Palette (ACoPa) algorithm and K-means method.

1.4. POSITIONING

For the five problems above, the three previous researches introduced and thisresearch are positioned as follows. In this research, by referring to the technique of the past research, the system is developed to solve five problems in architectural color icons creation.

	1-1-1 Landscape improvement	1-1-3① Labor & time saving	1-1-3② For non experts	1-1-3③ Dynamic framework	1-1-3④ Meaning of color
1-2-1	○	×	×	△	○
1-2-2	×	○	△	×	○
1-2-3	△	○	○	○	×
This Research	○	○	○	○	○

Figure 1. Positioning table of previous studies and this research.

1.5. 1-4. PURPOSE OF RESEARCH

In this research, the goal is to solve five problems among architectural color icons creation through the development of architectural color icons generating system using Google Map Platform and Tensorflow-Segmentation.

2. System development method

2.1. SYSTEM DEVELOPMENT FLOW

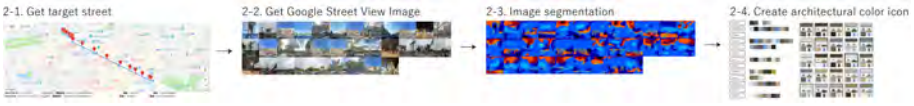


Figure 2. System development flow by 4 sections.

2.2. OBTAIN TARGET STREET

2.2.1. Reasons to use the Google Map Platform

Google Map holds enormous data of more than 200 countries and regions, and it can visualize the world. More than 25 million data are updated from over 1,000 data sources every day, and data can be used from Application Programming Interface (API). There is Google Street View Images, one of the services. Google Street View Images can acquire environmental information of a moving space

(street) experienced by a human as an image of visual information.

Human beings acquire visual information of landscape from experiences moving in everyday life and recognize the color of the environment. The information on the Google Map platform is inferred to be highly affinity when constructing a system to analyze the color of the environment. In addition, by using the Google Map platform, it is possible to acquire environmental information in areas where Google Map is supported no matter where in the world.

2.2.2. Obtain target street

Get color tendency on the environment represent for target street using information on the Google Map platform. Open a web site using the Google JavaScript API so that target street can be set from website. Therefore, the target street can be changed as necessary. If you want to analyze not only linear analysis but also planar area, cover the information of the area you want to analyze by increasing the number of streets.

2.2.3. Target Street Acquisition Flow

1. Enter start point and end point in natural language. (It is also possible to input latitude and longitude as it is)
2. Acquire target street.

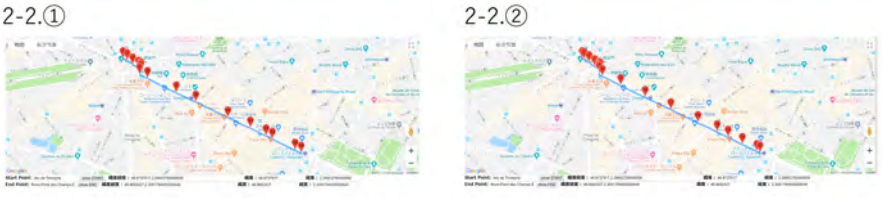


Figure 3. Target street acquisition flow.

2.3. 2-2. GET GOOGLE STREET VIEW IMAGE

From the same web site, obtain as much of the Google Street View image of the target street as possible with the major latitude and longitude constituting the target street.

2.3.1. 2-2-1. Flow of acquisition of Google Street View image

1. Obtain the major latitude and longitude of target street.
2. Adjust the main latitude and longitude of the target street so that it catches the building.
3. Automatically calculate the location and heading operations of Street View Options and capture the front of the facade of the building as an image in a state close to a rectangle.
4. Download the Google Street View image using the Google Chrome extension

Image Downloader * on the terminal that runs the image segmentation program.

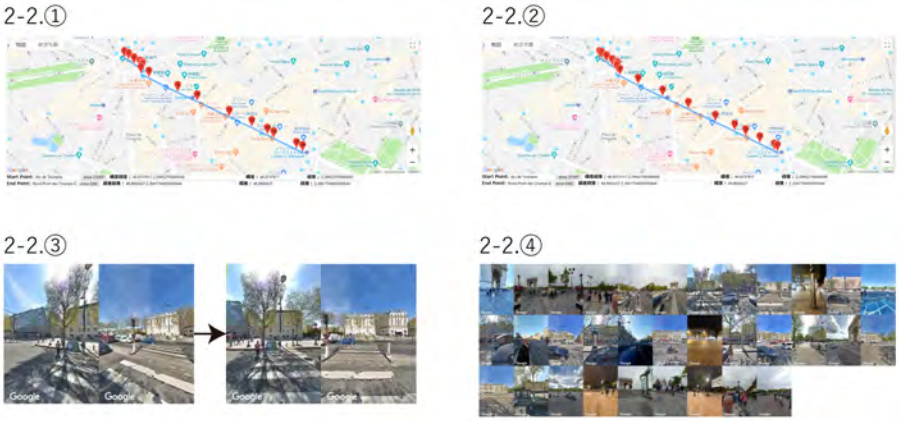


Figure 4. Flow of acquisition of Google Street View image.

2.4. INFERENCE BY IMAGE SEGMENTATION

By making a color pallet for each building element, it becomes easier to apply it to architectural design. We identify building elements from the Google Street View image and use image segmentation to automatically analyze what colors are used for each building element.

Many applications of image classification technology using machine learning exist. Generally widely known are image classification for identifying what the image is, image detection for identifying what is in the image, and so forth. The image segmentation (segmentation) which identifies the meaning of the image area. In image segmentation called Semantic Segmentation, the meaning indicated by that pixel is classified into classes for each pixel rather than detection of the entire image or part of the image.

In this study, a learning model is prepared in advance using the program Tensorflow-Segmentation of image segmentation and using CMP Facade Database as teacher learning data. For this time, keep mini batch size 100 and epoch number 500 with default settings. Further, the inference result is allocated to the teacher class 12 by quantifying the color difference.

2.4.1. Tensorflow-Segmentation

Learning and inference based on convolutional encoder-decoder architecture of Tensorflow-Segmentation using machine learning open source software library TensorFlow (TM). Google Street View Add modifications to make it easier to imagine the image.

2.4.2. CMP Facade Database

Use CMP Facade Database of the Center for Machine Perception as teacher data. This consists of 378 rectified facades images with 13 classes. (Facade, molding, cornice, pillar, window, door, sill, blind, balcony, shop, deco).

2.4.3. Class distribution by quantifying color difference

Distribute inference results to teacher class 12 by quantifying color differences. We compare class distribution results by different calculation formulas and used a low-cost approximation equation for matching RGB values to human vision based on the Euclidean distance method.

2.4.4. Flow of inference by image segmentation

1. Load the downloaded Google Street View image
2. Correct the Google Street View image to the image size of the teacher data
3. Infer the meaning for each pixel of all images based on the model created at the time of learning
4. Distribute gradation-like inference results to classes by pixel
5. Save the segmentation result assigned to 12 classes as an image

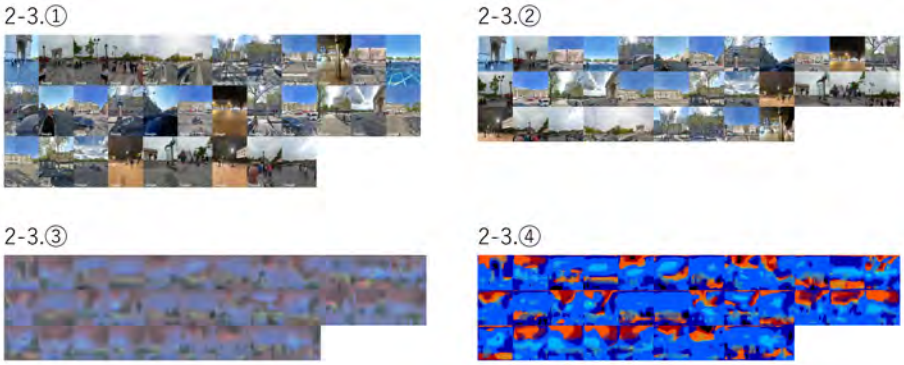


Figure 5. Flow of inference by image segmentation.

2.5. GENERATION OF COLOR PALETTE AND ARCHITECTURAL COLOR PATTERN

The color information acquired for each building element from the image is clustered by the K-means method to acquire up to 10 representative colors of up to 10 types. At this time, add all the segmentation results of the downloaded Google Street View image and create a color palette for each building element. (Frequently used in descending order from the left) 12 classes Choose colors randomly from the color palette of some building elements and generate infographics with 25 kinds of architectural color icons imitating a two-story house. By doing so, it can express the color trends appearing on the analysis target street, making it easier to compare

for each region analyzed.

2.5.1. Flow of generation of color palette and architectural color pattern

1. Summarize what colors are used for each class for each target street
2. Clustering is performed using the specified number of times K-means method based on Euclidean distance in RGB space
3. Select colors one by one from inside the color palette of each class and generate the building color icon.
4. Generate the icon of 25 and make it the architectural color pattern.

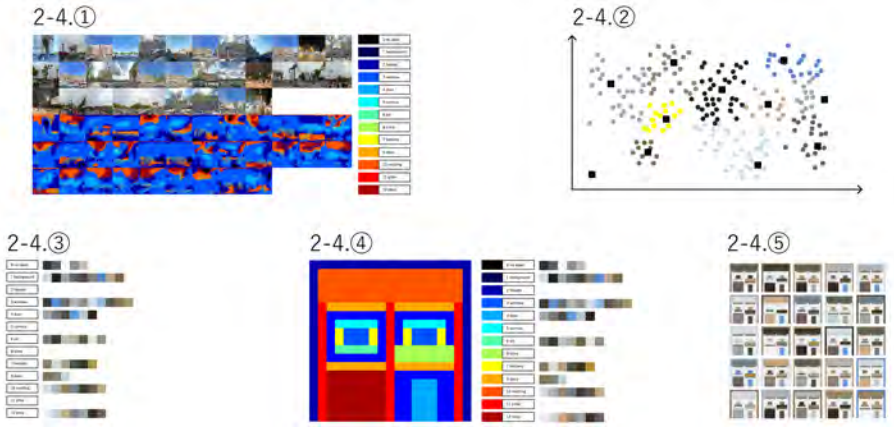


Figure 6. Flow of generation of color palette and architectural color pattern.

3. Use experiment

It is conducted an experiment using this developed system, for following four sample target streets; Champs Elysées in Paris, Times Square in New York, Hellengrat Avenue in the center of Amsterdam, Sannasaka in Kyoto.

Target area name, number of acquired Google Street View images, latitude and longitude of start point and end point, target street on Google Map, Google Street View image, inference result of image segmentation, color palette for each building element, target street Compare architectural color icons.

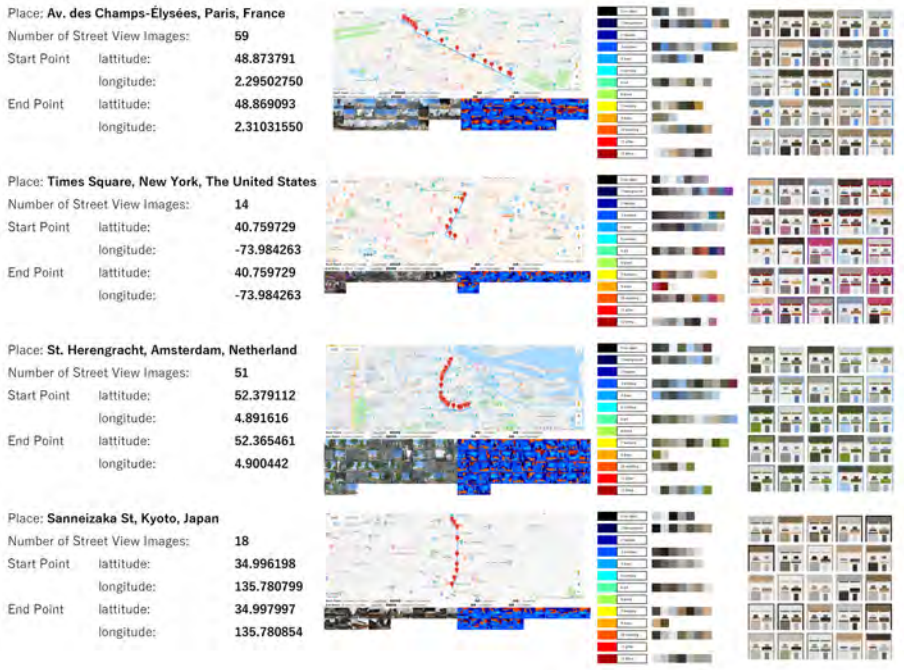


Figure 7. use experiment of this system for following four sample target streets.

4. Consideration

4.1. FIVE PROBLEMS IN ARCHITECTURAL COLOR ICONS CREATION

A system to clarify the current state of architectural colors are developed in various regions. From the experiments, it was demonstrated that the architectural color icons of four different cities were developed. This section considers the effectiveness of the system on whether the five issues in the generation of the architectural color icon are solved.

1. The color of the landscape greatly affected the area, and the colors of the architectural color icons changed. In addition, it became possible to represent the color as a sequence due to the feature of Google Map.
2. With the area where Google Maps Platform is compatible, it is possible to generate the architectural color icon from anywhere, saving the labor and time of visiting the site. Depending on the number of images, processing time can be varied.
3. This system is developed to automate and to enables creation of architectural color icons without expert knowledge. Experiments on usage including experts and non-experts is set as future tasks.
4. With the automation using the Google Map Platform, it was possible to dynamically generate architectural color icons of different scales.
5. Architectural color icons express the color tendency of the target street and presented a combination of multiple colors to clarify how the landscape is created

by many architectures.

4.2. FUTURE IMPROVEMENTS

Many problems remain in improving accuracy. We assume that these problems will be improved with future technological improvements. Experiments on the usefulness of this system and experiments on the method of use are subjects for the future.

2-1: With the route that can be obtained from Google Map, it is necessary to exclude factors that hinder the acquisition of building information by taking pictures from both pedestrian spaces on a large road.

2-2: The number of points acquired from Google Map uses the maximum number of latitude and longitude values that can be directly acquired at present. When it comes to increasing the number of points more than now, it is considered that results closer to the real environment can be obtained. In addition, since the color values from the Google Street View image have been referenced, values different from the actual color will come out due to time, season, weather, camera type etc etc. By improving the technology of Google Map Platform, it is predicted that color value correction with high precision will be possible by linking information on the conditions captured on the Google Street View image.

2-3: Since learning data deformed into a rectangle is used, it is difficult to recognize objects often included in Google Street View images such as sky, road, planting, people. By predicting that sky, road, planting, people and building elements often included in Google Street View images are generated as learning data, it is predicted that more accurate building color icons can be created.Also, because the architectural styles used in the learning CMP Facade Database are limited, image segmentation with a different architectural style is difficult. By creating data including various architectural styles, it will be possible to deal with various architectures around the world.

2-4: From the inference result of image segmentation, it is necessary to improve teacher data and discretization method by color difference quantification for the problem that 12 classes of building elements do not exist.Since the icons expressing the building elements were unified in a uniform form, it is a system that makes it easy to recall two-storied houses as an example of application to the design. By recognizing the type of building included in the Google Street View image from image recognition and by changing the display icon it will be possible to deal with various styles of architecture as well.

Since the icons expressing the building elements were unified in a uniform form, it is a system that makes it easy to recall two-storied houses as an example of application to the design. By recognizing the type of building included in the Google Street View image from image recognition and by changing the display icon it will be possible to deal with various styles of architecture as well.

4.3. PROSPECTIVE

Due to the spread of this system, it becomes possible to visualize which “part” affects the landscape and how the “whole” is changed. From the passage of time, the co-evolved “part” and the “whole” will create distinctive features of color for each region in the state of half bottom up, half top down. It can be said that the architectural color icons generation system, which is a new selection indicator of colors used in anywhere, will create diversity in architectural color and enrich the world.

References

“Colour metric, equation for a low-cost approximation” : no year given. Available from <https: //www.compuphase.com/cmetric.htm> (accessed 9th December 2018).

Delon, J., Desolneux, A., Lisani, J.L. and Petro, A.B.: 2005, Automatic color palette, *IEEE International Conference on Image Processing 2005*.

Koura, H.: 2008, Study of Planning and Implementation of Landscape Plan Legislated in Landscape Act - Case Studies of Landscape Plans decided in the early stage, *Journal of the City Planning Institute of Japan*, **No.43-3**, 211-216.

Lenclos, J.P.: 1995, *Les Coulrurs de L’Europe Geographie de la Couleur*, Publication de Moniteur, Paris.

Mitsuboshi, M.: 2013, Noisy Color Pollution and Landscape Problems - Actual Condition and Solution -, *Humanities Institute Report*, **50**, 41-67.

Naplava, J., Kluj, J. and Svec, O.: 2017, “Semantic image segmentation in Tensorflow” . Available from <https://github.com/arahusky/Tensorflow-Segmentation> (accessed June 2018).

Sabev,, V.: no year given, “Image Downloader” . Available from <https://github.com/vdsabev/ image-downloader> (accessed 9th December 2018).

Tyleˇcek, R. and S´ara, R.: 2013, “Spatial Pattern Templates for Recognition of Objects with Regular Structure” . Available from CMP Facade Database<http://cmp.felk.cvut.cz/tylecr1 /facade/> (accessed June 2018).

COMMUNICATION FRAMEWORK AND EMOJIS-DANMAKU APPLIED TO COOPERATION WORKSHOPS

YI-SIN WU[1] and TENG-WEN CHANG[2]
[1,2]*National Yunlin University of Science and Technology, Taiwan*
[1]*wu.rilla918@gmail.com* [2]*tengwen@softlab.tw*

Abstract. When different fields work together, like the designers and engineers, many problems may arise. The interaction and communication between team members are important factors that affect success. This study proposes a service design: The Emojis-Danmaku framework as a communication medium to assist planners and participants in inter-disciplinary cooperation and optimization of the workshop processes.

Keywords. Interdisciplinary collaboration; Communication; Emoji; Danmaku; Communication framework.

1. Introduction

While interdisciplinary is the key factor of computational design, there still are many unresolved communication issues, especially in the process of organizing interdisciplinary workshops. The interaction and communication between multidisciplinary team members are the important factors affecting success of workshop. In this paper, we propose an interactive framework that can be used in workshop programs, such as a warm-up activity, design thinking, teaching feedback for overcomes the initial stage of collaboration. In the interdisciplinary collaborative design issues, there are many works done by through the cooperation of their own disciplinaries problem countermeasures (Carroll 2000, Tang and Lin 2011). Nigel and Anita (1995) summarize several key issues for the team members: (1) Roles and Relationships; (2) Planning and Acting; (3) Information gathering and Sharing; (4) Problem Analyzing and Understanding; (5) Concept Generating and Adopting; (6) Conflict-Avoiding and Resolving.

1.1. ROLES AND RELATIONSHIPS IN THE WORKSHOP

Adapting the key issue proposed by Nigel and Anita (1995), the roles of people involved in the workshop are defined into three groups: (1) Organizers-including organizer, director, coordinator, staff and teaching assistant; (2) Lecturers-including keynote speaker, lecturers, and teaching assistant. (3) Participants-including native and overseas participants (Figure 1).

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 91-100. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

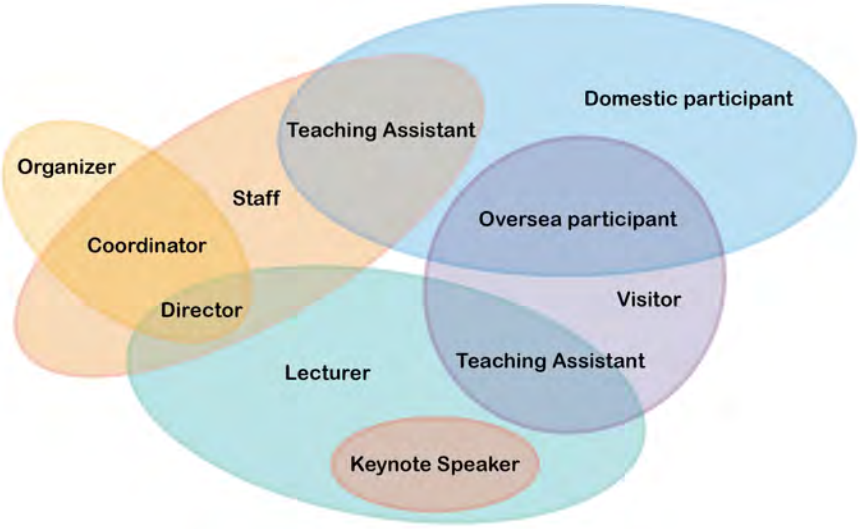


Figure 1. Roles and relationships in the workshop.

As can be seen from Figure 1, everyone acts at least one role in the workshop. Some has multiple roles, such as students who might only participate in workshop, or are teaching assistants to support the learning as well. If we explore the role of learners at in a bit more details, we can find that learners have more conversions of their own (Figure 2): Design professional learners, architectural professional learners, engineering professional learners, or other professional learners; Immersive learners in the learning situation or learners who are coming out of the learning situation. The relationships between tutor, facilitator and learners.

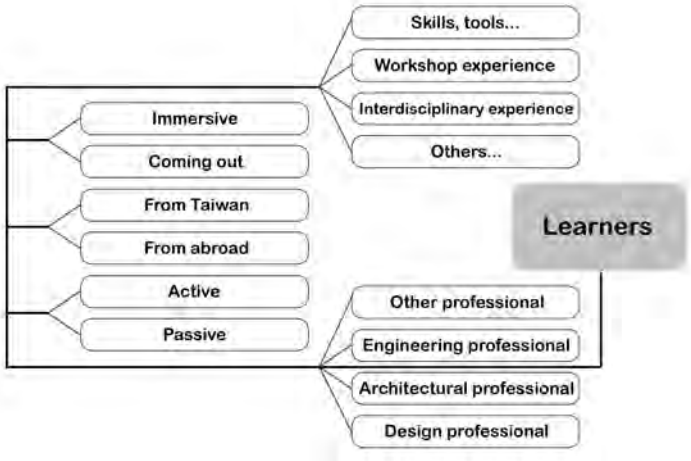


Figure 2. Switching roles in different situation.

1.2. PARTICIPANT FEEDBACK

Through the 2018 Symbiotic international workshops, a total of 32 student questionnaires were collected that their many feedbacks were received. This study shows the participants' suggestions through the word cloud (Figure 3). The first layer is: clearer, content, course, information, lecturer, need; the second layer is: much, official, website, communication; the third layer is: better, confirm, payment. After the workshop, the lecture's advice was also inconsistent with the student's suggestion.



Figure 3. The word cloud in 2018 Symbiotic international workshop.

According to the background of 1-1 and 1-2, a specific event will cause the role to be converted, we think that the learner or facilitator coming out of the situation when they are teaching or learning. That times that may are the point of the problem. Therefore, how do we know there is a problem event, and their emotions. We will carry out a series of processes and interactions.

2. Communication case study

There are many ways to communicate those different ways leads to a series of different effects. Here we explore a variety of communication tools, methods and processes in an attempt to find the best way to communicate in the workshop.

2.1. INFORMATION CAN BE VISUALIZED

With the development of the internet of things (IoT) and the smart industry, the ability to acquire data has been significantly improved. At the same time, information visualization has been widely used in the trans-mission and assistance of data messaging (Heer, et al. 2008). Information can be visualized in many different ways, and users can choose different tools based on the imported data, such as providing reports to managers or sharing their own behaviours on social networks (Mei, Ma et al. 2018).

According the crowd flow in the park, and various other factors linked to the crowd dynamics and human behavior. By insight into visitor behavior can help theme parks devise competitive strategies for improved customer experience (Steptoe et al. 2018) (Figure 4).

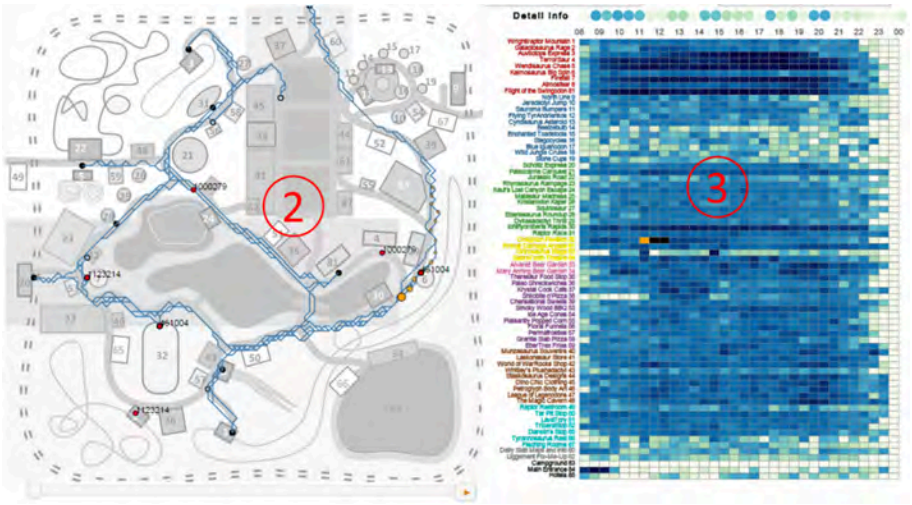


Figure 4. System overview. (2) shows a map of DinoFun World and the trajectories of selected visitors. (3) shows a calendar which represents each attraction in the park and displays the count of visitors in 30-minute intervals.

2.2. EMOJIS, THE NEW LANGUAGE

With the constant growth in information and communication technology (ICT), electronic communication has become part of the present day system of living (Jibril, 2013). Since the written form was replaced by electronic communication, people lack face-to-face (F2F) situation at-tributes. emoticons are seen as socio-emotional suppliers to the computer-mediated communication (CMC). Emojis, like the older smileys or emoticons, today adopted by almost any social media service and instant messaging platform (Barbieri, 2016).

The project of Salling Lights was shortlisted for the Danish lighting award 2017 (Kollision, 2017). The facades are using Kollision's player software to control a number of lighting designs, and the facade is inter-active allowing users to paint with light or emojis on the large canvas (Figure 5).

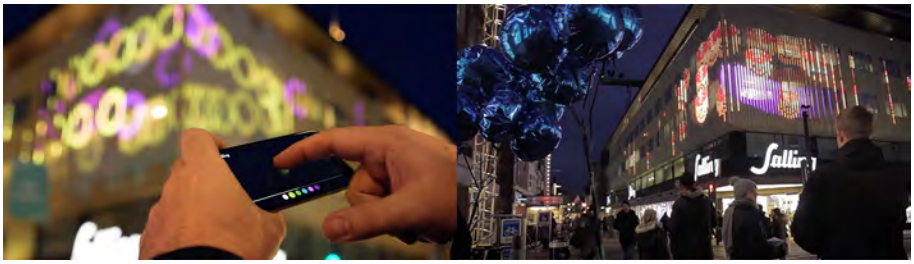


Figure 5. The project of Salling Lights.

2.3. BULLET SCREEN. COMBINES VIDEOS WITH TEXT MESSAGING

Recently, a new type of social network called Daamaku (Danmu, Bullet Screen) is becoming increasingly popular on video sharing sites in Asia. The Japanese term danmaku (danmu in Chinese) literally means barrage - "a curtain of artillery fire". It enables real-time commentary and serves as a valuable source for further analyzing social networks. Also, danmaku offers an entertaining and interactive way of expressing ideas anonymously and openly (Tang, 2017). For instance, a movie called "Moon in the Qin Dynasty" puts two large screens for users to send danmu while watching the movie (Figure 6 left side).



Figure 6. Figure 6. (left side) The movie used danmaku. (right side) Users superimpose their comments on the video .

According to Ma and Cao (2017) preliminary danmaku usage survey, it was an information seeking and emotion venting channel for users (Figure 5 right side). The researchers discussed four topics: (1) why do people use the danmaku social sharing feature; (2) whom do they interact with; (3) what do they share; and (4) how do they adapt to this "fragmented, grammatical and interactionally disjointed". Ma and Cao through the archival analysis of real-world data of videos, they

learned danmaku messages are rich in emotions and together create an immersive, engaging illusion of group viewing.

3. Related work

As discussed above, we take advantage of the features of emojis and danmaku, extracting their advantages to design communication framework that can be applied to cooperation workshop. As discussed above, we take advantage of the features of emojis and danmaku, extracting their advantages to design communication framework that can be applied to cooperation workshop.

We build interactive devices and methods to explore users' emotions, thinking and level of participation through time. Emojis-Danmaku inter-action makes users to give feedback to the organization without knowing it. When the learners are in the course, the learner coming out of learning situation, they press the Emojis-Danmaku button through the mobile phone. At this time, the facilitators will receive feedback from the emotions. When the feedback of the emotions reaches a certain level, the facilitator will inform the tutors of these feedbacks, and the tutors will be able to trigger the learners return the learning situation. This creates a mutual trigger mechanism that is fed back by three parties (Figure 7).

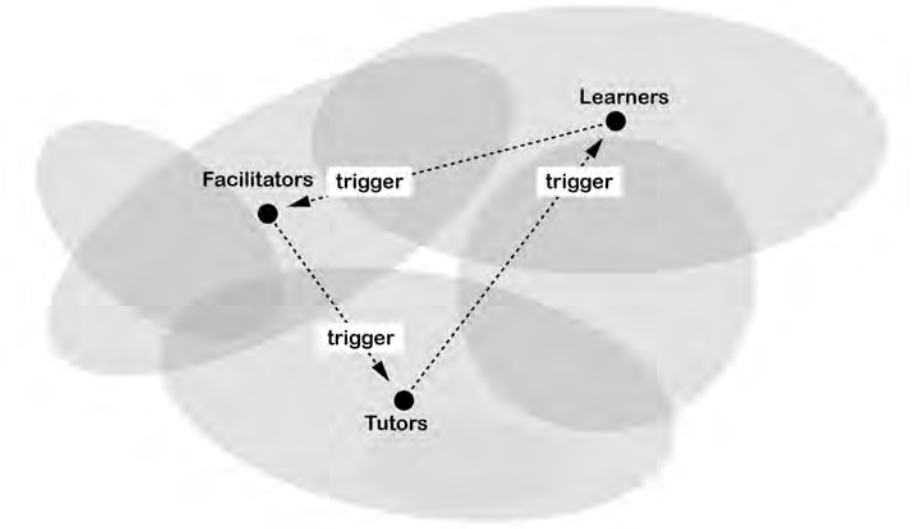


Figure 7. The mutual trigger mechanism.

3.1. WHERE CAN USE EMOJIS-DANMAKU

There is a lot of information that often appears on official websites (Figure 8). For instance, about organization, topic, course proposal, schedule, course introduction, schedule, traffic, hotels, location, contact and registration.

In the process of preparation and the end of the workshop, in addition to teaching, there are many processes. Based on 1-2 learner's feedback, we place Emojis-Danmaku interaction where the process needs to be optimized: course proposal, course introduction, schedule, hotels and registration. We will also be placed in the course of teaching, middle presentation and final presentation.

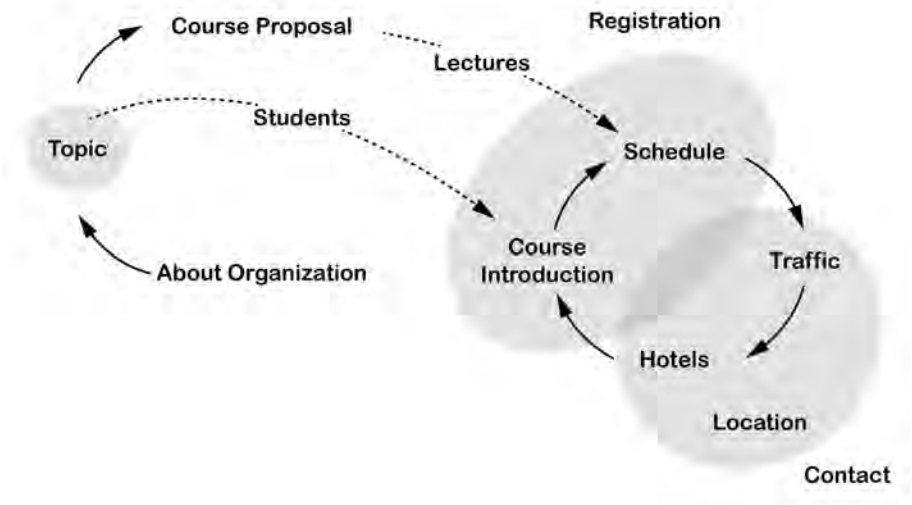


Figure 8. The information in the official websites.

The design of the interface is divided into two folds: (1) placed on the official website; (2) placed in the course group. Placed on the official website is presented in a straight-line operation, users often place their phones in an upright position when searching for information. The Emo-jis-Danmaku interaction is designed in

a way that can be transmitted separately (Figure 9 left side). The feedback is not presented to all participants and is sent to the page of the facilitator only. In the course group, there may be more text feedback situations, and learners will dis-cuss classroom questions through this page, so the page is presented in a horizontal operation (Figure 9 right side).



Figure 9. The Emojis-Danmaku interface. (left side) On the official website. (right side) In the course group.

3.2. EMOJIS-DANMAKU VISUALIZATION

To post Emojis-Danmaku comments, users need to sign in, specify the emojis, and then click the submit button. So we were able to collect questions from different roles of learner's ideas, thinking and feedback. After collecting Emojis-Danmaku comments, the facilitator will be able to get information and further assistance:

- **Through Emojis-Danmaku comments, the facilitator can clearly know what the user cares about.** When the user browses the official website, the user can immediately give back, that the facilitator can correct it.
- **Emojis-Danmaku comments can show which group have the problems.** At the beginning of the workshop, the role of learners is different, so there are different learning needs, although they will give advice, if the problem is not immediate feedback, then facilitator have no way to know or help, so it is necessary to display the demand immediately.
- **Which topic is attracting learners.** There are many topics in the workshop, and Emojis-Danmaku comments can reflect the participation level of learners. With the group Emojis-Danmaku comments, it is possible to advise the tutors and the facilitator which topic is to attract learners.

Through the visualization of Emojis-Danmaku comments, the organizers can see people, things, time, place, and as discussed above (Figure 10).

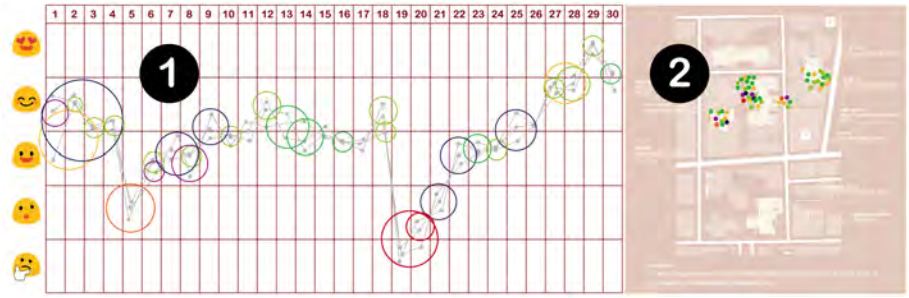


Figure 10. The Emojis-Danmaku visualization. (1) display the user's emotional when the user browses the official website's information. (2) shows the emotions of each scattered classroom learners, indirectly showing participation level.

4. Conclusion

This paper proposed a communication framework and Emojis-Danmaku comments. This framework can help organizing interdisciplinary workshops get information and further assistance: (1) more clearly know what the user cares about; (2) display which group have the problems; (3) Which topic is attracting learners; (4) trigger mechanism of tutor, facilitator and learners that increase the frequency of their communication.

There are many communication issues that haven't yet been resolved in the process of organizing interdisciplinary workshops. Therefore, we propose a framework to help participants, this framework can be used in workshop programs. In the first, we define the roles of the people involved in the workshop, everyone has multiple roles in the workshop. We create a mutual trigger mechanism that is fed back by three parties: tutor, facilitator and learners. We conclude that (1) when learners coming out of learning situation; (2) when users (tutors and learners) coming out of the situation of browsing the official website. That times that may are the point of the problem. Therefore, Emojis-Danmaku comments can know there is a problem event, and their emotions by.

In the next workshop experiment, we will adjust the way to receive Emojis-Danmaku comments. In addition to this, the number of Emojis-Danmak comments is also our concern. When the quantity of comments is very small, does it mean that learners are concentrating on the workshop? There are more details that we want to explore.

References

Barbieri, F., Kruszewski, G., Ronzano, F. and Saggion, H.: 2016, How Cosmopolitan Are Emojis?: Exploring Emojis Usage and Meaning over Different Languages with Distributional Semantics, *Proceedings of the 24th ACM international conference on*

Multimedia, Amsterdam, The Netherlands, 531-535.
Carroll, J.M.: 2000, Five reasons for scenario-based design, *Interacting with Computers*, **13**(1), 43-60.
Cross, N. and Cross, A.: 1995, Observations of teamwork and social processes in design, *Design Studies*, **16**(2), 143-170.
Heer, J., Ham, F., Carpendale, S., Weaver, C. and Isenberg, P.: 2008, Creation and Collaboration: Engaging New Audiences for Information Visualization, *Information Visualization*, 92-133.
Jibril, T. A. and Abdullah, M. H.: 2013, Relevance of Emoticons in Computer-Mediated Communication Contexts: An Overview, *Asian Social Science*, **9**(4), 201-207.
Kollision, initials missing: 2017, "Salling Lights" . Available from Aarhus<http://kollision.dk/en/salling-lights.>.
Ma, X. and Cao, N.: 2017, Video-based Evanescent, Anonymous, Asynchronous Social Interaction: Motivation and Adaption to Medium, *CSCW*, Portland, OR, USA, 770-782.
Mei, H., Ma, Y., Wei, Y. and Chen, W.: 2018, The design space of construction tools for information visualization: A survey, *Journal of Visual Languages & Computing*, **44**, 120-132.
Steptoe, M., Kruger, R., Garcia, R., Liang, X. and Maciejewski, R.: 2018, A Visual Analytics Framework for Exploring Theme Park Dynamics, *ACM Transactions on Interactive Intelligent Systems*, **8**(1), 1-27.
Tang, Y., Gong, Y., Xu, L., Zhang, Q., Liu, H., Wang, S., Wang, Q. and Gao, X.: 2017, Is Danmaku an Effective Way for Promoting Event based Social Network?, *Companion of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*, Portland, Oregon, USA, 319-322.
Tang, H.-H. and Lin, Y.-Q.: 2011, The Influence and Problems of Scenario Design Approach on Multi-disciplinary Collaboration Design, *Journal of Design*, **16**(3), 21-44.

CONTEXT-AWARE MASS CUSTOMIZATION CONSTRUCTION SYSTEM

Methods for user captured as-built plans

FILIPE JS BRANDAO[1] and ALEXANDRA PAIO[2]
[1]*ISCTE-IUL / ISTAR -IUL*
[1]*fjsbo@iscte-iul.pt*
[2]*ISCTE-IUL / ISTAR-IUL*
[2]*alexandra.paio@iscte-iul.pt*

Abstract. The problem of context, a fundamental aspect of dealing with built environments, has not been adequately addressed by mass customization systems so far, which has limited their scope of application. The aim of the present article is to evaluate the adequacy of existing methods of producing as-built plans of rooms by non-expert users for the automatic generation and production of partition walls for building renovation. This paper highlights criteria to develop appropriate methods of capturing context for mass customization construction systems.

Keywords. Mass Customization; As-built Plans; Building Renovation; Computational design.

As computational design becomes common in architectural practice, alternate modes of production, such as Mass Customization (MC), arise as viable models for architecture and the building industry (Kolarevic, 2013). MC allows distribution of control between the actors in the construction process, empowering the building owner to make intelligent and informed decisions and take the production closer to his/her context (Davis, 1987).

This paper is part of an ongoing research with the aim of developing a disassemble-able and mass customizable construction system of partition walls for building renovation by building owners. This design-to-production system will generate drawings for fabrication, instructions for assembly, and cost estimation. Therefore, it is necessary to develop the construction system, the generative process for digital design and fabrication and a graphical user interface for building owners to interact. The interface must allow a generic user to manipulate the parametric model and generate solutions for the intended space. To generate a design solution for building renovation, the shape of the space boundaries needs to be input to the design system. In previous research (Brandao et al., 2016), the definition of the boundaries was circumvented by requiring the user to input dimensions of the wall to be designed, height, width and length. This process is less than ideal, as it makes many assumptions on the boundary conditions: that

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 101-110. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

the wall will span two existing walls and will go from the floor up to the ceiling; that the angles of the wall to the existing walls are close to perpendicular; that the floor, walls and ceiling are level within a specified tolerance. Also, as the number of generated walls increases, the complexity of the interfaces of the walls with the space boundaries grows, complicating the planning process for the building owner.

Tang et al (2010) reviews several methods of automatic reconstruction of as-built models for BIM from laser-scanned point clouds. Several authors (Bhatla et al., 2012; Tanskanen et al., 2013) have proposed 3D reconstruction pipelines using single lens cameras or smartphones to generate dense 3D models. Lowe et al (2011) proposed an automated method for context capturing and virtual navigation within a game environment. Yet, at the architectural scale, these methods are still out of reach of non-expert users, whose needs are catered for by mobile apps that generate semi-automated as-built 2D parametric plans. In this context, two questions emerge: Are existing methods of capturing or generating floor plans for non-expert users sufficiently accurate to use as a basis for generating walls for digital fabrication? Are non-expert users able to use these methods reliably to produce sufficiently accurate plans?

The present article reviews existing manual and semi-automated methods of capturing the geometry of the space boundaries, both directed at experts and non-experts, with the aim of reflecting on the adequacy of the existing tools and identifying criteria for the development of a semi-automated process of generating as-built models, a more intelligent way for users to capture their context.

1. Methodology

To answer the previous questions two experiments were conducted; the first one by the researchers, using several surveying methods to produce as-built plans of three rooms; and a second experiment where a group of non-expert users and group of expert users were asked to survey one of the rooms using phone application-based methods. In the context of this research, an expert user is a person with professional experience in doing building surveys.

The goals of the first experiment are to gather insights on the accuracy, time and usability of the different methods, and for researchers to become acquainted with the workflow of each app. The second experiment aims to evaluate the usability of the applications by carrying out usability testing (Molich and Dumas, 2008). What errors does the user make while using the selected workflow / method? How accurate are their tape / laser measurements? Is the user aware of the room's geometrical properties? Was the user capable of using the app(s) to draw a polygon with the correct number of sides? Is the user confident that the result faithfully represents the space and its dimensions? Is the user satisfied?

For the experiments, three rooms in a to-be renovated building were selected and surveyed using expert methods such as photogrammetry (PHG), terrestrial laser scanning (TLS) and manual survey techniques (Manual), and non-expert methods such as existing mobile phone applications. The selected rooms are in a XIX century building in the historical city centre of Braga in Portugal. It

is a common building typology with stone façades and party walls, wooden floors and roofs, located in a narrow plot. It is part of a 4-building complex which is due to be renovated. The rooms were selected for the challenges they present to surveying, but also because they represent the typical situations that are encountered in building renovation in Portugal, particularly in XIX century buildings. Identified challenges are high geometric complexity: such as rooms with more than 4 sides, without right angle corners, uneven walls, floors or ceilings, rooms cluttered with furniture or objects, challenging wall finishes, such as black painted or high reflective surfaces. All the previously specified characteristics pose problems to the perception of the space by users and are challenging to some surveying methods.

1.1. 1ST EXPERIMENT

The TLS campaign was realized with a FARO FOCUS S120 station, a Leica GPS 1200 GNSS station and a Leica 1203 TCRP total station. It comprised the 4 buildings interiors, backyards, street and backyard façades. The survey took 3 days and produced a point-cloud composed of 258 scans grouped in 23 clusters. A typical interior scan took 2 minutes to complete and an exterior one 8 minutes. To scan Room 1 three scans where needed, Room 2 and 3 required two scans. The point clouds were aligned in SCENE with an average error of 2,36 mm. To compare the results with the remaining methods, horizontal sections of the rooms were then exported in DXF format to AutoCAD and the 2D plans manually designed. A similar workflow was used for the photogrammetry survey. Photographs were taken inside the three selected rooms with a Nikon D700 camera in RAW format, using a 25mm manual focus lens. The images were post-processed in Lightroom, exported to JPEG and imported to PhotoScan, where the point clouds were generated and exported to Cloud Compare to create sections of the point clouds to use for designing the 2D plan of the room. The rooms were also surveyed using manual methods of survey commonly used by architects, comprising paper sketches of the room and measurements taken with laser distance meter or tape measure (Figure 1). These measurements and sketches were later used to design the plan in a 2D CAD program.

Two applications available for phones were used to test non-expert surveying methods. At the time of testing, these were highest ranking free apps with a complete feature set for designing room plans on the App Store. Both applications were designed to be used by experts and non-experts alike and provide several different workflows. The first application (App 1) provides 4 workflows for surveying rooms: by capturing the corners using the phone's camera; designing a square room using the editor; designing a free shape using the editor; design the space using an underlayer plan. The second application (App 2) provides three workflows for producing as-built plans: Scan by touching walls, scan with camera, draw manually. Two workflows where selected that seemed to represent the most common types available across multiple applications. On App 1 the camera method was selected. This first workflow involves using a mix of Augmented Reality, the phone's camera and orientation sensors and user input to map the room corners, captured in a clockwise or anticlockwise sequence. On App 2 the

workflow of touching walls with the phone was selected. This workflow involves placing the phone against all the walls in clockwise or anti-clockwise sequence, requiring user input only to determine the type of object the phone is placed against, whether a wall, door or window. It uses the phone's accelerometer and orientation sensors, combined with user movement, to determine the shape and dimensions of the space. Both workflows generate a room plan which the user edit, inputting wall lengths, adding/subtracting corners or walls. Both the automatically generated output and the manually edited plan, with the measurements obtained in the manual method, were recorded and reproduced in CAD for comparison purposes.

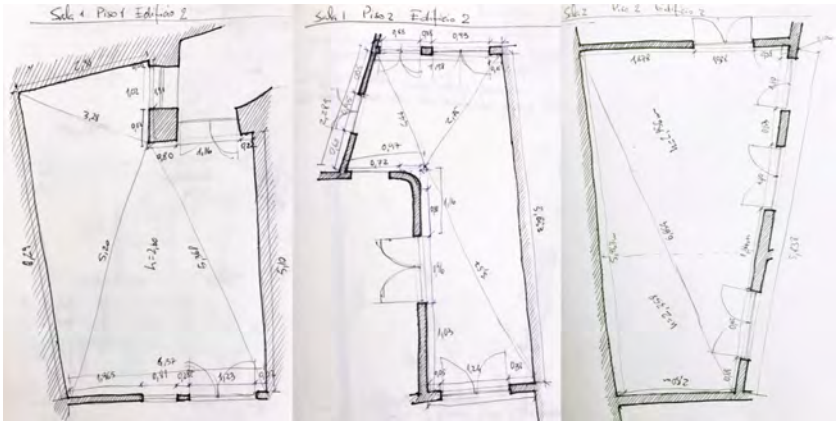


Figure 1. Manual on-site survey plans left to right: Room 1, Room 2, Room 3.

1.2. 2ND EXPERIMENT

The second experiment was conducted with a group of 5 non-expert users and 4 expert users, in line with usability tests for an iterative development process (Molich and Dumas, 2008). They were asked to survey Room 1 with mobile phone applications to produce an as-built plan of the existing space. The aim of the survey was not specified to the participants, and they were free to use one or both applications. No limitations on workflow were imposed, consequently, the users had at their disposal all 7 workflows to survey the room. A laser distance meter and a tape measure were provided. None of the users had previously used the applications or has acquainted with similar applications. The process was recorded in video by the researcher, and the user was told terminate the experience when a satisfactory result was achieved. The output of each of the users was recorded and reproduced in 2D CAD.

2. Results

The plans produced in experiment 1 are compared in Figure 2. For the sake of clarity all the windows and doors have been removed and only the inner outline of the space is kept. TLS and PHG output plans contain more detail than the remaining methods. Automated app-based methods are significantly less accurate

than the expert methods. Introducing onsite measurement to correct the plans does increase the accuracy of the side's dimensions, as would be expected, but decreases the accuracy of the angles of the polygon (Table 1). It was also noted that the final plan of the Apps workflows (APP 1 + M and APP 2 + M) can vary significantly depending on the side where the introduction of the manual measurements starts.

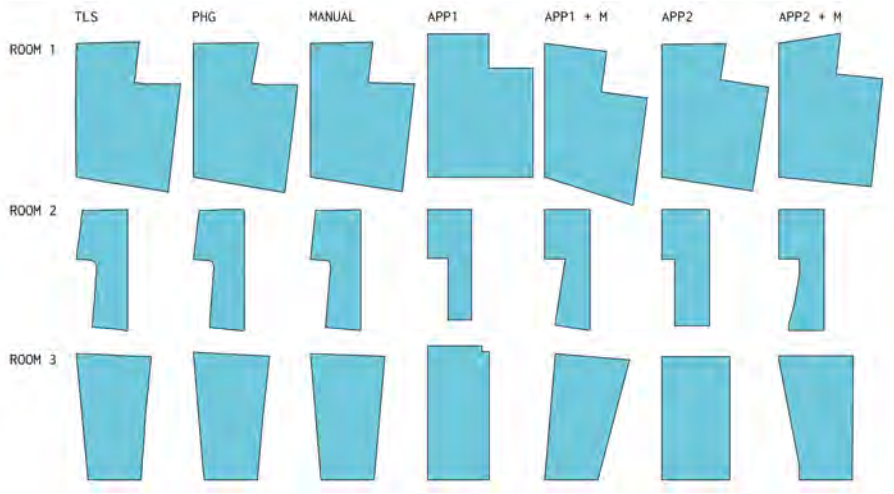


Figure 2. Matrix of plans by surveying method and room.

Figure 3 presents a comparison of the different outcomes of the workflow of APP 1 plus manual measurements. Taking the output plan of App 1 on Room 1 (Figure 2), the manual measurements were inserted on the application clockwise, beginning on the side marked with the arrow for each of the plans. This workflow produced 5 significantly different plans of the same room.



Figure 3. Outcomes of the workflow App1 + M of the plan of Room 1 by starting side.

The observed behaviour of the applications is: (1) the application automatically locks the user introduced dimensions and scales the remaining unlocked dimensions to maintain the angular properties of the space; (2) The shape of the space is kept constrained to an ortho-polygon until all the lengths of the "third side" are introduced; (3) When the total dimension of a wall where there is a door is changed, the dimension of the door is kept, and the wall's partial dimensions are changed; (4) The form of the room polygon is the result of the introduced

dimensions; and (5) There is no way to edit the angular dimensions or to add diagonal measurements. Both applications have the issues presented in Figure 3 and similar observed behaviour. App 2 presents a further problem, when the second last side measurement is introduced the last side can be split in multiple segments. This behaviour was observed in Room 2 and 3.

Table 1. Standard Deviation (SD) by room and across all rooms.

		PHG	Manual	APP 1	APP1 + M	APP 2	APP2 + M
Room 1	SD Length (m)	0,0511	0,0155	0,3658	0,0155	0,1421	0,0155
	SD Angle (°)	2,1642	0,3439	6,5926	8,2282	3,5088	5,8688
Room 2	SD Length (m)	0,0157	0,0116	0,3586	0,0116	0,2038	0,1191
	SD Angle (°)	1,9616	1,9863	4,9769	6,4596	4,9769	8,2132
Room 3	SD Length (m)	0,0532	0,0216	0,5495	0,0216	0,4620	0,0400
	SD Angle (°)	0,4991	0,4982	6,1628	10,3100	6,1628	3,6906
All Rooms	**SD Length (m)**	**0,0390**	**0,0148**	**0,3845**	**0,0148**	**0,2515**	**0,0716**
	SD Angle (°)	**1,7011**	**1,1850**	**5,5082**	**7,5984**	**4,4673**	**6,0572**

For length and angle comparisons between the several outputs, the TLS and PHG output were simplified to a polygon of 4 or 6 sides, depending on the room. The results for Room 1 are presented in Table 1. This process alone demonstrated that important details, that would have impact on fabrication, are not captured. For example, in Room3 a bulge on the wall of 4cm is eliminated. TLS is used as a reference for calculation of the standard deviation (SD). Manual survey process was found to have a smaller SD than PHG. PHG can be severely affected by bad lighting conditions, lack of detail, or reflective objects such as mirrors. The use of a full-frame DSLR improves image quality but the low room lighting required the use of a large aperture, thus decreasing the depth of field. Room 1 presented the highest SD on angle and length measurements amongst the rooms surveyed with PHG (Table 2). This room's walls and ceiling are half painted in white and half painted in black. The high contrast between white and black walls requires a compromise on exposure because of the high dynamic range of the scene. Using high dynamic range images might improve the quality of the results but this was not tested. Nonetheless, all the expert methods of survey presented much better results than app-based methods.

To compare the consequences of using the produced plans as a basis for planning the subdivision of the space and the production of partitions walls with digital fabrication, several possible subdivisions of Room 1 where considered. For space constrains we present the one that is most likely to happen, Sub 2. In Sub 2, the space is divided in three spaces. A corridor that connects the interior door to the exterior door and serves a room with a en suite bathroom. This is a common trait of the renovation interventions in these building typologies, since many of these XIX century buildings do not have interior bathrooms as is expected in contemporary housing in Portugal. These rooms would naturally require doors but as these are generally within the partition walls, the impact of dimensioning errors of the walls would only affect the doors if these are at the extreme edges of the partitions. To design the subdivision the following rules where used: (1) subdivide the space with a wall parallel to the exiting wall with an offset of 1.42m; and, (2) subdivide the

larger space by creating a wall parallel to the interior partition wall with an offset of 1,8m. The first rule places the wall between the interior window and door on one side and next to the exterior door on the other. Onsite there are visible remnants of a wall in this position that was demolished at some point. This position is optimal but there is space on both sides to accommodate some rotation. The second rule is meant to create a bathroom with a bathtub, with 1,80x0,8m standard dimensions, a toilet, a wash basin and a bidet. The parallelism of opposing walls should ideally be kept, particularly because of the bathtub, however that it is not mandatory, as it would still be possible to install the standard bathtub if the shortest distance between walls is larger than the length of the bathtub

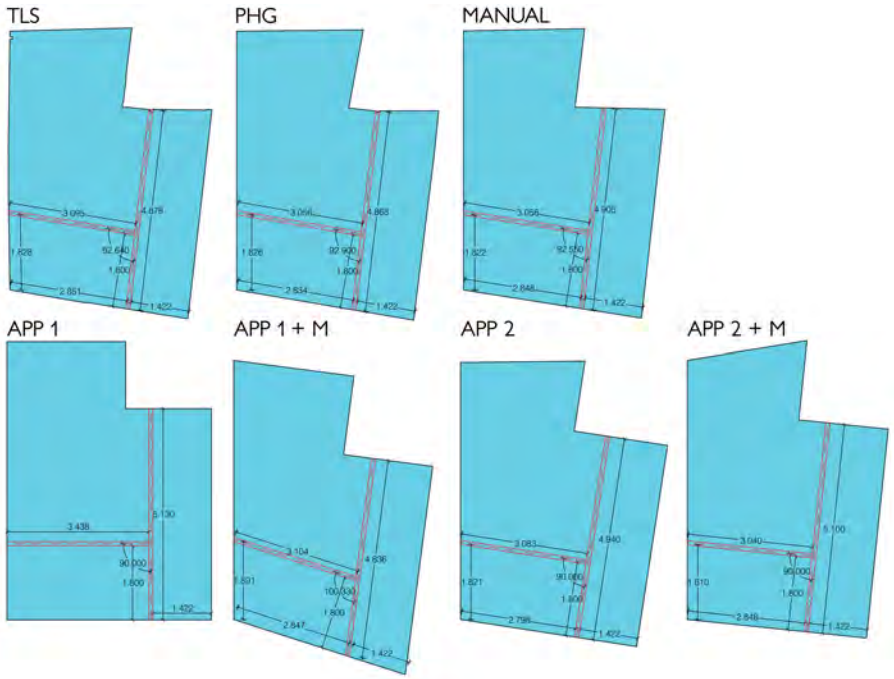


Figure 4. Outcomes of the application of rules of wall generation to each of the plans.

Figure 4 presents the results of the application of the proposed rules to each of the as-built plans. Henceforth, for briefness we will refer to the walls generated by the application of the rules to each as-built plan by the name of the respective method used to survey it. PHG walls are shorter and have an internal angle 0,26 degrees larger than TLS walls. This indicates that no problems would arise in the assembly of the walls on-site due to space constraints. The same is true for the Manual walls, except for the longer wall which is 3 cm longer. Depending on the characteristics of the constructive system used, this could cause fitting problems. In all the remaining cases the differences are larger both in wall lengths and internal angle. Both App1 plans are significantly different in terms of shape. App 1 + M plan in particular might lead the user to change the design rules or select an

altogether different design solution to avoid spaces with acute angles. Of all the Apps walls, App 2 and App 2 +M are the most similar to the walls generated in the TLS plan. Figure 5 presents the application of the generated walls in the Manual, APP 2 and APP 2 + M as-built plans to the TLS as-built plan. The walls have been positioned aiming to follow the design rules. This was possible with the walls generated over the Manual as-built plan but not with the other two. In both instances, to keep the parallelism of the bathroom wall to the existing wall, the longer wall overlaps the interior window on one side and the exterior door on the other. If on the other hand, the parallelism of the longer wall to the party wall is kept, it would not be possible to install the bathtub. Furthermore, in both cases the longer wall is 6,2 to 22,2 cm longer than the existing space.

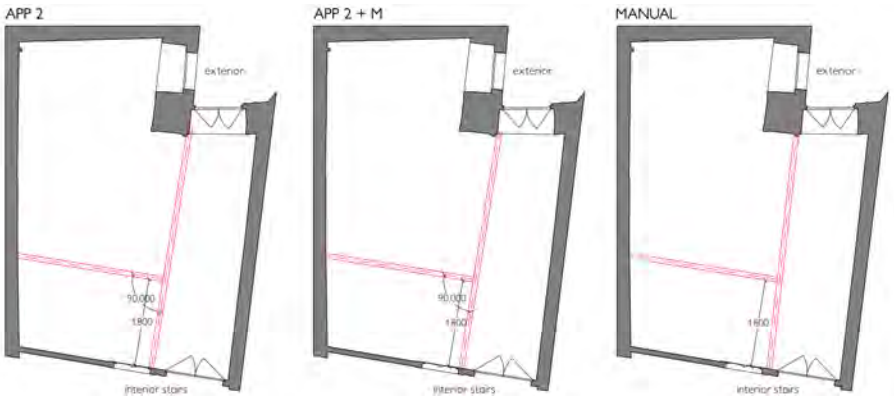


Figure 5. Application of walls generated in APP 2, APP 2 + M and Manual plans to TLS plan.

Experience 2 shown that all expert users were able to design a plan of the existing room, but only two non-expert users, User 1 and User 3, were able to design a plan topologically similar to the surveyed room, i.e. a polygon with six sides. Both of these users only tried the capture method in App 1. User 2 tried several methods in App 1, first to manually design the room in the application but could not construct a closed polygon, then to start with a square room but did not find a way of adding the remaining 2 sides. Lastly, User 2 also tried App 2 using the camera method but did not understand there was a need to click the interface to capture the intersection of the walls with floor after recognizing the floor. Instead tried to use the floor recognition method to capture the walls. In the end the user designed two 4-sided rooms because the user could not find a way of designing a six sided one. User 4 used the capture method of App 2 first but faced similar difficulties as User 2 and gave up, then switched to App 1 but gave up without designing any plan. User 5 used App 1 Capture method. Initially did not understand there was a need to click to confirm the corners. On a second try, User 5 realised it was required to point the camera at the intersection of the floor with two walls and to click a button to confirm. When going around the space in sequence user 5 missed one corner. User 5 was not familiar with using a laser measurement tool but quickly managed to understand how measurements are made.

Despite that, this user was not aware of the need to measure the distances close to the walls, instead measurements were taken at least 1,5m away from the corner. Only the User 1 and 3 were satisfied with the results produced and did not express frustration on using the apps. All the remaining expert or non-expert users felt that the results didn't match their perception of the space. Experts 1, 2 and 4 doubted the accuracy of the angles generated by the app-based method. Expert 1 and 2 referred the need for triangulations to validate results. Expert 3 understood that results were not accurate but felt these were sufficient for a preliminary assessment, despite that the expert only checked the dimensions of two walls. Several users expressed frustration with the number of steps required before starting to measure the space, particularly with the requirement to add information about the space being measured. Only the experts 1 and 2 shown sufficiently meticulous method on conducting the measurements of the space both with the tape measure or the laser distance meter.

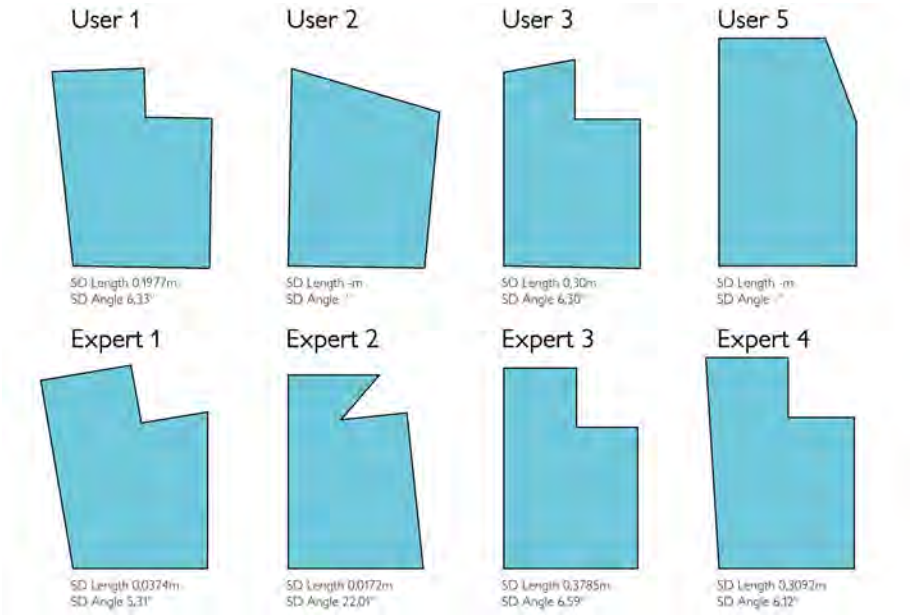


Figure 6. Comparison of user generated plans and respective standard deviations to TLS.

3. Discussion and Conclusions

Results of Experience 1 shown that non-expert methods do not produce accurate plans of non-orthogonal rooms, and while these findings are generally applicable, the design-to-production workflows of MC require higher precision than conventional construction workflows that rely on on-site fabrication. The sample size does not allow us to draw conclusions on average angular errors. Yet, statistical significance is pointless when the app-based methods display the angle control problems this research uncovered. Polygon perimeter is not sufficient to

accurately draw an irregular non-orthogonal polygon. Also, as the wall planning exercise demonstrated, even small angular deviations have a high impact on the partition walls lengths. Although our research only compared two applications, all the applications we are currently aware of share this problem. Nonetheless, these methods require simple inputs from users which makes them an appealing option for MC construction systems. We believe this issue can be overcome with better polygon drawing algorithms that include diagonal measurements, which could be informed with architect's practical knowledge in surveying building interiors. Directly measuring angles on site is error prone and requires specialized tools. Surveyors circumvent this by measuring diagonals. The process is similar to subdividing a shape into triangles. By measuring all of the sides an accurate position is obtained. In practice, it is hardly ever necessary or possible to measure all diagonals of a space, so a classical triangulation algorithms would be unwarranted, triangulations in this case are a means to close the polygon.

Non-expert users experienced difficulties in using the interfaces and collecting measurements. While some of the usability issues causing the first problem are app specific, both apps need to reduce unnecessary room classification steps, introduce clear and concise stepwise workflow instructions, introduce ways of guiding the user, namely better initial tutorials and contextual interface hints. Also, the interface and workflow should be unobtrusive to allow the user to focus on the room.

MC requires a link between the product variation and the features of the user's context, physical and social. Thus, a MC system in architecture should offer ways for users to provide the needed contextual information on the physical environment. Tested methods of generating floor plans for non-expert users are not adequate. Future research should focus on ways of improving the accuracy of these methods or introducing automated methods which rely less on user input. In conclusion, better methods of capturing context by building owners are needed to allow the implementation of a MC system of partition walls for building renovation.

References

Bhatla, A., Choe, S.Y., Fierro, O. and Leite, F.: 2012, Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras, *Automation in Construction*, **28**, 116-127.

Brandao, F., Paio, A., Sousa, J.P. and Rato, V.: 2016, Cork Re-Wall: Computational Methods of Automatic Generation and Digital Fabrication of Cork Partition Walls for Building Renovation, *Gestão e Tecnologia de Projetos*, **11**(2), 9-24.

Davis, S.: 1987, *Future Perfect*, Addison-Wesley, New York.

Kolarevic, B.: 2013, Mass Customization + Non-Standard Modes of (Re) Production, *ACSA101: New Constelations / New Ecologies*.

Molich, R. and Dumas, J.S.: 2008, Comparative usability evaluation (CUE-4), *Behaviour & Information Technology*, **27**(3), 263-281.

Tang, P., Huber, D., Akinci, B., Lipman, R. and Lytle, A.: 2010, Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques, *Automation in Construction*, **19**(7), 829-843.

Tanskanen, P., Kolev, K., Meier, L., Camposeco, F., Saurer, O. and Pollefeys, M.: 2013, Live Metric 3D Reconstruction on Mobile Phones, *Proceedings of the IEEE International Conference on Computer Vision*, Sydney, 65-72.

BESPOKE TOOLS PROVIDING SOLUTIONS FOR CONTEMPORARY PROBLEMS

Novel BIM practice for architects

WILL WANG[1] and RALPH SPENCER STEENBLIK[2]
[1]*Pelli Clarke Pelli Architects*
[1]*wwang@pcparch.com*
[2]*Kean University*
[2]*rsteenbl@kean.edu*

Abstract. This paper examines the process and the importance of designing and implementing intelligent, informed and bespoke information modeling solutions within the architectural design discipline. Along with the need for such tools comes the need for fluency in architectural principles, digital tool facility, and computational development skill sets (the combination are, still uncommon). This skill set combination are becoming more and more necessary for design teams to incorporate. This paper argues (through a series of case study projects produced by an internal platform) a way forward for the architectural design discipline through intelligent, informed and bespoke tool sets tailored to the needs of architectural designers.

Keywords. BIM; Data in design; Custom workflow; Facade paneling; Design computation.

1. Introduction

Design teams are pursuing increasing levels of integrated intelligence into the final product. By staying informed of the computation behind designed forms and making Intelligent tools to maneuver around them, architects not only avoid design reductions due to technical inadequacies, but also gain higher levels of agency in affecting the design product. Like many peers, our studio has a research arm specifically focused on the future of the practice. It is an internationally distributed platform, named REACH, charged with integrating innovation into the design process. The group is involved in analyzing, and designing intelligent and informed software tools for designers. Our approach in making these tools is a similar design process to that of designing buildings. These toolkits are built upon the principles of building/city information modeling. Our questions are specific to the tool, but in general terms, we seek a more streamlined building design process through computational assistance. Moreover, how can machine intelligence and informed databases help us to create more sensitive design solutions.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 111-120. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

2. Background

The profession now faces a landscape requiring a whole suite of digital tools to produce a piece of architecture with any level of intelligence, complexity, sophistication, or significance. There are interesting examples of a single digital tool being too heavily relied upon, within the built environment; creating designs which are too closely predicated on the underlying logics of the tool without adequate design process. On the other hand, with the departure from a singular heavy reliance on one tool as the primary design methodology comes a familiarity with a multitude of software tools, with an intimacy that makes one acutely aware of the challenges, and shortcomings of each tool in time. This creates an interesting conundrum, passively slog through the limitations of the existing off the shelf tools in a customized design process, or invest resources to develop intelligent, informed and bespoke toolsets attempting to meet the needs of the design processes of a particular studio culture and quite possible useful for an entire industry.

Off the shelf digital design tools are no longer sufficient to adequately address contemporary challenges within the architectural design process. Building Information Modeling (BIM) was developed as a way to move passed the traditional digital modeling methods. Yet even BIM proves to have major limitations. Some BIM softwares, for example, become a proprietary black box, so much that the designer loses intelligence on the geometric properties. This can cause significant modeling resources by inefficient trial and error.

The REACH team has several case studies which help to solidify the importance of intelligent, informed and bespoke tools. Recently the platform has been working on several large, resource intensive efforts resulting in toolkits made to work with existing software packages already used in the studio. As was introduced earlier these tools suggest a modal shift in the practice away from a lack of "...in-depth analysis, adaptation, and evolution of [designers'] work" (Celanto 2007), towards one where "...analytical models...coexist simultaneously with parametric models, so that they are immediately usable" (Aguiar et al. 2017, 29). Or in other words a shift toward intelligent, informed and bespoke information modeling solutions. Beyond greater iterative and analysis capabilities, developing these toolkits pushes the knowledge base from heuristics that get lost with staffing changes, into algorithms internalized into the workflow for an ever increasing repository the studio can build upon; we present evidence toward this argument below with the following case studies: 1. REACHTower, 2. REACHCampus and REACHUP 3. Customized Toolbars. These case studies are introduced in the methodology section and expounded upon in the results section.

3. Methodology

The concept, fundamental to our team's process, is design data: harvesting BIM data and the utilization of "softBIM" strategies. This concepts can also be characterised by the terms intelligent, and informed software solutions. In the most concrete way, the main focus of the team's efforts are to create tools with an interface developed to integrate data into digital 3D models, quickly informing designers of solutions with "fingertip" accessible analytics, and empowering

them to achieve more effective solutions. Some of these tools are highlighted in this paper. Without a meta-dataset focused on the design practice and the design process of past projects, the ability for computational aid is minimal; thus emphasizing the collection of metadata also becomes pertinent.

Our bespoke workflow, wrapped in a user interface called REACHTower, keeps architects informed each step of the way in terms of the balance between feasibility and aesthetics of design while attaining precise and rapid documentation. REACHUP is an urban planning design assistant, organizer, and interface for complex objective representations. The tool allows designers as well as clients to see the strength of BIM even as early as the Schematic or even conceptual design phase within the urban planning process. It combines 3D digital models with a database by providing live queries and instant feedback loops on modeled geometries. The tool enables decisions to be made based on any number of complex design parameters presented all in one place, in a succinct way. A similar project dubbed REACHCampus, has been created for use in higher education planning. Additionally, the team has worked on more traditional toolbars in several design software packages. From this work has grown some innovative solutions applicable to the architectural design disciplines.

4. Results

4.1. REACHTOWER

Part of REACHTower is a paneling exercise which expresses the custom workflow previously mentioned, mediated by a proprietarily crafted user interface built on industry accepted architectural modeling tools. In early stages of the project, the design team has tried paneling in more singular software environments but that only highlights the limitations of the standalone softwares themselves. Even with readily made plugins such as Paneling Tools and Hummingbird, the risk of discontinued external support runs high. A big advantage of our method is the controlled accuracy of interoperation. Nate Miller (Proving Ground) has written about the problem of different geometry generations between Revit and RH. In our workflow the data transferred are all point coordinates. There is no interpolation, and decimal precision can be prescribed by the user.

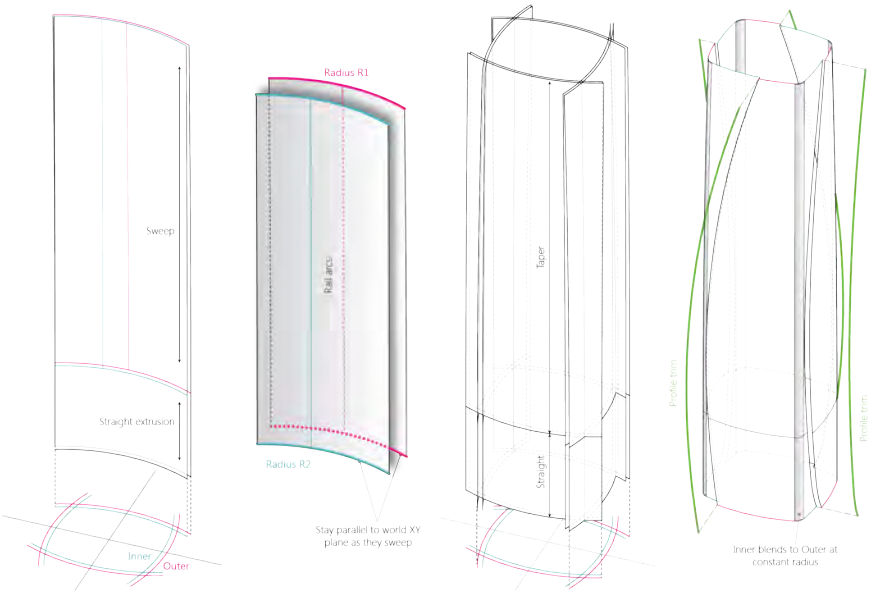


Figure 1. preparing parametric model for software interoperability.

Our method for façade modeling, deployment, and documentation is maturing. We have pushed it far enough that the most daunting aspects of making design changes (i.e. modeling) is mostly computing time per se. The interoperability workflow is only one custom, integrated, tool built into the REACHTower toolkit. Additional tools include an industry collaboration with a software company working on VR sculpting. This collaboration allows the toolkit to have a greater life of its own beyond the singular modeling environment, as was previously discussed as an original impetus for the teams conception in the first place.

4.2. REACHCAMPUS AND REACHUP

2. REACHCampus and REACHUP || In developing REACHCampus the case study campus asks for a master plan at a high level, focusing on strategies. Massing schemes should come later in the process and in fact at a lower resolution. Therefore a large amount of overall campus information was given. Data includes energy uses, campus transportation, well-documented tree species (including GPS locations), etc. It becomes static to only look at each category on its own, and difficult to keep track when multiple categories are juxtaposed to study connections or influences. REACHCampus is a prime example of leveraging data to increase designers access to intelligent and informed tools.

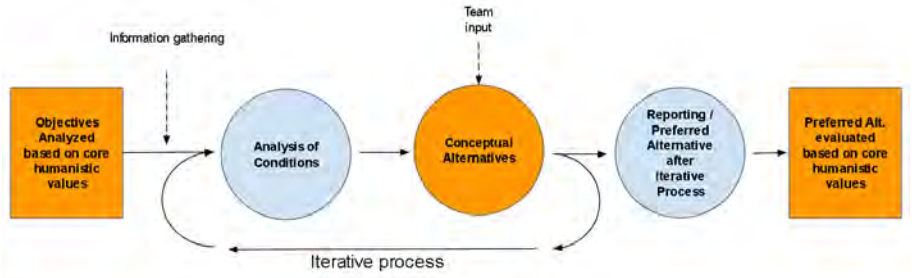


Figure 2. Iterative process the prime opportunity to turn into algorithms.

One of two main features of the REACHcampus toolkit aims to provide a more dynamic query mechanism than is currently used in the industry (printed reports and on-screen text files). We use two kinds of data. One can exist entirely independent of a 3D digital model, and the other is actually modeled in the digital modeling environment RH. The other main feature of REACHcampus contains most of the computing. It searches through the database, matches entries with 3D model elements, and calculates relevant statistics and analytics. A distinct phase of master-planning called data gathering, often at the beginning of the architectural masterplan workflow, involves the painstaking process of extrapolating as many diagrammatic representations as possible. These diagrams are then compiled in a hefty printed medium as a design reference. Digital copies of such material only exacerbates the deluge of un-synthesized information a designer is expected to digest, as concurrent visibility of multiple categories of information becomes clumsy under most circumstances. A more flexible way of data representations is due. REACHcampus is comprised of a user interface (UI) and back end algorithmic collection connected to a database specific to a particular project. The database in this data-driven process has been termed ”DesignData” by the authors of softBIM: an Open-ended Building Information Model in Design Practice. ”Through associating raw data with objects, meaning is given to the data, thereby turning it into useful information for the design process.” It consists of simple data visualization interface components which express the queries of the back-end database and link them to 3D elements. This combination extends the functionality of 3D geometries beyond the scope of its traditional, native CAD software. The majority of REACHcampus’ functionalities also apply to urban planning, because college campuses are either in urban settings or creating their own ”urban” (National Geographics, n.d.) environments. The toolkit is geared towards university master plans, where complex design objectives and large collections of iterations can be rapidly represented in an organized fashion empowering designers to make more informed design decisions more rapidly.

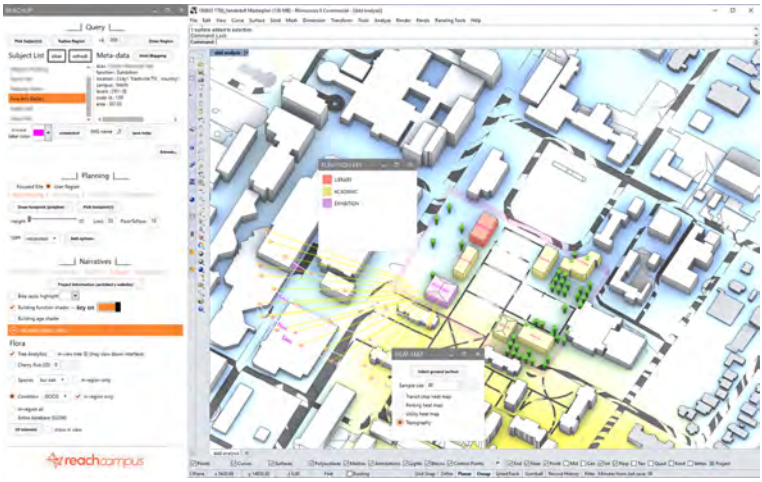


Figure 3. REACHcampus interface overlays multiple anlytics for study.

On-the-fly optioning tools are integrated into our interface for near real-time feedback. Similar "reflexive" design methods have seen increased implementation on the object level. In Towards an Architecture of Cyber-physical Systems, Kathy Velikov and Geoffrey Thun furthered the idea of "...placing the act of design within the highest order of system hierarchy, being simultaneously purposed and reflexive." (Velikov and Thun 2014, 333) REACHcampus brings the information feedback loop to larger scales and reduces myopic planning in isolation. With solver integration we are able to optimize for desired parameters. This gives the designer benchmarks and intelligent cues from which to begin the design process in a much more informed way. A key metric in master planning is area calculation. A traditional approach to acquiring this information is through 3D-modeling surfaces or polygon curves that represent building floor plates (CAD software often have a command that calculates the area either as an aggregate or as individuals). After the area has been calculated it must be manually entered as text values, updated with every design revision affecting areas. With REACHcampus, as is common with BIM solutions, building level information is stored in the database as text strings. The interface reads them, matching buildings via identifiers, and produces floor plates dynamically. In REACHCampus there is no modeled geometry of the floor plate unless desired, keeping a leaner digital model optimized for performance. A change in level elevations in the database is precisely reflected in the model upon a new query. This eliminates the need of human tracking, which is often error-prone, as well as automating the calculation process. Once area is calculated, many related key metrics can be computed such as floor-area ratio (FAR), daytime population, and estimates by unit cost, etc. These algorithmic procedures are also built into the interface so the designer can quickly see results with a toggle, or can even edit the definition of the parameters in the equation. Although the math mostly involves common arithmetic operations, the expedience afforded by an automated, simplified interface improves experience by pushing metrics right to the designer's fingertips. The strength of our toolkit's metrics

computation is flexibility. Because the specialist has access to the back-end of the tool, it is highly customizable for creative use or adaptations. Besides existing conditions and their representations, we have created a massing generator capable of repeating the same marriage between metadata and geometry. Even though a designer is more than competent to model in the native RH interface, the massing generators and their UI enables interweaving options into the script computation - the result is DesignData.

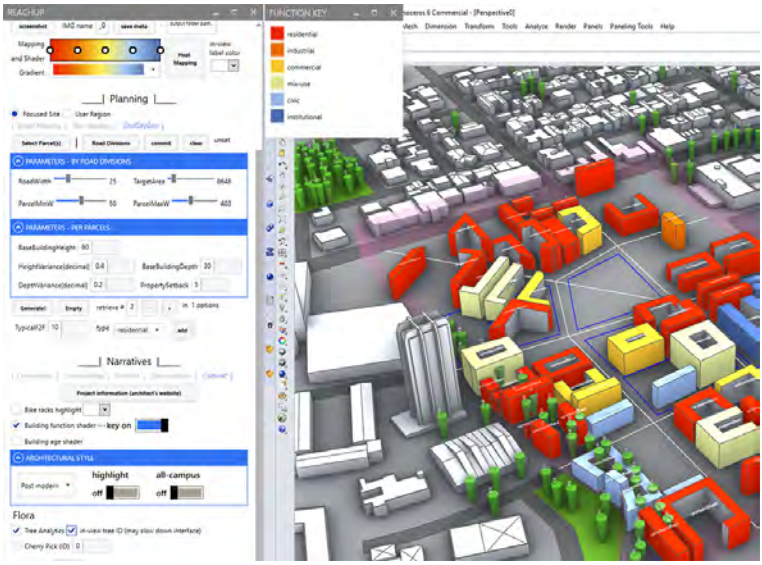


Figure 4. randomized massing with programmed functions.

In order to produce the organic effect of city growth, we embed a pseudo-randomization algorithm into the REACHCampus massing generators. Due to the nature of the visual scripting environment's computation sequence, the common practice in producing pseudo-randomization is through a "seed" controller. In other words, there is a known one-to-one relationship between a solution and an input seed number, albeit solutions seem arbitrary to each other. This phenomenon runs against the concept of randomization. So we decide to iterate through options in a completely unpredictable and ephemeral manner. To compensate for the lack of indexing in this arbitrary process, we have to create our own temporary storage in computer memory where solutions can be deposited upon a toggle switch. This way we can retrieve an option.

4.3. CUSTOM TOOLBARS

Anecdotally, this mechanism applies a paradigm of machine learning in a way that is uncommon within architecture. There has been some difficulty for designers to integrate true machine learning processes into the design process, because of the "learning" period. Most designers are able to find the solution during the time it takes for the learning to take place. With the use of the analytical tools and the

stored solution sets we are able to cross beyond the learning barrier prior to first use by an end user, and as more users engage the tool the so called AI will become smarter. This breakthrough has the potential to fundamentally alter the method of working within the firm if not large portions of the industry.

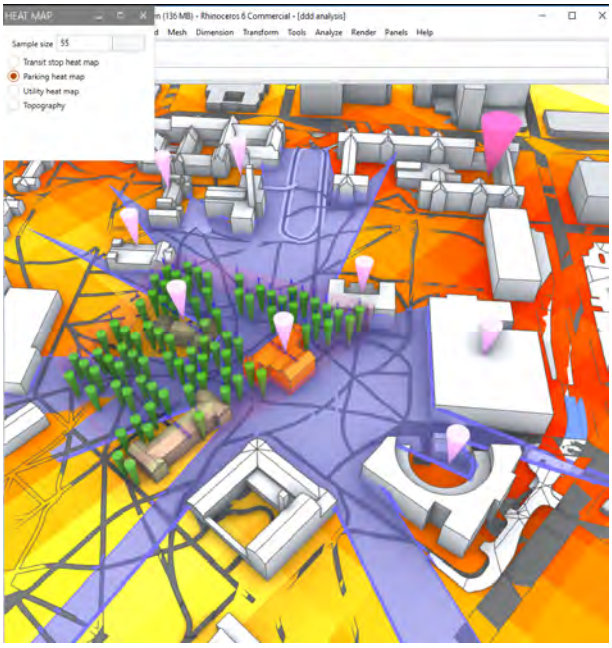


Figure 5. Isovist(blue) graph in relation to context information.

We have observed that one derivative, in the process of researching new processes or techniques, may be studio-wide increases in productivity through implementation of these new methods and solutions. By understanding software API's, a collection of functionalities specific to the studio can be made to a customized toolbar. Take stairs for example. They are a very familiar object to architects but rarely a concern for naval engineers or jewelry designers. In dedicated environments for architects, there are stair tools readily available. But in freeform environments, the architect has to model the object from scratch. With scripting, we can make a parametric tool that sits next to all the out-of-the-box toolbar buttons. Over time, the effort saved adds up to greater efficiency (See Figure 7). Other outgrowths of the bespoke tool creation have been specific functions manifested as toolbar commands, within the different software packages used within the studio. Sometimes these tools have been the predecessors of the custom interfaces and other times they have been independent. Regardless, we have been able to incorporate many features into our toolbars which make them very appealing for the productivity of the studio. For example while creating the urban/masterplanning exercises we were able to produce many tools with standalone application within the studio outside of the specific custom interface.

The native IsoVist tool inside of RH is primitive and limited in utility by itself. With simple, strategic embellishment, tools such as the IsoVist can become very powerful visual tools. Properly automated, the tools are then quickly integrated into the everyday analytical toolkit. After innovating on top of the existing tools available in the platform they become new tools in their own right. In the case of the enhanced IsoVist tool, for example, has become something other, called View Lilly.



Figure 6. tool usage analytics.

After implementing such a tool in the design studio we are able to begin gathering data on its use. This allows us to mold the tools and the collections of tools in ways that are more intuitively useful to designers ways of working. Additionally, these datasets point us in directions that are useful and point to holes in the custom tools not yet implemented. Beyond the data on the actual tools themselves we are most interested in capturing data on the designs the tools are used on. By gathering this data we can begin to understand more about the spaces that come across the studio drawing boards. After time the data sets will gain robustness toward more acute solutions within the design and analytics or informed future projects. Understanding past projects to this level of granular detail is rarely achieved within contemporary architecture studios.

5. Discussion and Conclusion

The territories of intelligent, and informed computational design, can prove elusive, but learning to leverage these modes is key in the progress of the design disciplines and particularly the architectural discipline. The technology and expertise have already arrived. It is a matter of harnessing skill sets in a way that encourages innovation. Young talent is increasingly equipped with the proper knowledge. Moreover if a design studio can encapsulate its knowledge via algorithms, databases, and automated procedures, they will enjoy

not only boosted productivity but also answers to “wicked problems” (Martin 2009, 92). Without the understanding of parametric geometries and efficient documentation, design exercises can easily get lost in the cycles of manual drafting and coordination. Without an analytical dashboard, design exercises can only address very few criteria within a given timeframe. These increases in capability allow us to more acutely begin designing toward solutions to problems such as climate change, measurable marketability, cost and feasibility, increased regulatory hurdles, etc in a way previously unavailable to designers at large. Bespoke tools are a way of innovation within this design profession too often “dismayed by the elusiveness of success... [and] diminished impact” (Celanto 2007). Computationally intelligent, and informed research through, data harvesting, and softBIM are hopeful ways forward for many of our disciplinary challenges. At the 2017 Thornton Tomasetti’s AEC Technology Symposium, Andrew Heumann and Brian Ringley of WeWork spoke on the impracticality of the single platform fantasy. They emphasized that the industry has shifted into a paradigm of multi-software data exchange. Having personnel who can make this exchange process transparent and seemless, while integrating levels of intelligence is a necessary asset on any architect’s team. Operating outside of the traditional software platform mode by creating intelligent, and informed customized tools, we are able to increase the freedom with which one works by ditching preconceptions upon which proprietary software packages are predicated, and by operating based on our own terms. Architecture is inherently top-down, regardless of our efforts to incorporate bottom up processes. Architects therefore must gain the highest level of intelligence and understanding of their product.

References

“Raffles City: Knowledge Based Design & Engineering Applications” : 2017. Available from <https://www.unstudio.com/en/page/9051/raffles-city-knowledge-based-design-engineering-applications> (accessed 15 March 2018).

“Urban Area” : n.d.. Available from <https://www.nationalgeographic.org/encyclopedia/urban-area/> (accessed 2 Sep 2018).

Aguitar, R.A., Cardoso, C.C. and Leitao, A.L.: 2017, Algorithmic Design and Analysis Fusing Disciplines, *Proceedings of the 37th Annual Conference of the ACADIA*, 28-37.

Almeida, N.A., van Berkel, B.V.B., Fagerstrom, G.F., Hoppermann, M.H., Rocchetti, S.R. and Zangerl, M.Z.: 2012, softBIM: an Open-ended Building Information Model in Design Practice, *Proceedings of the 32nd Annual Conference of ACADIA*, 37-46.

Celanto, D.C.: 2007, “Innovate or Perish: New Technologies and Architecture’s Future” . Available from <http://www.harvarddesignmagazine.org/issues/26/innovate-or-perish-new-technologies-and-architectures-future> (accessed 4 September 2018).

D.J.G. Gerber and M.I. Ibanez (eds.): 2014, *Paradigms in Computing*, eVolo Press, Lois Angeles.

Martin, R.M.: 2009, *The Design of Business: Why Design Thinking is the Next Competitive Advantage*, Harvard Business Press, Boston.

Miller, N.M.: 2012, “Interoperable Geometry” . Available from <http://www.theprovinggroun d.org/2012/09/interoperable-geometry-part-1-curves.html> (accessed 1 Dec 2017).

DEVELOPING ALGORITHMIC METHODOLOGY TO VISUALIZE & EVALUATE THE DYNAMICS OF URBAN FORM IN THE EARLY DESIGN PHASE

SHAO-YU CHA[1] and TAY-SHENG JENG[2]
[1,2]*National Cheng Kung University*
[1]*cha.aoup@gmail.com* [2]*tsjeng@mail.ncku.edu.tw*

Abstract. Advances in algorithmic and architectural methodology is challenging the current practice of conventional and participatory urban design. This paper presents a prototype implementation of a computational urban design tool. This implementation provides a rule-based approach to urban design by developing algorithmic methodology to visualize, analyze the dynamics of urban form in the early design phase. We focus on synthesizing data and demonstrate how data synthesis approaches can be used to support performance analysis at early planning and design stages. The implementation shows a flexible workflow that supports performance analyses and can easily be integrated into design and planning processes.

Keywords. Algorithmic Methodology; Urban Form; Generative Design; Analysis Tool.

1. Introduction

Algorithms have been widely used in architecture, designers have been concerned with the use of computational tools combined with new methodology for the exploration of formal systems (Terzidis, 2006)(Menges and Ahlquist, 2011)(Jabi 2013)(Stouffs and Janssen, 2015). Algorithmic methodology has been incrementally extended to the generative process of urban development using simulation tools and big data analysis. The complexity of urban development demands new urban design methodology with large-scale computation. It is still difficult to comprehensively analyze quantitative information of urban development due to lack of sufficiently detailed information (Beirão and Duarte, 2005)(Ferreira, et.al, 2015)(Stouffs and Janssen, 2016).

Urban design involves many aspects and various disciplines. For the last two decades, planners and designers have been concerned with the use of computational tools with algorithms for the exploration of formal systems. Algorithmic methodology has focused on computational methods of formal exploration and expression. It offers a computational approach to support urban design by providing computational design tools in the early design phase. It has been attempted to readdress formal logic of urban design using new techniques, algorithms, and methods.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 121-130. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

One of the problems in the urban design and planning processes is how to integrate generation and evaluation of designs in the early phase. The use of performance analysis, either to inform the design process or to assess design solutions, though available, is still sparse. Part of the problems may be the absence of, or the difficulty in retrieving, sufficient amounts of data to support performance analysis. Nevertheless, there is always a limitation to the data that is readily available and any specific design queries may necessitate data that cannot be obtained by regular means.

Another part of the problem may be the lack of simple and flexible workflows that support performance analyses and can easily be integrated into design and planning processes. Especially when such processes are characterized as dynamic, collaborative and constrained by time, skills and the availability of tools. While various tools and systems are available to support performance analysis within urban planning and design processes, these tend to be neither simple to use, nor flexible in their ways of usage, nor can they be easily integrated with other tools that may serve other parts of the workflow. Modular workflows that can easily be adapted by the user to apply within a particular design context or process are of special interest. Such workflows often rely on various software tools that must be seamlessly connected in order to allow the user to switch back and forth between modeling and analysis.

To overcome the problem, we propose three complementary elements of algorithmic methodology: extracting data, synthesizing data and mining data, as shown in Figure 1. Extracting data refers to data that can be found online, yet not in a readily downloadable or applicable format and requires manual processing or the development of dedicated scripts to extract the data from the source. Synthesizing data refers to data that is generated from existing (design or analysis) data based on assumptions, heuristics and/or typologies. Mining data refers to the application of data mining techniques in order to understand relationships between data.



Figure 1. Three elements of algorithmic methodology for urban design.

The objective of this paper is developing algorithmic methodology to visualize and evaluate the dynamics of urban form in the early design phase.We focus on synthesizing data and demonstrate how data synthesis approaches can be used to support performance analysis at early planning and design stages when urban criteria have been defined only conceptually and still need to be elaborated in terms of planning or modeling. Specifically, we present a rule-based approach to generate relevant building data that can serve to analyze and assess urban plans with respect to relevant criteria, requirements and targets. Such urban form generation must necessarily take into account local conditions, building typologies, codes and regulations. We also address the integration of data synthesis and performance analysis and identify some obstacles for developing integrative workflows on the fly in response to specific questions that may arise in the planning and design process. In urban design, algorithmic methodology can be thought of as analogous to engineering productivity for repeating or continuous processes. There is a clear tendency to seek and explore formal properties as sources of ordering systems in urban design.

2. Related Work

Algorithms play an important role in developing methods for evaluating various visibility-based design characteristics. Progress in algorithmic architecture has been made in supporting parametric and generative design. There has been very little research work reported on the effectiveness of such use of algorithmic methodology in the early phase of urban design.

There are three parallel approaches to develop algorithmic methodology. The first approach is to develop algorithms for parametric and generative designs. The current transition from Computer Aided Design (CAD) to parametric design represents a profound shift in design thinking and methods. Representation is being replaced by simulation, and the crafting of objects is moving towards the generation of integrated systems through designer-authored computational processes (Menges and Ahlquist 2011). Parametric design tools allow designers to specify relationships among various parameters of design models, where algorithmic methodology is developed to come up with interesting design solutions (Terzidis, 2006) (Jabi, 2013). Another approach is the development of rules or algorithms for design evaluation. A generalized parametric model can be used as an analytical device to investigate how different parametric modelling methods provide for iteration (Stouffs and Janssen, 2015). Space syntax theory is developed for analyzing spatial configurations of designs, districts, and cities (Hillier and Hanson, 1984) (Desyllas and Duxbury, 2001) (Batty 2001). The third approach is urban optimization through evolutionary computation (Ferreira, et. al., 2015) (Navarro-Mateu, Makki and Cocho-Bermejo, 2018). It indicates the demand of public participation in decision-making for more accountability on the parts of stakeholders (Healey, 1997). A mixed top-down and bottom-up strategies is developed to integrate each participant's point of views in urban planning practices (Forester, 1988)(Murray, Greer, Houston, McKay, & Murtagh, 2009).

3. An Example

In order to demonstrate the proposed algorithmic methodology, we present a real-world urban design example to test the implementation. The example has been drawn from the Green Energy Science Village Project, as shown in Figure 2a. We tried to use the local range of Zone A as the experimental implementation, as shown in Figure 2b.



Figure 2. (Figure. 2a) The Green Energy Science Village Project; (Figure. 2b) use the local range of Zone A as the experimental implementation.

4. Research Method

This paper proposes a design method that employs a three-stage algorithm on each participant's point of interest. By Definition, the geometric, environmental, and social relationships constitute the basis of urban design. These relationships become a complex system with a behavior and efficiency that are difficult to evaluate and predict. Furthermore, being able to establish geometric relationships within urban patterns in 3D modeling software allows us to manipulate geometry's mathematical definition. Once the definition is established, analyses and manipulations of geometrical variables together with social and environmental ones can be developed through a range of existing plugins. These plugins allow researchers from the architectural and engineering fields to manipulate such a complex mathematical set of relationships, as shown in Figure 3.

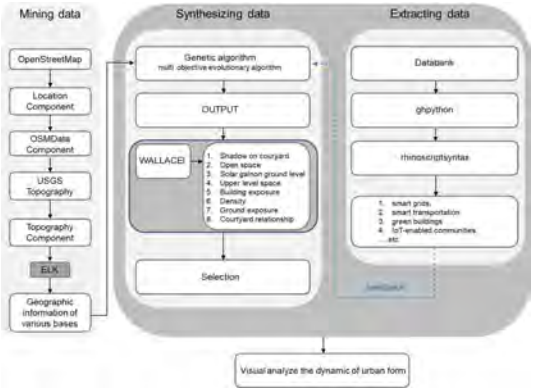


Figure 3. A three-stage algorithmic methodology is developed to visualize and analyze the dynamics of urban form.

4.1. Mining Data

OpenStreetMap (OSM) is used as a collaborative tool to create a free editable map of the world. Rather than the map itself, the data generated by the project is considered its primary output. The creation and growth of OSM has been motivated by restrictions on use or availability of map information across much of the world, and the advent of inexpensive portable satellite navigation devices. OpenStretMap.org is an open/crowd sourced website of mapping data. It allows you to export XML formatted data of a selected area and then Elk will organize and construct collections of point and tag data so that you can begin creating curves and other Rhino/Grasshopper geometry, as shown in Figure 4.

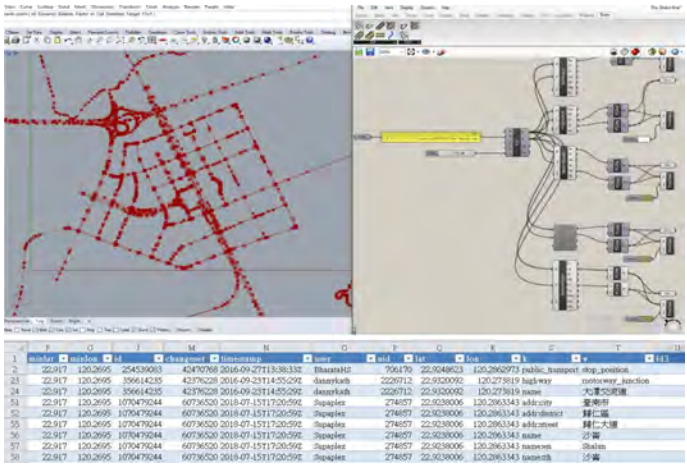


Figure 4. Example for a fast urban fabric prototyping for the Green Energy Science Village Project. The data of the environment including the 3D information of the buildings are imported from open street maps via the Grasshopper plugin Elk2.

4.2. Synthesizing data

In the example, Grasshopper3D served as the primary platform for visual algorithmic modeling. Wallacei is used as an analytic engine for data outputted by the EA, which was developed by Mohammed Makki and Milad Showkatbakhsh. It makes more informed decisions at all stages of their evolutionary simulations; including setting up the design problem, analysing the outputted results and selecting the desired solution or solutions for the final output. The plugin is streamlined to give all of the user efficient access to the data outputted by their evolutionary simulations, and enable clear and efficient methods for analysis and selection - The aim is for users (of all degrees of expertise) to better understand their evolutionary simulations in Figure 5, gain a thorough understanding of the outputted numeric values, and seamlessly extract the optimised data; all within one user interface.

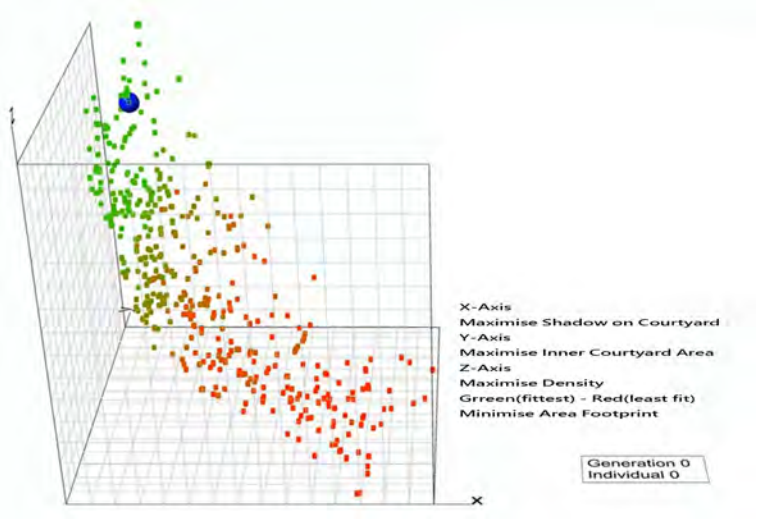


Figure 5. Visualize and evaluate the dynamics evolutionary simulations .

The experiment is inspired by the multiple objectives and goals originally aimed by Ildefons Cerdà(1876). The experiment sets out to generate an urban patch that optimizes for four primary objectives, as shown in Figure 6.

- Larger courtyards for open public spaces (number of mesh faces exposed).
- High solar exposure on the building façades (number of mesh faces exposed).
- Greater block connectivity.
- Urban Density

Building height is defined by the following rules:

The shadow area of the building projected on the road in front of the vertical building line with a slope of 3.6:1 shall not exceed half the product of the length of the road in front of the base and the width of the road, and the maximum shadow shall not exceed the opposite side of the road ahead.

The building base has a permanent open space on the opposite side of the road in front of it, and the shadow area is doubled to calculate the shadow and height as follows: $As \leq \frac{L \times Sw}{2}$; $H \leq 3.6(Sw + D)$

- As: The building is projected at the slope of the road in front of the road with a slope of 3.6 to 1 in the direction of the vertical building line.
- L: The length of the road in front of the base.
- Sw: The width of the road ahead.
- H: Building height
- D: Horizontal distance from each part of the building to the building line

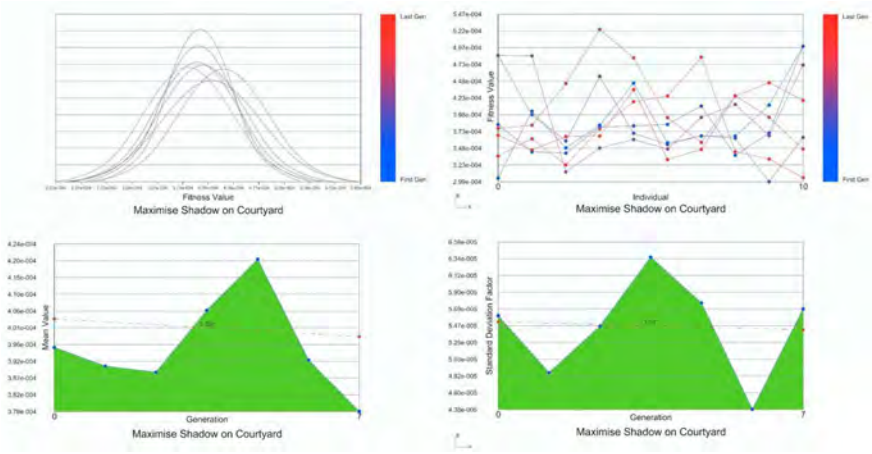


Figure 6. Evolution of maximise shadow on courtyard spaces when optimizing for increasing their areas. .

As an initial dataset for the algorithm we can use existing spatial configurations, which are freely available through OpenStreetMap. We have an initial data sample X0 = x1; ...xn0 in a design space Ω, and a corresponding matrix of features (criteria) $F(X_0) = F^0 \in \{(0,1)\}^{n0\times m}$ (formula by ETH). The aim of the add-on is to assist users to more comprehensively understand how their implemented evolutionary algorithm performs by comparatively evaluating empirical data outputted by the algorithm. Thus possible strategies are presented towards modifying the algorithmic approach in order to gain more efficiency in evolving solutions that generate variation yet simultaneously increase in fitness. It seeks to address this problem through utilizing an analytic approach that aims to untangle and dissect the plethora of empirical data outputted by an evolutionary simulation. The evolutionary algorithm is developed by means of a detailed analysis of each solution and its parameters. Thus it assists the user in making a highly informed decision for the solutions to be selected at the end of the simulation. The computational setup for the design experiments have been developed according to the complexity of the problem being investigated.

In response to the complexity of the urban problems, the experiment utilized a highly simplified phenotype as the base primitive. The complex fitness landscapes present multi-objective problems. We use the Grasshopper plug-in Wallacei to generate a multi-objective evolutionary algorithm that calculates the density and inner courtyard area and the maximum and minimum shadow values. The initial experiment is 50 generation, as shown in Figure 7.

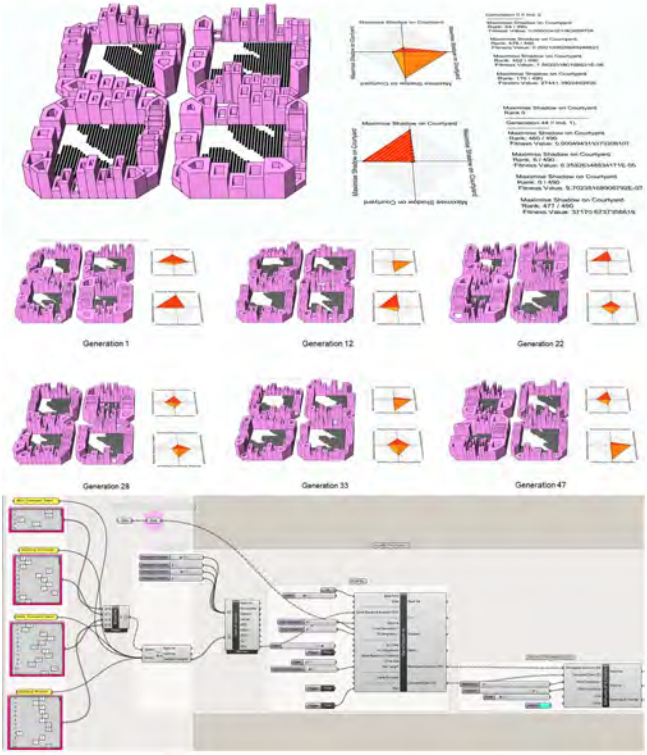


Figure 7. Use the grasshopper plug-in Wallacei to generate a multi-objective evolutionary algorithm that calculates the density and inner courtyard area and the maximum and minimum shadow values.

4.3. Extracting data

Prior to the development of decision-support information system, the feasibility of employing automatic data collection and structuring was estimated according to the algorithm proposed in the intelligent information system. The measurement points are placed in the appropriate position using the defined function to generate model. Practicable frequency of data collection and improvements are explored over traditional methods. Many data are short-lived, so data extraction should be performed daily, which seems technologically possible. The improvements include better timeliness, more extensive body of data, and somehow lower costs.

The system implementation has three major tiers, as shown in Figure 8.

- The data collection module that is responsible for accessing the source websites and grabbing data from web pages. Technical data are removed from cloud databank to optimize the system's database for storage space, but otherwise the entire web page's code is saved.
- The processing module that is responsible for structuring the data. Currently it extracts information related to smart grids, smart transportation, green

buildings, and IoT-enabled communities, as well as divides the properties by urban form , using two thesauri to perform intelligent natural language processing.

- The analysis module that is directly responsible for decision making support and providing capabilities for reports generation, filtering, notifications, etc. The On-line Analytical Processing technology allows interactive mode in data analysis, and Data Warehouse approach permits aggregation of data on multiple dimensions and provides a potent mechanism for creating and running any kinds of queries.

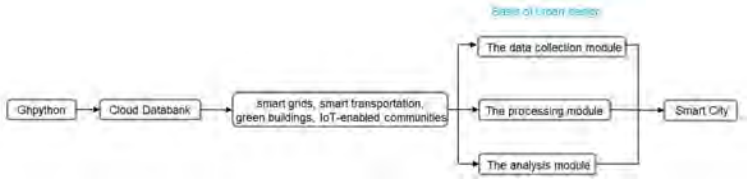


Figure 8. The schematic diagram shows a three-tiered intelligence system to capture real-time information .

5. Conclusion

We presented a rule-based approach to developing a computational urban design tool that uses algorithmic methodology to visualize, analyze the dynamics of urban form in the early design phase. In order to demonstrate the algorithmic methodology, we implement the proposed method in a real-world example. The example has been drawn from the Green Energy Science Village Project, a real-world smart city using cloud databank, computation, and algorithms to support smart grids, smart transportation, green buildings, and IoT-enabled communities. The implementation include:

- A parametric design platform that combines with computational tools where all the stakeholders can participate and visualize multiple urban scenarios in real-time feedback.
- A novel decision-making platform that combines city-planning level and local neighborhood data to aid participatory urban design decisions.
- A platform that allows for stakeholders to collaborate effectively and engage in complex urban design processes.

The platform is applied within a design studio context. The implementation generates relevant urban and building data from 2D urban plans that can serve to analyze and assess such urban plans with respect to different criteria, requirements and targets. The urban form generation takes into account local conditions and building typologies.

Future research will explore both computational methods and interactive workflows. The former investigation will include a grammar-based data synthesis approach. This approach will require the conception of a relevant representational and description model for the generation and analysis of building information from

urban plans. The model will draw on existing research and development on shape grammars, description grammars, sortal grammars and structures, and be driven by relevant analysis requirements.

Acknowledgement

This work was supported by the Taiwan Ministry of Science and Technology, grant No. MOST 106-3116-F-006-001

References

Batty, M.: 2001, Exploring isovist fields: space and shape in architectural and urban morphology, *Environment and Planning B: Planning and Design 2001*, **28**(1), 123 -150.

Beirao, J.N., Nourian Ghadi Kolaee, P. and Mashhoodi, B.: 2011, Parametric urban design An interactive sketching system for shaping neighborhoods, *eCAADe 2011*, University of Ljubljana.

Chirkin, A.M. and Koenig, R.: 2016, Concept of Interactive Machine Learning in Urban Design Problems, *SEACHI 2016*, San Jose, CA, USA, 10-13.

Chirkin, A. and Koenig, R.: 2017, Concept of Interactive Machine Learning in UrbanDesign Problems, *Proceedings of the 8th Workshop on Semantic AmbientMedia Experiences*, Finland, 1-8.

CHIRKIN, A., PISHNIY, M. and SENDER, A.: 2018, Generilized Visibility-Based Design Evaluation Using GPU, *caadria*, **(2)**, 483-492.

Jabi, W. and Johnson, B.: 2013, *Parametric Design for Architecture*, Laurence King Publishing.

Koenig, R., Miao, Y., Knecht, K., Buš, P. and Mei-Chih, C. 2017, Interactive Urban Synthesis: Computational Methods for Fast Prototyping of Urban Design Proposals, *in* G. Çağdaş, Ö Mine, G. Leman Figen and G. Ethem (eds.), *Computer-Aided Architectural Design Future Trajectories*, Springer, 23-41.

Koltsova, A. and Tuncer, B.a.: 2013, Visibility Analysis for 3D Urban Environments, *eCAADe 2013*, Delft, 375-384.

Makki, M., Navarro, D. and Farzaneh, A.: 2015, The Evolutionary Adaptation of Urban Tissues through Computational Analysis, *eCAADe 2015*, Vienna, 563-571.

Makki, m. and SHOWKATBAKHSH, M.: 2018, CONTROL OF MORPHOLOGICAL VARIATION THROUGH POPULATION BASED FITNESS CRITERIA, *caadria 2018*.

Martin, D., Sven, S., Reinhard, K., Abdulmalik, A. and Dirk, D.: 2017, Towards a modular design strategy for urban masterplanning - Experiences from a parametric urban design studio on emerging cities in Ethiopia, *eCAADe 2017*.

Maxim, B. and Tatiana, A.: 2015, Intelligent information system to support decision-making based on unstructured web data, *ICIC Express Letters*, **9**(4), 1-7.

Mei-Chih, C., Bus, P. and Gerhard, S.: 2017, Feature Extraction and K-means Clustering Approach to Explore Important Features of Urban Identity, *16th IEEE International Conference on Machine Learning and Applications (ICMLA)*, Cancun, Mexico.

Stouffs, R. and Janssen, P. 2016, A Rule-Based Generative Analysis Approach for Urban Planning, *in* L. Ji-Hyun (ed.), *Morphological Analysis of Cultural DNA*, Springer.

Terzidis, K.: 2006, *Algorithmic Architecture*, Architectural Press.

PIXELGREEN

A hybrid green media wall for existing high-rise buildings

CHIN KOI KHOO[1] and H. KOON WEE[2]
[1]*MInD Lab, Deakin University*
[1]*chin.khoo@deakin.edu.au*
[2]*The University of Hong Kong*
[2]*koonwee@hku.hk*

Abstract. Vertical farms and gardens are not new in dense urban environments, but few examples further explore the architectural potential and possibilities of the form to apply the same design approach to existing surfaces and walls of buildings. In addition, there is a design opportunity to exploit existing wall surfaces as 'analogue' media screens by using the vertical farm and garden as a medium of representation. In this paper we explore the opportunity for new design possibilities to achieve a hybrid architectural wall system as a reciprocal retrofit for existing building surfaces, integrating a vertical micro-farm and media screen. This architectural opportunity is explored through agile methods and the early design stages of a hybrid green media wall, PixelGreen. PixelGreen will be retrofitted to an existing wall of a high-rise building to convey mediated, graphical, artistic content and provide edible plant micro-farming simultaneously. The physical proof of concept is given through a modular mock-up with a programmed UAV (unmanned aerial vehicle) serving as the 'agent' for constant updating of mediated content, maintenance and a regular farming cycle. The outcome of this approach provides preliminary insight into how to feasibly implement a hybrid green media wall with autonomous robotics and computation technology.

Keywords. Green wall; media facade; vertical farm; architectural intervention.

1. Introduction

Traditional farming is ruining the environment, and not enough arable land remains to feed a projected 9.5 billion people by 2050. To overcome this challenge, farming in dense cities and existing built environments is becoming popular, involving the growing of crops indoors or semi-outdoors under rigorously controlled conditions. Although not a complete replacement for traditional farms, vertical farms are one viable alternative method of growing edible plants in high-rise buildings and multistorey rooftop greenhouses (Despommier 2009).

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 131-140. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

The vast vertical surface areas of the existing walls or façades of high-rise buildings in crowded, highly populated cities not only provide an opportunity to design and implement green walls; architectural features such as media screens have also been created on building walls and façades for purposes of commerce, advertisement, communication, art installation and social interaction (Dalsgaard and Halskov 2010, Fortin et al. 2014). Typically media screens take a form where media content is shown via LED displays or projection systems embedded into the surface of a façade. The agenda for such urban media façades is to facilitate public participation and foster social interactions in urban settings (Gehring and Wiethoff 2014).

But what if, instead of using typical LED or projection techniques, the media screen was conceived of as a low-resolution analogue medium formed by a series of vertically arranged edible plants? Each plant could serve as an individual 'pixel', allowing a range of content and use scenarios to be considered. Such scenarios and content could include community media and public art, and could potentially generate income through advertising (Wiethoff and Hussmann 2017). Due to the life cycle of the edible plants, the content of this analogue media screen could be updated at timely intervals through each harvest.

Research on urban vertical farms and media screens is not new, especially in the fields of architecture and the built environment. The fields consider these topics differently, with distinct research focuses and questions, but the potential value of existing vertical building surfaces in dense urban contexts serves as a common research interest and direction. The integration of a range of disciplinary concerns will achieve a hybrid green media wall to offer a retrofittable, flexible and replaceable wall system for simple media communication, art installation and self-sufficient food supply.

This research brings together two subsets of the general fields of farming and building façade design: vertical farms and media walls. The project seeks to reveal the new design potential of a reciprocal hybrid green media wall, PixelGreen, as an architectural intervention. PixelGreen is controlled and maintained by a programmed unmanned aerial vehicle (UAV) to achieve constant media content updates and to maintain edible plants as they pass through three repeatable stages: plant, grow and harvest.

The research is conducted in two stages. The first stage includes the literature review, conceptual framework and early schematic experiments, to articulate a system for designing a hybrid green media wall. The second stage moves beyond the theoretical framework to develop a proof of concept in the form of an early mock-up of PixelGreen, demonstrating its technical and economic feasibility. The output of this research provides introductory insight into the new design possibilities presented by a hybrid green media wall in its achievement of a reciprocal and sustainable wall system for the existing built environment.

2. Integration of the vertical farm and media wall

Contemporary cities are experiencing vast changes and transformations through the current influx of hard infrastructure and industrialisation. These changes not

only introduce the opportunity to review the viability and sustainability of existing urban built environments and buildings, but also suggest novel architectural programs and functions that can enhance the adaptability of existing old buildings. Eventually, these changes could transform existing buildings into a new kind of architecture that responds to current and future social, cultural and economic needs.

Our cities are also increasingly affected by problems of high density and a lack of greenery and softscapes in built-up areas. Vacant land in cities for potential use in urban gardens and farming has become scarce, especially in the highly populated cities of Asia.

The transition from natural land to hard infrastructure has caused loss of vegetation and habitat. However, cities in Asia have recognised the importance of green infrastructure that can incorporate farming and vegetation into existing urban structure and function (Growing Green Guide 2014). Green infrastructure such as green walls and façades is not only recognised as being beneficial to human health and well-being; it also provides commercial and economic benefits including farming and food production. Green walls are commonly plants grown in vertical systems that are independently attached to internal and external walls of buildings as one integrated system of vegetation, growing medium, irrigation and drainage (Growing Green Guide 2014). Additionally, green walls largely use a hydroponic growing medium that provides effective passive cooling, a cooler microclimate and improvements to local air quality while serving as an attractive wall-design feature. However, green walls added to existing building surfaces, which can also serve as self-sustaining micro-farms with similar benefits mentioned above, remain unexplored; further research will help to exploit their full potential. Current vertical farms, such as Vertical Fresh Farms in Buffalo and SkyGreens in Singapore, provide some insights into the new design possibilities of green walls in achieving production of fresh vegetables, herbs and salad greens with minimal land, water and energy resources (Marks 2014).

Current approaches to creating vertical farms have been challenged due to their high building cost, low profitability, high energy usage and even for emitting more greenhouse gases compared to traditional field production for cities with abundant agriculture land (The Economist Technology Quarterly 2010). However, crowded and highly populated cities with limited farmland, such as Hong Kong, Singapore and New York, present a more viable context for the implementation and validity of vertical farms, in which to explore new opportunities and eventually overcome the shortcomings and challenges of existing approaches. Instead of replacing traditional farms, vertical farms retrofitted to dense urban infrastructure could serve as reciprocal green walls that contribute complementary food sources with sustainable commercial value.

The vast surface areas of the existing walls and façades of high-rise buildings in crowded and highly populated cities not only provide an opportunity to design and implement green walls; architectural features such as media walls have also been placed on building walls and façades for purposes of commerce, advertisement, communication and social interaction. Recent advances in affordable and accessible LED and fluorescent lighting, and in projection technology, have led

to the appearance of large-scale ‘media façades’, especially in dense urban areas. The GreenPix media screen in Beijing, designed by Simon Giostra & Partners, is a salient example involving the use of conventional LED displays to facilitate public social interaction and communication through video installations and live performances by artists (GreenPix 2008). The BIX façade in the Kunsthaus Graz in Austria and the interactive computer display of the Haus des Lehrers office building at Berlin are other significant precedents of the media façade approach, and use relatively simple fluorescent lighting to create large-scale graphical displays (Elder & Elder, 2003). In addition, media façades adopting augmented digital projection are becoming popular. Tokyo’s N Building provides one example of an augmented architectural surface that performs dynamic aesthetic alterations to the original appearance of its existing building façade that present real-time media experiences, communicated through two-dimensional QR codes that can be read using a smartphone (Teradadesign 2009). Such examples illustrate the range of media façades that can be achieved, turning buildings themselves into gigantic ‘displays’ that can be novel media for communication and art installation, especially in presenting graphical content. (Gehring and Kruger 2012, Schoch 2006). In general, the medium of the media façade is implemented through lighting or display systems with high energy consumption, which contribute to urban heat island effects that significantly warmer than the surrounding rural areas due to increase human activities.

Green walls and media façades serve as two distinct ways to augment building façades, and both involve research into building surfaces in areas including architecture, urban design, social interaction, landscape and sustainability. They participate in a common enquiry into how to fully exploit and utilise the vertical surfaces of buildings to achieve reciprocal and interactive architectural features. The present research addresses this enquiry and investigate the opportunity for new design possibilities presented by a hybrid architectural wall system as a responsive and interactive intervention for existing buildings that integrates a vertical micro-farm and media screen.



Figure 1. The identified vertical ‘sites’ or ‘platforms’ (highlighted in green) for PixelGreen in a dense area of Hong Kong.

3. PixelGreen as a reciprocal hybrid green media wall

PixelGreen serves as a reciprocal retrofit to the existing surface or wall of a building, exploring an architectural potential to improve the shortcomings of an existing structure. As a site for implementation, a series of existing walls and vertical surfaces have been identified in the dense central area of Hong Kong (Figure 1). The identified vertical surfaces are existing fire walls of the high-rise buildings, which serve as potential vertical 'platforms' for PixelGreen, allowing it to become an architectural reciprocal hybrid green media wall system that can perform media and micro-farming functions simultaneously. As PixelGreen is based on a flexible modular system, its size and form are customisable and configurable to accommodate different shapes and conditions of existing walls.

The initial schematic development of PixelGreen involves a conceptual design with mediated content represented by multiple species of edible plants in different colours. Each edible plant will be hosted by a rectangular 'pigeonhole' serving as an analogue 'pixel' of PixelGreen. The overall structure of PixelGreen is formed by a flexible modular system, with each module consisting of 25 'pigeonholes' that can be used to construct various configurations that adapt to differently shaped vertical building surfaces.

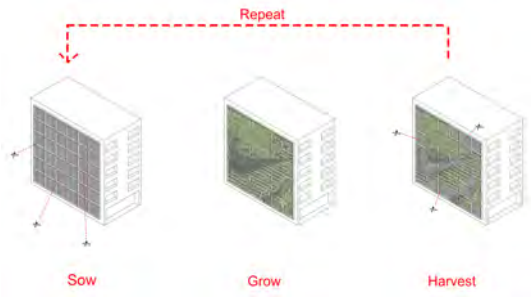


Figure 2. A conceptual diagram of PixelGreen with mediated content formed by multiple species of edible plants within 'pigeonhole pixels'. Progress through three repeatable steps—sow, grow and harvest—is controlled and maintained by programmed UAVs.

Three repeatable steps-sow, grow and harvest-are proposed for the early phase of PixelGreen to facilitate the representation of media content through the different species of edible plants (Figure 2). These steps could be controlled and maintained by a programmed UAV or drone to update the media content as it maintains and harvests the edible plants at intervals. There is a monthly interval between sow and harvest steps.

'Sow' is the initial step, in which the programmed UAVs sow the seeds of various species and colours into designated 'pigeonholes' according to the pre-set pixelated graphic of the mediated content or message. This step will be repeatable to update or change the mediated content of PixelGreen. 'Grow' is the next step, in which the edible plants might take 14 days or more to mature with appropriate irrigation system. In normal circumstances, the involvement of the programmed UAVs in this step is minimal, beside occasional visual inspections

and maintenance. In the 'harvest' step, the programmed UAVs are required again to collect the edible plants and empty each 'pigeonhole' to prepare it for the following 'sow' step.

4. Mock-ups of and experiments with PixelGreen

A physical proof of concept, constructed as a modular mock-up, was explored to test and evaluate the feasibility of PixelGreen. As mentioned in the previous section, each module consists of 25 'pigeonholes' that host edible plants, and each 'pigeonhole' serves as an analogue 'pixel'. In this section, several experiments and tests involving the physical modules of PixelGreen demonstrated the simple programming schema for the UAV that enables it to sow a capsule containing seeds of an edible plant. Due to resource constraints and limitations, only the 'sow' step was tested in this phase to demonstrate the feasibility of the physical implementation.

4.1. THE PHYSICAL MODULE OF PIXELGREEN

The physical module was fabricated from 12 laser-cut MDF components, forming a modular assembly with 25 'pigeonhole pixels' (Figure 3). A waterproof seed-holder containing soil and water was located in each 'pigeonhole pixel' to provide suitable conditions for sowing and growing the seeds of edible plants.



Figure 3. Left: The components of the physical module of PixelGreen. Right: The complete assembly for the physical module of PixelGreen consists of 25 'pigeonhole pixels' containing a waterproof seed-holder.



Figure 4. Left: Seeds of edible plants contained in the water-soluble gelatine capsule. Right: Seeds of light-coloured edible plants (mustard, coriander and garland) and seeds of dark-coloured edible plants (broccoli, radish, red radish and kale).

4.2. THE SEED CAPSULE

To allow the UAV to carry the seeds of edible plants and sow them in a specific, designated 'pigeonhole pixel', a water-soluble gelatine capsule was used to hold the seeds in a format that the grabber of the UAV could carry. Capsules contained one of two types of seed for various species of edible plants, in either a dark or light colour (Figure 4). When grown in the designated 'pigeonhole pixel' after the

dissolve of the gelatine capsule, these two types of edible plants will generate a pixelated graphical pixel representing the mediated content (discussed further in the subsequent section).



Figure 5. Left: Each 'pigeonhole pixel' is assigned a unique coordinate. Right: The physical module of PixelGreen with 25 assigned coordinates.

4.3. THE INITIAL TEST OF THE 'SOW' STEP VIA UAV

Although there are three steps (sow, grow and harvest) in the overall planting cycle of PixelGreen, in this section only the 'sow' step will be tested for feasibility, using a manually controlled UAV. In this initial test, each 'pigeonhole pixel' of PixelGreen is assigned to a specific coordinate so the UAV can identify the location at which to place the seed (Figure 5). Coordinates A1 and A2 were selected to implement the early feasibility test of the 'sow' step. First, the landing site for the UAV is identified and the seed capsule located in its designated location. Second, the UAV grabs the seed capsule and takes off to sow it at the designated A1 coordinate. Third, the UAV returns to land at its original point of departure. This initial test demonstrated the feasibility of the 'sow' step of PixelGreen being performed by a UAV (Figure 6).

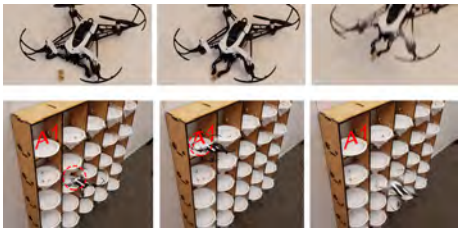


Figure 6. Top: Seed capsule in its designated position. Middle: UAV taking off with its grabber closed. Bottom: Initial test of sowing seed capsule at designated coordinate (A1) using a manually controlled UAV.

4.4. A UAV PROGRAMMED WITH A SIMPLE SCHEMA

Following the initial test of the manually controlled UAV for the 'sow' step, subsequent testing involved the programmed and autonomous flight path of the UAV to designated coordinates according to a simple schema. Figure 7 shows the programmed flight path of the UAV as it autonomously completes the 'sow' step

for coordinate A1, following a simple schema that includes the major processes of grabbing, taking off, sowing, moving backwards, descending and landing, which were tested previously under manual operation. A subsequent 'sow' step for two coordinates (A1 and A2) was also implemented with a similar schema to sow different seed capsules for the specific 'pigeonhole pixels' simultaneously (Figure 7).



Figure 7. Left: A simple schema for the flight path of the UAV as it sows a seed capsule at the A1 coordinate (grabbing, taking off, sowing, moving backwards, descending and landing). Right: A simple schema for the steps of the UAV in sowing the seed capsule to the A1 and A2 coordinates (grabbing, taking off, drifting, sowing, moving backwards, descending and landing).



Figure 8. Screenshots of the growth timeline for edible plants in the fertilised soil of the 'pigeonhole pixel'.

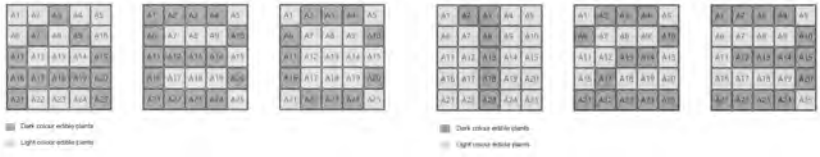


Figure 9. Right: A potential binary text representation formed by dark- and light-coloured edible plants. Left: Binary numeric presentation formed through the specific arrangement of dark- and light-coloured edible plants.

5. Potential mediated content representation through PixelGreen

The promising outcomes of early testing and implementation of the physical modules of PixelGreen and the programmed UAV provided initial insights into the system's potential for mediated content representation. As discussed, the mediated content could be represented using different species and colours of edible plants grown in the fertilised soil of the 'pigeonhole pixels' (Figure 8). Besides binary images, simple messages and information could also be represented using text and numbers formed through the specific arrangement of the edible plants. For instance, Figure 9 shows the possible binary representations of text and numbers composed using the individual coordinates of the 25 'pigeonhole pixels'. Adding

different arrangements of analogue text and numeric representation create vast possibilities of mediated and graphical representation. This potential is realised through the sowing process followed by the UAV programmed with simple schemas that place the seeds of light- and dark-coloured edible plants in specific 'pigeonhole pixels'.

The update cycle of this media representation, which coincides with the micro-veggie sowing and harvesting process, will be constantly maintained through the three repeatable steps controlled and executed by the programmed UAVs as they sow, grow and harvest. Figure 10 shows a proposal to visualise this approach through a hypothetical implementation of PixelGreen at the site of a temporary market in Hong Kong, demonstrating its design feasibility in the relevant urban context. In this proposal, the scale and the size of PixelGreen are customised to adapt to the specific conditions and constraints of the site. Besides serving as a media façade with potential commercial value, PixelGreen also produce edible plants that can be harvested and distributed to the adjacent market to achieve a reciprocal and sustainable relationship. Following this scenario, PixelGreen could be developed to become a 'pop-up' architectural feature serving as a vertical greenhouse accommodating different functions such as a café and viewing platform.



Figure 10. Left: The hypothetical implementation of PixelGreen in the dense urban context of Hong Kong. Right: Potential sites that combine the vertical and horizontal surfaces (highlighted in green) of existing high-rise buildings in the development of PixelGreen.

6. Conclusion and future work

The implementation and realisation of the green media wall in an existing urban environment still confronted us with challenges and limitations, especially in the areas of government policy, the building code, commercial feasibility and the property rights. Current limitations in what technologies and techniques are feasible to implement also hinder advancement of the design implications of this architectural approach. However, the potential value of the hybrid green media wall at the urban scale is to provide a range of commercial content and public social interactions; it may disseminate news, have the capacity to generate income through advertisements, or provide interactive public services, games and art. In addition, the contemporary city may suffer problems of high density, lack of greenery and softscapes in built-up areas, and a lack of food safety and food security due to over-reliance on imports. And though it may not replace the traditional farm, the greening and food-production potential of the hybrid green

media wall will create awareness among the general public of a sustainable future for urban farming.

The promising outcomes generated in this research will eventually lead to a demonstration of a large-scale architectural interface in a dense urban area with commercial, social and environmental value. The early mock-ups of PixelGreen described here serve as a proof of concept giving initial insight into the possible implementation of an autonomous hybrid green media wall in the existing urban built environment. Although the preliminary outcomes of this paper represent merely the initial design stages of PixelGreen, tests of and experimentation with the physical modules in conjunction with a programmed UAV shows both the feasibility and flexibility of an implementation of PixelGreen. The next stage of this research will include the development of PixelGreen with the social interaction through commercial and art installation to adopt an approach that integrates horizontal (roof) and vertical (wall) surfaces of existing urban infrastructure to more fully exploit those surfaces, eventually providing a platform to study the advanced design implications of urban farms and media screens such as façade farming (Figure 10). User studies will also be included to collect and evaluate valuable feedback data from users and participants to be used in further advancement of the design.

References

"Teradadesign: N Building" : 2009. Available from <http://www.teradadesign.com/works/architecture/n-building.html> (accessed 3rd August 2018).

"The Economist Technology Quarterly: Does it really stack up?" : 2010. Available from <http://gothamgreens.com/files/pdf/vertical_farming_98848600.pdf> (accessed 2nd September 2018).

"GreenPix: The Zero Energy Media Wall, 2008" : 2011. Available from <http://www.greenpix.org/> (accessed 2nd October 2018).

"Growing Green Guide: A guide to green roofs, walls and facades in Melbourne and Victoria." : 2014. Available from <http://www.growinggreenguide.org> (accessed 15th September 2018).

Dalsgaard, P. and Halskov, K.: 2010, Designing Urban Media Facades: Cases and Challenges, *Proceedings of CHI 2010*, 2277-2286.

Despommier, D.: 2009, The Rise of Vertical Farms, *Scientific American*, **301**(5), 80-87.

Elder, J. and Elder, T. 2003, Communicative Display Skin for Buildings: BIX at the Kunsthaus Graz, *in* B. Kolarevic and A. Malkawi (eds.), *Performative Architecture – Beyond Instrumentality*, Taylor & Francis Books Ltd, New York/London, 150-160.

Fortin, C., Hennessy, K. and Sweeney, H.: 2014, Roles of an Interactive Media Façade in a Digital Agora, *Proceedings of The International Symposium on Pervasive Displays (PerDis'14)*, 7-12.

Gehring, S. and Kruger, A.: 2012, Façade Map – Continuous Interaction with Media Facades Using Cartographic Map Projections, *Proceedings of UbiComp 12*, 471-480.

Gehring, S. and Wiethoff, A.: 2014, Interaction with media façades, *Informatik-Spektrum*, **37**(5), 474-482.

Marks, P.: 2014, Vertical farms sprouting all over the world, *New Scientist*, **2952**.

Schoch, O.: 2006, My Building is my Display: Omnipresent graphical output as hybrid communicators, *Proceedings of the eCAADe 24*, 610-616.

Wiethoff, A. and Hussmann, H.: 2017, *Media Architecture: Using Information and Media as Construction material*, Walter de Gruyter, Berlin / Boston.

CO-DESIGNING IN SOCIAL VR

Process awareness and suitable representations to empower user participation

TOMÁS DORTA[1], STÉPHANE SAFIN[2], SANA BOUDHRAÂ[3] and EMMANUEL BEAUDRY MARCHAND[4]
[1,3,4]*Design Research Laboratory Hybridlab, University of Montreal*
[1,3,4]*{tomas.dorta|sana.boudhraa|emmanuel.beaudry.marchand}@umontreal.ca*
[2]*Télécom ParisTech i3-CNRS*
[2]*stephane.safin@telecom-paristech.fr*

Abstract. To allow non-designers' involvement in design projects new methods are needed. Co-design gives the same opportunity to all the multidisciplinary participants to co-create ideas simultaneously. Nevertheless, current co-design processes involving such users tend to limit their contribution to the proposal of basic design ideas only through brainstorming. The co-design approach needs to be enhanced by a properly suited representational ecosystem supporting active participation and by conscious use of structured verbal exchanges giving awareness of the creative process. In this respect, we developed two social virtual reality co-design systems, and a co-design verbal exchange methodology to favour participants' awareness of the co-creative process. By using such representations and verbal exchanges, participants could co-create with more ease by benefiting from being informed of the process and from the collective immersion, empowering their participation. This paper presents the rationale behind this approach of using Social VR in co-design and the feedback of three co-design workshops.

Keywords. Social VR; Project awareness; Representational ecosystem; User participation; Co-design.

1. Introduction

Design projects are complex because they relate to a wide variety of end-users and also involve multiple stakeholders along the process. Going beyond current participatory design approaches, we claim new methods are needed to allow better involvement of users in these projects, in a perspective of active co-design (bottom-up), instead of merely looking for user approval or consensus on previously set decisions (top-down). But involving non-designers in the hearth of design raises two major issues. On one hand, public organizations and design offices dictate or mediate the engagement of projects' prime stakeholders by

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 141-150. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

using processes, representations, methodologies and technologies that are not well adapted for lay persons, reducing them to the role of receptors instead of actors to whom the final designs belong. On the other hand, spontaneous initiatives coming from users themselves as non-designers need the appropriate means to result in relevant design solutions. Co-design must give the opportunity to all the participants to co-create ideas upstream, simultaneously (co-ideation), in a democratic (horizontal) and multidisciplinary way. Nowadays, co-design processes involving non-designers tend to limit their contribution to proposing general, abstract and ”immature” design ideas through creative techniques like brainstorming and post-it notes, without further diving into design concepts at a mature level and resolving them. Consequently, the co-design approach needs to be enhanced by an appropriate representational ecosystem supporting active participant intervention and through the identification of structured verbal exchanges providing *awareness* of the ongoing creative process. To this end, we developed two Social VR (Virtual Reality) co-design systems (see section 6), to support democratic user participation. Thanks to its natural interaction, immersion and embodiment without wearing VR headsets, users can resolve design problems together with other specialist collaborators, using life-sized representations, immersive and 3D sketches, actively interacting with design ideas. Diverse groups of co-located participants (including architects) are immersed within different kinds of representations. Because complexe codified representations like plans or scaled presentation mock-ups are challenging to grasp for neophytes, Social VR supports representations suited for the creative phases: real-scale, immersive, with high evocative power, and with the easiness of sketch-based graphical expression. Also, we developed a co-design methodology to support and bring design process awareness to participants through structured conversations. Pairing such structuring of discourse along with the aforementioned representational ecosystem, supports user co-creation and exchanges with greater ease by being more aware and immersed in the project, thus empowering them through facilitated participation via Social VR.

2. Participatory design

Participatory design projects aim for user implication during the process but nevertheless, users rarely have the power to be fully involved due to several reasons. One is that the project’s owner often arrives with projects designed beforehand, only seeking for user approval (Jutand 2013), persuading them that they were involved in the creative process while all decisions are already set. Another reason is that users themselves as non-designers are not properly supported to fully engage during the first steps of the design process (ideation) where main, driving ideas are generated and most important decisions are made. Consequently, end-users have problems appropriating or embracing such projects. Risks of integration conflicts within the context could arise (Lehtovuori 2016) and designs could even fail to fulfill their initial goals. Moreover new initiatives are emerging, allowing users to participate firsthand in design processes that concern them, no more only as passive subjects to be consulted, but rather as co-authors of design proposals (e.g. Living Labs). Nonetheless, under the appearance of

participation, these initiatives are often limited to a collection of primitive ideas or are intended only to obtain the approval of people. Receivers or users must assume new roles. They should no longer be passive or solely capable of a posteriori reaction but should become more and more considered as referents of the project. There is a need for *informed, conscious awareness* of the creative process (Farina et al. 2014). From being simple users, they have to be more involved as the ones for whom the projects are truly conceived, then becoming active contributors along the process (Jutand 2013). The "author project" is replaced by a networked, pluralistic design, where the user also becomes a co-author and participates in the design. The role of the designer then evolves towards that of a "midwife" or, as Sanders and Stappers (2008) describe, an *accompanist*.

3. Co-design approach

To cope with this, new design approaches named co-design or co-creation consist in a creative and collective activity where two or more persons, or a community, get involved along with designers and architects in a design project that matters to them (Sanders and Stappers 2008). Kleinsmann and Valkenburg (2008) describe co-design as a process where actors from various disciplines share their knowledge of the process and the design content in order to create a shared understanding of both aspects and achieve a common goal. Besides, co-design has been proposed as a way to improve idea generation, decision making, communication and creativity (Steen et al. 2011). Steen (2013) emphasizes that co-design focuses on the concrete practices of people, their experiences and the role of practical knowledge. Co-design is also understood as a technique of collaborative design involving participants simultaneously in a co-creation process. The simultaneous character of co-design is an important component in the process compared to cooperative design consisting in an asynchronous process (Kvan 2000). Here, cooperative design refers to when a group of individuals accomplish different tasks separately in order to achieve a common goal (Achten 2002). Participatory design and co-design both share the advantages of integrating individuals' skills and experience(s), as revealed through the unfolding exchanges (Schuler and Namioka 1993). Moles (1986) calls them *repertoire*, that is to say, a constitutive knowledge of each one, which joins Schön's own notion of repertoire (1985). Mattelmäki et al. (2011) raise the question of power attribution to all participants in a fair way (democratic) in collaborative design processes. We define co-design as a particular collaborative design process. It requires engaging the group in simultaneous mutual collaboration and actively involving all participants. The generation of concepts then takes place together through a spontaneous exchange where ideas are built, negotiated and accomplished by a common agreement. To build on these concepts, our proposed co-design approach using Social VR (see section 6) has two main ingredients: a process made aware to the participants through the structure of verbal exchanges, and a particular representational ecosystem that allows layperson to fully understand design proposals and fully engage in the co-design process.

4. Process awareness: informed through verbal exchanges

Verbal communication constitutes, above sketches, the prime design tool allowing designers to externalize intentions and launch ideation (Jonson 2005). In a collaborative setting, designers communicate their ideas verbally, but also through gestures and representations (graphical and physical). The conversation around collaborative ideation is a kind of rhetoric that seeks to build consensus where all stakeholders aim to resolve a common problem (Asher and Lascarides 2003). In previous work where we analyzed the design discourse during collaborative ideation between designers, we identified recurrent conversational patterns at different moments of the process (Dorta et al. 2011). These patterns characterize the designers' thinking in action as well as the maturity degree of design ideas. We distinguished six main elements: *naming, constraining, proposing* (key element), *negotiating (questioning and explaining), decision making and moving forward the idea* via representations (sketching and gesturing). The first five relate to verbal exchanges while the latter is an act of representation that transforms the design situation (Goldschmidt 1990; Valkenbug and Dorst 1998). In addition, we also identified four recurrent conversational patterns that are linked to different phases of the co-ideation process and different levels of idea maturity: collaborative conversations (presenting and discussing), immature collaborative ideation loops (immature CI-loop), mature CI-loop and collaborative moving. The two kinds of CI-loops are the most important patterns in the process since they are where ideas are proposed and negotiated. During immature CI-loops participants are focusing on *what* they have to design using longer negotiations, while in mature CI-loops they reflect on *how* the design concept will be anchored to reality (Dorta et al. 2011). Moreover, in 2015 we developed a co-design course at the university level where we teach this patterns identification as a design strategy to students, in order to make them *aware of the creative process*. In addition, we have been realizing multiple local and international co-design workshops (involving mainly non-designers) using this approach to make the co-design process more explicit to further support participation and contribution from all actors.

5. Representational ecosystem and Social VR

Involving design lay persons (untrained in design) in collaborative design projects faces a major practical challenge: an adapted representational ecosystem. Non-designers can have trouble visualizing and placing themselves into design ideas. In particular, the representations that are mobilized by design professionals (scaled models, technical drawings, Computer-Aided Design "CAD" models) do not always make it possible to evoke effectively the characteristics of the project (Van de Vreken and Safin 2010). In addition, there is a lack of adequate representational tools for inter-professional actors (designers, engineers, users, etc.) to graphically and physically externalize their ideas, that is, to involve positively users in design and ultimately transform non-specialists into real actors. Indeed, non-designers are rarely trained in freehand sketches, perspective views or 3D modelling, tools that are central in "professional" design practice. Externalizing and framing design ideas are also critical for the construction of a common ground in collective processes, which is necessary for the development

of quality projects (Stempfe and Badke-Schaub 2002). Kvan (2000) indicates that collaboration is more complicated than the mere participation of a group of individuals. It requires a greater synchronization of work and simply bringing new software and hardware is not sufficient to create the right environment to foster collaboration (Kvan 2000). Thus, communication plays a decisive role for this synchronization which subsequently allows the evolution of each person's mental representations (Darses 2006).

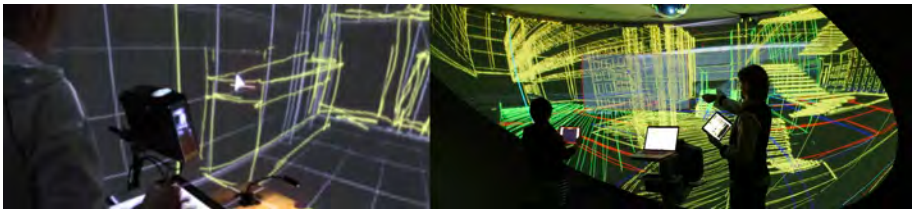


Figure 1. HIS, individual immersive sketching + model making; Hyve-3D, multi-user immersive 3D sketching.

We have previously studied the characteristics of the representational ecosystem that support or enhance the co-design processes (Dorta et al. 2016). Four main required elements were found: it has to (1) be *hybrid*, mixing analog (made by hand) and digital representations; (2) allow project visualization *using several scales* including life-sized; (3) *support active co-design* by allowing all users to represent through sketches and physical models and manipulate these representations, all in an intuitive way; and finally, (4) the ecosystem must grant opportunities to use and *bridge across several kinds of representations*, including physical (models) and graphical (different views, photos, etc.). For this purpose, since 2007 we have been developing immersive co-design platforms HIS (Dorta 2007) and Hyve-3D (Dorta et al. 2016), its successor (Figure1), improving local and remote design communication. These systems allow local immersive co-ideation while integrating themselves to the representational ecosystem. The systems consolidate multiple representations which support co-ideation without interfering with the process, in contrast to traditional CAD tools. It permits to work at different scales (including life-sized) with hybrid representations and to co-ideate in an active way via immersive and 3D sketches, immersive model making (using physical mock-ups) and interaction using handheld devices. Both systems are Social VR systems supporting the communication between local participants because they don't use occlusive headsets that hinder their verbal and non-verbal communication (e.g. design gestures) allowing to share the collective design experience.

6. Co-designing in Social VR approach

This paper presents the Co-designing in Social VR approach we put in place on six-hour (9am to 4pm) workshops, a duration which ensure people participation. During the workshops, participants *that are not designers or architects* are able to generate *mature* design proposals in the form of scaled physical models and

immersive virtual representations (immersive and 3D sketches on a basic 3D geometry used as context). Designers and architects can also get involved in the project as well as engineers, other specialists, and design students as *design accompanists*. The workshop is structured in different sessions, each focused on a specific project stage: problem framing, immature co-ideation, mature co-ideation and final presentation. During each session, participants alternate between Master classes on core concepts (co-design vs. cooperation, verbal design exchanges and the representational ecosystem) and design studio in the representational ecosystem. The goal is to show the rationale underpinning the design's verbal and representational exchanges, after each step is realized, to favour a better comprehension of the process by the participants. Concerning the representational ecosystem, participants alternate using two kinds of representations. (1) *Traditional graphical and physical representations* consisting mostly in freehand sketching on paper and working with a physical model where all the architectural components (walls, furniture, columns, etc.) are already pre-cut in foam-board or cardboard at the right scale (depending on the dimension of the given project). The model can be easily assembled and manipulated collaboratively by the participants This facilitates project discussion and manipulation through their modification as *boundary objects* (Arias and Fischer 2000). (2) *Social VR system* in order to visualize the project life-sized and sketch immersively or in 3D (Hyve-3D). The mock-up can be brought inside the system's space by using a small 360° camera inside the model and experience it in immersion, from within (HIS). At the end, the physical models and the virtual models on the Social VR system are used to deliberate the best proposition (several if the group of participants is large). The physical and virtual models then also provide final 3D representations of the project used to show to project makers. The schedule of the day consists of four one-hour sessions, in rooms dedicated to each group (around 6 persons each max.). During each session, the groups are called in turn in the Social VR system for 20 minutes to design within the immersive environment. These sessions are interspersed with pauses and theoretical returns on their co-design activities by the facilitators. Each session is focused on a specific aspect of design conversation: the first session on the problem (re-)definition and the collaborative conversations CC; the second session on proposing a large set of ideas (Immature CI loops); the third session on the concept deepening (Mature CI loops); and the last on the preparation of the final presentation. At the end of the day, formal presentations are held, using physical models and hybrid representations in the Social VR system as support. These presentations lead to the selection of the most collegially promising project among the proposed solutions made by each team.

7. Examples of Co-designing in Social VR workshops

We realized several co-design workshops using this approach and using different kind of user interactions: *mixed reality*, installing the Social VR system in the same space to be designed; *scale model endoscopy*, where the participants were immersed inside their physical models; and *collective 3D sketches* using the Hyve-3D, in which several users sketch simultaneously in 3D using as contextual background a dynamic 3D model. In this paper we present only those workshops

involving non-designers as participants. Each of these projects was focused on preliminaray phase of the (re)design of the interior of an existing space, or a space currently being buit. The first two were executed in the context of a business school of an university campus and the third for a university's library in another country. All involved were participants institutions' employees and users (professors and students that attend that facility). As mentioned before, in these workshops some architects and design students participated as accompanists to facilitate the design process. Among their tasks, the accompanists focused on the proper use of the different kinds of representations, on exploring alternatives to avoid getting stuck with only one idea or on helping in the discussions and the development of design arguments.

7.1. MIXED REALITY: BUSINESS SCHOOL'S TEACHING SPACE



Figure 2. (Right) Space to be redesigned and the sub-spaces of the workshop for each group (Left) Social VR displaying a virtual model and digital sketches combined with a scaled model.

The workshop we conducted consists in the re-design of an existing teaching space in the building of the business school, underused and inappropriate (Figure 2). This space is composed of a large main room and six small rooms and is designed to support negotiation courses. Participants (24) were divided into three groups, and each group had the goal to achieve a design proposal for the future space. Since the Social VR systems are mobile, this workshop took place into the same space to be redesigned, allowing participants to use elements of the real space as a support and as referents for discussion in a context of mixed reality (Safin et al. 2013). Figure 2 shows the different sub-spaces (one room per group) and a central room with the Social VR system (HIS) installed in the center of the redesigned space. Digital models of this space were built and displayed in the HIS as 360° panoramas. Participants therefore had the opportunity to see an immersive projection of a digital model of the design space in the heart of this real space, with the possibility of aligning the same point of view. In the HIS, no special skills was required since the participants were sketching (life-sized) over the immersive panorama. Spontaneously, some participants were manipulating the digital pencil of the Wacom Cintiq tablet of the HIS, while others were designing and discussing alternating from the immersive representation and the real space, visually accessible from the HIS.

7.2. SCALE MODEL ENDOSCOPY: BUSINESS SCHOOL'S LIBRARY

This workshop was related to the redesign of the business school's main library. Several library users and employees also participating in the workshop (25), using the same representational ecosystem and the HIS of the previous workshop. However, this time the activity took place in our laboratory's rooms. They developed several physical models and became immersed inside those scaled model by using the 360° camera (Figure 3).



Figure 3. (Left) Life-sized immersive view on HIS of the rough physical model using the 360° camera (Right).

7.3. COLLECTIVE 3D SKETCHING: UNIVERSITY'S LIBRARY



Figure 4. Hyve-3D allowing collective 3D sketching; and rough scaled physical models.

This last example took place in another university (in another country) where, this time the Hyve-3D was transported and installed. The participants were again users and employees of the the library and 1 design accompanists per team (2 teams of 6). Concerning the representational ecosystem, once again scale model pieces were pre-cut and used as boundary objects to assemble the physical model while designing the ideas. The Hyve-3D, compared to HIS, allows collective 3D sketching using two handheld tablets. In that concern, we also provide a basic 3D model as a contextual background, made from SketchUp and textured in a baking process using a rendering software (Figure 4). In two periods of 30 min., four participants were trained to sketching in 3D using the two tablets of the Hyve-3D.

8. Feedback from the workshops

All groups came to interesting results, even surprising, given the initial objectives, and according to the client and the participants. All participants reported having experienced a rich and interesting day, and having actually contributed to their project. Although this informal observation can't allow us to draw definitive conclusions, it sheds light on the relevance of this new co-design approach, which is based on the representational ecosystem (Social VR and traditional tools such as pen-and-paper and physical models) and the process awareness through verbal exchanges. Another interesting informal observation relates to the relevance of the phenomenon of Social VR for the construction of a shared vision of the project. Indeed, we found that the different teams right out of Social VR directly address new issues of design, without going through a reformulation of the discussions made in the system. So it seems that the teams are directly operational for the design starting from Social VR, indicating its capacity to support a truly shared vision of the problem. The Social VR and the physical models have been widely used both by all participants, even those who were not familiar with design (business students, teachers, etc.). These representation modes seem more intuitive than the conventional representation tools like 2D or perspective sketches. The directly perceptible scale that these two modes of representation convey seems to be a determinant of the perceived effectiveness. It appears that both the Social VR systems that the physical model were relevant platforms for supporting multidisciplinary collaborative design. These two elements of the representational ecosystem seem to support different ways to design, which are complementary: mock-ups afford assembly of elements, spatial arrangement with a global view of the space, whereas Social VR support the contextual sketching and proporsions of proposed design elements in space (new furniture, walls, etc.). Finally, we made another interesting observation: as the workshops were progressing, we have seen an evolution of the commitment of the participants. While the first sessions were held calmly, with very fluid speech turns, the last sessions were characterized by more assertive behaviours from all the participants: more verbal exchanges, many collective actions on representation tools (mainly physical model) and more engaged postures. Finally, although all stakeholders were very enthusiast about the process and the project, the impact of these workshops on the design project has not been formally assessed.

9. Conclusions

This paper presented a new co-design approach based on Social VR combined with physical mock-ups as boundary objects. Also, verbal exchanges structuration method allows non-designers participants to get informed and be aware of the creative process. Feedback from real co-design workshops involving lay persons as participants was reported. Different kinds of interaction were exposed: mixed reality, endoscopy of physical models and collective immersive 3D sketching. The approach allows during a single day workshop to propose mature designs via 3D representations to engage with real project makers. Even if specific Social VR devices were used, other VR systems as headsets combined with big projections and immersive walls could be used. The goal is to consider the use of the

appropriate representational ecosystem and structured verbal exchanges to allow awareness and improve participations of non-designers in co-design processes.

References

Achten, H.: 2002, Requirements for collaborative design in architecture, *6th Design & Decision Support Systems in Architecture & Urban Planning Conference*, Eindhoven, 1-13.

Arias, E. G. and Fischer, G.: 2000, Boundary objects: Their role in articulating the task at hand and making information relevant to it, *International ICSC Symposium on Interactive & Collaborative Computing*, Australia, 567–574.

Asher, N. and Lascarides, A.: 2003, *Logics of conversation*, Cambridge University Press.

Darses, F.: 2006, Analyse du processus d'argumentation dans une situation de reconception collective d'outillages, *Le travail humain*, **69**(4), 317-347.

Dorta, T.: 2007, Implementing and Assessing the Hybrid Ideation Space: a Cognitive Artifact for Conceptual Design, *Int. Journal of Design Sciences and Technology*, **14**(2), 119-133.

Dorta, T., Kalay, Y. E., Lesage, A. and Pérez, E.: 2011, Elements of Design Conversation in the interconnected HIS, *Int. Journal of Design Sciences and Technology*, **18**(2), 65-80.

Dorta, T., Kinayoglu, G. and Hoffmann, M.: 2016, Hyve-3D and the 3D Cursor: Architectural co-design with freedom in Virtual Reality, *International Journal of Architectural Computing*, **14**(2), 87-102.

Farina, C., Kong, H., Blake, C., Newhart, M. and Luka, N.: 2014, Democratic deliberation in the wild: The McGill Online Design Studio and the RegulationRoom Project, *Fordham Urban Law Journal*, **41**(5), 1527-1580.

Goldschmidt, G.: 1990, Linkography: assessing design productivity, *Cyberbetics and System'90, Proceedings of the Tenth European Meeting on Cybernetics and Systems Research*, 291-298.

Jonson, B.: 2005, Design ideation: the conceptual sketch in the digital age, *Design Studies*, **26**(6), 613-624.

Jutand, F. and Dartiguepeyrou, C.: 2013, *La métamorphose numérique: vers une société de la connaissance et de la coopération*, Alternatives, Paris.

Kleinsmann, M. and Valkenburg, R.: 2008, Barriers and enablers for creating shared understanding in co-design projects, *Design Studies*, **29**(4), 369-386.

Kvan, T.: 2000, Collaborative design: what is it?, *Automation in construction*, **9**(4), 409- 415.

Lehtovuori, P.: 2016, *Experience and conflict: The production of urban space*, Routledge.

Mattelmäki, T. and Sleeswijk Visser, F.: 2011, Lost in Co-X: Interpretations of Co-design and Co-creation, *Diversity and Unity, Proceedings of IASDR2011*.

Safin, S., Lesage, A., Hébert, A., Kinayoglu, G. and Dorta, T.: 2013, Analyse de référents de l'activité de co-design dans un contexte de Réalité Mixte, *Proceedings of Interaction Homme-Machine, IHM*, 23-32.

Sanders, E. B.-N. and Stappers, P. J.: 2008, Co-creation and the new landscapes of design, *Co-Design*, **4**(1), 5-18.

Schuler, D. and Namioka, A.: 1993, *Participatory design: Principles and practices*, CRC Press.

Steen, M.: 2011, Tensions in human-centred design, *CoDesign: International Journal of CoCreation in Design and the Arts*, **7**(1), 45-60.

Steen, M.: 2013, Co-design as a process of joint inquiry and imagination, *Design Issues*, **29**(2), 16-28.

Stempfle, J. and Badke-Schaub, P.: 2002, Thinking in design teams: an analysis of team communication, *Design Studies*, **23**, 473-496.

Valkenburg, R. and Dorst, K.: 1998, The reflective practice of design teams, *Design Studies*, **19**(3), 249-271.

Van de Vreken, A. and Safin, S.: 2010, Influence du type de représentation visuelle sur l'évaluation de l'ambiance d'un espace architectural, *Proceedings of Interaction Homme-Machine, IHM*, 49-56.

INTELLIGENT INFORMED LANDSCAPES

The Eco-Systemic Prototypical Interventions' Generative and Iterative Co-Designing Co-Performances, Agencies and Processes

MARIE DAVIDOVÁ
[1] *Welsh School of Architecture / Collaborative Collective*
[1] *davidovam@cardiff.ac.uk*

Abstract. The work fights for a shift from Anthropocene in urban environment through both, analogue and digital eco-systemic prototypical urban interventions, mixing biological as well as digital performances of post-digital landscape. It directly engages with the local human and non-human communities as well as it offers its online recipes and codes for DIY local iterations tagged in public space. Such intelligent and informed cultural landscape therefore covers several multi-layered generative and iterative agencies for its self-development.

Keywords. Systemic Approach to Architectural Performance; Intelligent Informed Landscapes; Post-Anthropocene; Eco-Systemic Prototypical Urban Interventions; DIY.

1. Introduction

The paper discusses generative and iterative processes of two selected key designs from broader field of Systemic Approach to Architectural Performance: 1) the SpiralTreeHouse (see Figure 1), a treehouse that co-lives with trees and offers habitation to other species and 2) the TreeHugger, a responsive solid wood insect hotel, serving as well as a fast food restaurant for bats and birds (see Figure 5). The two have several prototypical iterations entering the public spaces' eco-systems with support of mediamix of low-tech biological and embedded digital technologies, thus generating the 'Intelligent Informed Landscapes'. This research by design is presented from a first person 'reflective practitioner' (Schön, 1982) perspective.

At the start of millennium, the prototypical urban interventions were introduced by CHORA office (CHORA, 2017). These represented a critique of master planning, suggesting that small input in an urban environment can generate large change through its public interaction (Doherty, 2005). Local specific fruitful synergy between technology development and community building that 'resemble various forms of indigenous and even pre-modern forms of knowledge creation and practice' was discussed by Kera (Kera, 2012). Sensible or not, culture has developed and was tested in context of local environment over generations and it often evolves in sustainable and well performing strategies that are easily

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 151-160. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

accepted by particular communities (Davidová, 2016; Davidová & Raková, 2018; Davidová & Uygan, 2017). Emotions have an impact on public desire and will (McIntyre-Mills, 2014) and digital design is powerful political process (Bratteteig, Wagner, Morrison, Stuedahl, & Mörtberg, 2010). Therefore this post-digital design-research not only suggests local specific examples but also 'schools of thoughts' (Hensel, 2015) for local specific adaptations addressing global problems reachable through DIY (do it yourself).

Our collaborative co-designed research by design synergises these agendas further as follows: 1) The interventions are trans-disciplinarily co-designed with the local community, therefore generated bottom up from the local input. 2) Their performance is co-designed with the local eco-system, including the human and the non-human community. 3) The prototypes are attached to related cultural events, to engage the interest of the human community and related professionals. 4) The complexity of the design process, the eco-systemic relations and speculations of the development are exhibited in the form of GIGA-map, the visual diagramming of complexity (Sevaldson, 2011). 5) The prototypes, the tangible interfaces, are marked with QR codes. The QR codes are leading to our site with recipes and grasshopper codes for DIY. Therefore, they are offering tangible processes experience for adjustments to local specific settings by other communities with Creative Commons Non-Commercial Use Licence (Creative Commons, 2017). 6) This site is promoted on related fairs and sites to reach the prototype's iterations, i.e. Maker Faire Prague (Kera, 2018) or Rhino News (related software news blog that appears to every user when starting the software). 7) The project updates itself based on its long lasting performance and generative development observations. It therefore follows third order cybernetics principle when the designer is time-to-time within and time-to-time outside of the system as well as it goes hand in hand with Joachim's justification of designers' foreseeing of better futures (Joachim, 2015).

2. Iterative and Generative Co-Performing Prototypical Design Cases - The Intelligent Landscapes

The following selected design cases focus on cross-species co-living, whilst engaging local human and non-human, living and non-living communities, offering interaction, exchange, transfer, nutrients and habitation. The prototypical iterations of two key concepts are built of wood from local forests, using its hygroscopic properties for material performance that generates suitable microclimate for different species' comfort for micro biotop habitats, material, food and genetic production and distribution on important bio-corridors across variety of cultural landscapes, updating them with collective cross- biotic and abiotic intelligence. They are therefore generating a multiple agency oriented 'rights to ground' (Hensel 2019).

2.1. SPIRALTREEHOUSE CASES

The initial project of SpiralTreeHouse led into several iterations, all adapted to its local environments, generating co-living and co-performing landscapes.

- SpiralTreeHouse, Cholín Forests, Czechia (2010)



Figure 1. SpiralTreeHouse for co-living with trees / Moss growing on the SpiralTreeHouse's platform • Authors: Davidová , Závada • Building Team: Závada, Davidová, Peterková, Závadová, Dioszegi, Vedral, Hradilek (photos: Zapletal 2014 / Davidová 2012) .

SpiralTreeHouse was built in the forest on top of the original Celtic settlement above a dam and its nearby village that is today covering mainly recreational character. It is an along oak trees sweeping structure (see Figure 1) and it uses the material from over densified pine forest from communist regime to support the eco-system. The structure offers co-habitation of different species that co-create and benefit from its performance (Davidová, 2017). I.e. the moss living on the platform benefits from the hygroscopicity of wood, receiving moist even in today so common draughts (see Figure 1). Being in touristic neighbourhood nearby the city of Prague, the concept getting spread for DIY.

- Co-oCo-oNest - Slavutych, Ukraine (2018)



Figure 2. Chernobyl urban environment taken over by the eco-system / CooCooNest co-builders and co-designers testing the structure - 86' Festival's Workshop (Slavutych, Ukraine 2018) • Workshop Tutors: Davidová, Prokop • Workshop Participants: Neshevets, Rezen, Dimitrishina, Zabolotnyi, Slavutych local community (photos: Davidová 2018).

Within the framework of the first international workshop series, organised by 86' International Ukrainian Film Festival, Collaborative Collective, Ukrainian trans-disciplinary workshop participants and the local community of Slavutych co-designed baby of SpiralTreeHouse, the Co-oCo-oNest (Davidová & Neshevets,

2018). The project builds on that due to the disaster in 1986, the Exclusion Zone of Chernobyl gave rise to an exclusive eco-system (Deryabina et al., 2015) that turned the nuclear zone into natural tourist destination (see Figure 2). This leads to the question of such adaptation of the local society and their built environment. In the time when we discuss about 80% of biodiversity or biomass loss in Western and Central Europe, this place is truly unique. Our workshop program claimed that the community needs to take an advantage of such local specificity and develop their cross-species co-living and co-habitation skills. These are advanced through community 'co-design and co-creation' (Sanders & Stappers, 2008). Many locals helped on the building site and local kids co-designed the structure when playing during the construction time. The participants photographed and draw the local references while seek for their relations (Davidová, 2018). While doing so, they co-designed eco-systemic prototypical urban interventions and their fusion of resting and social space in the trees as well as monkey bars was physically co-prototyped (see Figure 2), than also re-designed and iterated.

- SpiralMonkeyBars - Prague, Czechia (2018)

Iterated by second author of the STH, SpiralMonkeyBars is a climbing construction for kids made of local hazel branches with discarded firefighter's fire hoses. It is a villa like area community project in the only potential public social space in the neighbourhood - a little forest in its centre (see Figure 3).

- COLridor II, Třebíč, Czechia (2018)



Figure 3. SpiralMonkeyBars • Author: Závada • Building Team: Závada, Závada, Vavrda / COLridor II - The spiral structure on a square between park and city's eco-system • Design and Realisation Lead: Davidová, Zímová, Michálek, Zatloukal, Gazdová, Gönulf, David • Building Team: Stasiak, Čapková, Čapka, Nejedlý, Viceník, Belán, Novotný, Větrovec, Veselý, Herzán • Client - Exhibition Theme and Concept: Horák Goryczka (photos: Závada / Davidová 2018).

COLridor II (see Figure 3 and 4) has been built as an architectural solution by Collaborative Collective for Czech National Heritage Association's exhibition on wood building constructors' lineage Herzan (Davidová, Zímová, & Horák Goryczka, 2019). The project is to support bio-corridorial relations of an adjacent park and city's eco-system. Constructed and kept updated with local scouts, the structure holds, insulate and hydrates onions of blossoming plants to feed pollinators in very early spring's very first sun and holds local specific seeds for

birds. The interior part will invade the gallery space with an indoor eco-system and offer bird food to visitors for dissemination (see Figure 4).



Figure 4. COLridor II - Edible properties of the outdoor spiral structure covering sprout of blossoming plants and bird food and the living indoor extension of the generated micro bio-top • see caption of Figure 3 for authorship (photos: Zímová 2018).

2.2. TREEHUGGER CASES

TreeHugger concept is a prototypical intervention to support edible and habitable landscape within cities' bio-corridors. It serves as a dwelling for insects and algae and as a fast-food restaurant for bats and birds. TreeHugger's are applying responsive wood concept for generating a desirable microclimate for its internal chambers to be inhabited by insects and a desirably moist ground for algae. Cut in tangential section, its panels warp or narrow down based on the combination of relative humidity, temperature and the position of their origin in the log. Combining the last quality and world axis orientation, the prototypes generate various microclimates preferred by diverse insect species. Thanks to the hygroscopicity of the material, moisture is retained. Therefore, algae that would not otherwise survive in sunny, therefore dry, locations can inhabit the prototypes along all world axis orientations (Davidová & Prokop, 2018; Davidová & Zímová, 2017, 2018).

- TreeHugger CZ, Prague, Czechia (2017)



Figure 5. TreeHugger CZ Prototype in Prague after Nine Months of Co-Performance with the Local Eco-System. Please, note also the algae habitation. • Authors: Davidová, Prokop, Zímová, Michálek, Horák Goryczka, Hanzlík, Trgala, Oberhofnerová, the Local Biotic and Abiotic Community of Prague 2 District - Co-Design (photo: Davidová 2018).

TreeHugger CZ was the first prototype of its kind, built within joint co-design COLridor I project led by - Collaborative Collective and CooLAND NGOs. The project is to generate a bio-top on a bio-corridor passing through city centre of Prague. It is built for Central European climate, protecting from cool weather and high humidity, while generating ventilation flow in hot dry weather (see Figure 5).

- TreeHugger CY, Nicosia, Cyprus (2018)



Figure 6. View on United Nations Buffer Zone in Nicosia from Greek side / TreeHugger CY • Workshop Tutors: Davidová, Prokop • 6th eCAADe RIS Organisation: Kontovourkis • Site Analysis for Tree Pre-Selection and Permission Negotiation: Konatzii, Psaras • Prototyping Worksop Participants: Konatzii, Psaras, Kyprianou, Vucic, the Local Biotic and Abiotic Community of Nicosia Centre (Co-Design) (photos: Davidová 2018).

TreeHugger CY was built as a workshop result at 6th eCAADe RIS lead by Collaborative Collective. It is a Cypriot adaptation of the first concept, built for Mediterranean climate. Being placed few meters from United Nations Buffer Zone in Nicosia, it extends its non-human species' bio-corridor in city centre (see Figure 6). Contrary to the first prototype, the panels are placed to air the structure in humid and cold weather. As the high humidity and high temperature is the prevailing climate, the solution supports that the humidity does not concentrate inside (Davidová 2018).

3. Iterative and Generative Prototypical Agency - The Informed Landscapes

The prototypes' recipes and parametric codes are simultaneously placed on Systemic Approach to Architectural Performance blog for their local specific adaptation through communities' DIY under Creative Commons NonCommercial 4. International Attribution (Davidová, 2018). Based on the processes needed, it includes project's explanations, animations, Grasshopper 3D (Davidson, 2017) parametric code and storyboards, explaining different steps or manipulations of the parameters (see Figure 7). The site is therefore distributing the 'schools of thoughts' (Hensel, 2015) for generation of its local specific informed iterations. Such blog is further distributed through various analogue and online digital publicly accessible landscapes.

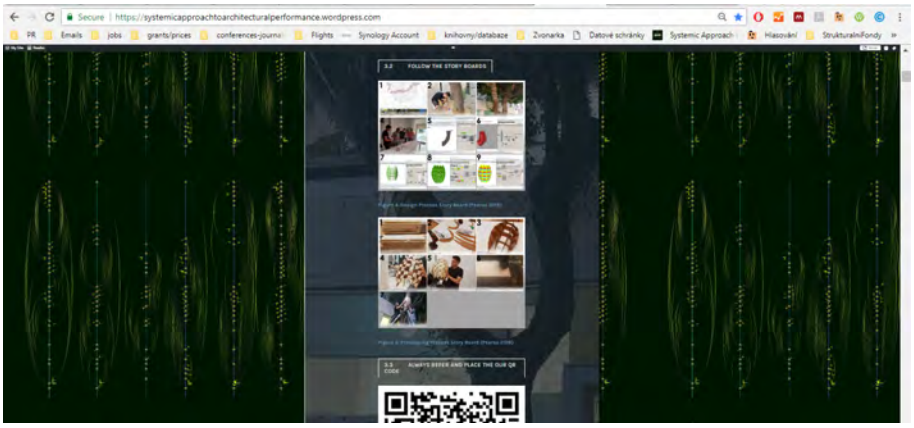


Figure 7. The On-Line Recipe with a Grasshopper Code for DIY (website: Davidová , manual: Psaras 2018).

3.1. TAGGING THE PUBLIC SPACE



Figure 8. Ondřej Michálek attaching the QR code to TreeHugger CZ / Non-Anthropocentric Refreshments at Maker Faire (photos: Davidová / Horák Goryczka 2018).

For each of such project's post there is generated a QR code leading to the web site. These are lasered into- or attached to- prototypes (see Figure 8). Therefore, the prototype, being always placed in public space, serves also as an advert to disseminate its iterations. This has been extended by Non-Anthropocentric Refreshments event at 'Maker Faire Prague' (Kera, 2018). Besides preparing a seed bombing picnicking cuisine with honey species, a QR code mapping game leading to our fast food oriented prototypes' recipes was installed for the makers (see Figure 8). Such concepts are embedding information generative and self-iterative agendas into urban landscapes with very low-tech technologies, parasitizing on individuals' personal devices and internet connection. To my knowledge, first of similar experiments of linking performance of mobile devices with architectural spaces were done by Ocean North in project project Intencities in 2000 through SMS or WAP in Finland, that time targeting sound generative interaction (Sotamaa, katastro.fi 2000).When linking to internet, the amount of

site visits is local specific, either very low or very high based on the community's digital culture. More local specific strategies need to be investigated.

3.2. TARGETING MEDIA

Besides other popular sites, to engage the digital prototyping community, the prototypes with links to recipes are published on Rhino News (Davidová 2018). Such posts are for certain time period displayed to every Rhinoceros program user when starting the software (see Figure 9). Taking the advantage of that such users often know the tool well, according to page statistics, the Grasshopper code is often downloaded by these web site visitors. Therefore the work is targeting two types of communities, a) the local specific neighbourhoods communities' tinkering and b) the digital fabrication makers.

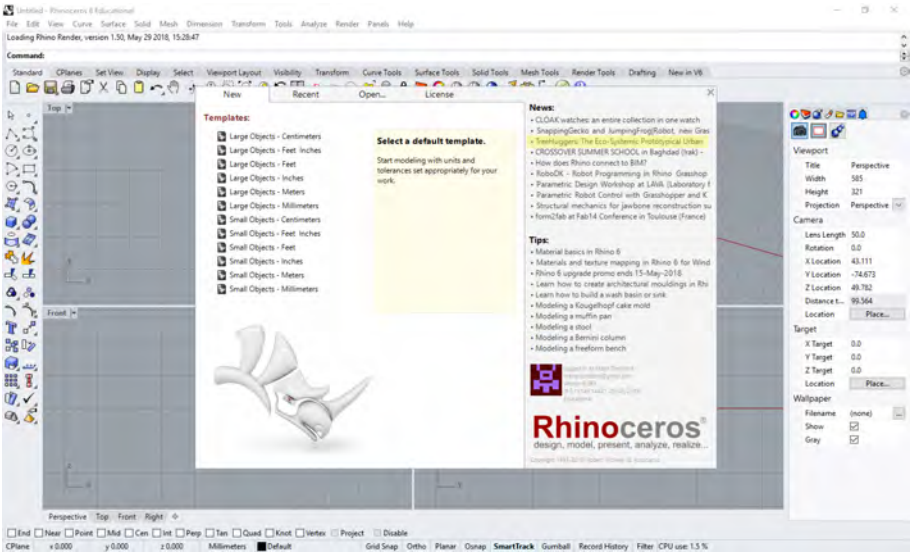


Figure 9. Starting of Rhinoceros program displaying TreeHuggers article with a link to DIY recipe (screenshot: Davidová 2018).

4. Discussion and Conclusions

Morrison and Chisin discuss in multi-species design context the importance of both design that generates thinking and design that generates functional objects both developed and scaled to local context (Morrison & Chisin, 2017), means also generating intelligent and informed landscapes. I would add to it the importance of cross-species co-design that generates interaction, agency, performance and its own iterations, means an active bio-digital intelligent informed landscape. These qualities always have to be adapted and in adapting dialogue with natural, social and cultural environment in a form of a 'real life laboratory'. Such 'speculative design' (Dunne & Raby, 2013) is to motivate bottom up

actions through interactions. The discussed 'non-anthropocentric architecture' (Hensel, 2013) is hands on speculating on the shift from Anthropocene in urban environment through twofold layers: a) it intervenes and interacts locally through environmentally co-designed prototypes; b) it offers recipes and parametric codes for local adaptations across the world. This post-digital 'Ecological Urbanism' (Mostafavi & Doherty, 2016) is approached both: a) locally, by tagging the public landscape with our online information (a low-cost and low-tech way of ubiquitous computing), b) it is spread through advertising targeted on relevant communities (accessible to whoever with internet connection across the globe). The research is not only targeted on motivating but also on giving the guidance and recipes to several design cases for the public to support climate change adaptation and biodiversity loss mitigation. Therefore, the originality is in its hybrid targeting on wider spectrum of application through diverse audience. It represents both a research by design itself but also a design manual for a DIY approach for an engagement and increase of urban biodiversity. At one point, the work discusses the theories generated through practice that we do not only need to dwell in the cities, but also eat. On the other hand it offers hands on recipes and codes in order to achieve this. It publishes the research open access so it can reach communities, future generations of professionals, practice, academy even from the locations that experience scarcity. Therefore, the work supports lowering instability in the world and fights climate change through its shared applicable content, fusing social and environmental justice. It is empowering the communities even at the places where finances are scarce, as long as there is an access to basic natural resources and internet. Such multi-layered urban design agenda is co-defining the new emerging design field of Systemic Approach to Architectural Performance.

References

"katastro.fi" : 2000. Available from <katastro.fi> (accessed 2018-12-13).

"Creative Commons - Attribution-NonCommercial 4.0 International — CC BY-NC 4.0" : 2017. Available from <https://creativecommons.org/licenses/by-nc/4.0/> (accessed 2017-12-09).

Bratteteig, T., Wagner, I., Morrison, A., Stuedahl, D. and Mörtberg, C. 2010, Research Practices in Digital Design., *in* I. Wagner, T. Bratteteig and D. Stuedahl (eds.), *Exploring Digital Design*, Springer, London, 17–54.

CHORA, C.H.O.R.A.: 2017, "CHORA – conscious city" . Available from <http://chora.org/> (accessed 2017-12-11).

Davidová, M.: 2016, Socio-Environmental Relations of Non-Discrete Spaces and Architectures: Systemic Approach to Performative Wood, *Relating Systems Thinking and Design 2016 Symposium Proceedings*, Toronto, 1-17.

Davidová, M.: 2017, Systemic Approach to Architectural Performance: The Media Mix in the Creative Design Process, *FORMakademisk*, **10**(1), 1-25.

Davidová, M.: 2018, "Rhino News - TreeHuggers" . Available from <http://blog.rhino3d.com/2018/07/treehuggers-eco-systemic-prototypical.html> (accessed 2019-2-1).

Davidová, M.: 2018, "TreeHugger CY" . Available from <https://systemicapproachtoarchitecturalperformance.wordpress.com/2018/05/24/treehuggercyprus-the-eco-systemic-prototypical-urban-intervention-by-the-united-nations-buffer-zone-for-diy/> (accessed 2019-2-1).

Davidová, M.: 2018, Trans-Co-Design in Systemic Approach to Architectural Performance: The Multi-Layered Media and Agency in Creative Design and Its Processes, *Proceedings of Relating Systems Thinking and Design (RSD7) 2018 Symposium*, Torino, 1-21.

Davidová, M. and Neshevets, N.: 2018, "Co-oCo-oNest" . Available from <https://systemicapproachtoarchitecturalperformance.wordpress.com/2018/05/08/eco-systemic-co-design-for-diy-coocoonest-the-baby-of-spiraltreehouse> (accessed 2019-2-1).

Davidová, M. and Prokop, Š: 2018, TreeHugger: The Eco-Systemic Prototypical Urban Intervention, *6th eCAADe RIS 2018 Proceedings*, Nicosia, 75-85.

Davidová, M. and Raková, D.: 2018, Biodiversity and Climate Change Adaptation through Non-Discrete Architectural Spaces and Architectures: Systemic Approach to Traditions for Sustainable Futures, *FORMakademisk*, **11**(4), 1-31.

Davidová, M. and Uygan, E.: 2017, Living in Bio-Climatic Layers: An Investigation of Cappadocian Caves in Relation to Today's Design and Its Futures, *International Design Conference: DESIGN EVOLUTION [Education and Practice]*, Karachi, 1-12.

Davidová, M. and Zímová, K.: 2017, COLridor: Co-Design and Co-Living for Sustainable Futures, *Relating Systems Thinking and Design 6 Symposium Proceedings*, Oslo, 1-20.

Davidová, M. and Zímová, K.: 2018, COLridor: Co-Design and Co-Living Urban Adaptation, *FORMakademisk*, **11**(4), 1-30.

Davidová, M., Zímová, K. and Horák Goryczka, K. 2019, COLridor II for Exhibition Herzan: The builders' family from Třebíč, *in* K. Horák Goryczka (ed.), *Herzan: The builders' family from Třebíč*, Czech National Heritage Institute, Prague, 1-4.

Davidson, S.: 2017, "Grasshopper - algorithmic modeling for Rhino" . Available from <http://www.grasshopper3d.com/> (accessed 2017-10-06).

Deryabina, T.G., Kuchmel, S.V., Nagorskaya, L.L., Hinton, T.G., Beasley, J.C., Lerebours, A. and Smith, J.T.: 2015, Long-term census data reveal abundant wildlife populations at Chernobyl, *Current biology: CB*, **25**, R824-R826.

Doherty, G.: 2005, Prototypes in Pinkenba, *Nordes 2005 - In the Making*, Copenhagen, 1-5.

Dunne, A. and Raby, F.: 2013, *Speculative everything: design, fiction, and social dreaming*, MIT Press, Massachusetts.

Hensel, M.: 2013, *Performance-Oriented Architecture: Rethinking Architectural Design and the Built Environment*, John Willey & Sons, West Sussex.

Hensel, M.: 2015, Thoughts and experiments en route to intensely local architectures, *Nordic Journal of Architectural Research*, **27**(1), 61-83.

Hensel, M.: 2019, The rights to ground: integrating human and non-human perspectives in an inclusive approach to sustainability, *Sustainable Development*, 1-7.

Joachim, M.: 2015, A Century of Ecological Innovation, *Architectural Design*, **85**(4), 68-73.

Kera, D.: 2012, Hackerspaces and DIYbio in Asia: connecting science and community with open data, kits and protocols, *Journal of Peer Production*, **1**(2), 1–8.

Kera, D.: 2018, "Maker Faire Prague" . Available from <http://prague.makerfaire.com/> (accessed 2018-07-09).

McIntyre-Mills, J. 2014, Systemic Ethics for Social and Environmental Justice, *in* J. McIntyre-Mills (ed.), *Systemic Ethics and Non-Anthropocentric Stewardship*, Springer, Cham, 121-153.

Morrison, A. and Chisin, A.: 2017, Design fiction, culture and climate change. Weaving together personas, collaboration and fabulous futures, *The Design Journal*, **20**, S146-S159.

Mostafavi, M. and Doherty, G.: 2016, *Ecological Urbanism*, Lars Müller Publishers, Cambridge.

Sanders, E. and Stappers, P.J.: 2008, Co-creation and the new landscapes of design, *CoDesign*, **4**, 5-18.

Schön, D.: 1982, *The Reflective Practitioner*, Basic Books, London.

Sevaldson, B.: 2011, GIGA-mapping: Visualisation for complexity and systems thinking in design, *Nordes '11: The 4th Nordic Design Research Conference*, Aalto, 137-156.

Sevaldson, B.: 2015, Gigamaps: Their role as bridging artefacts and a new Sense Sharing Model, *Relating Systems Thinking and Design 4*, Banff, 1–11.

Sotamaa, K.: 2000, "Kivi Sotamaa" . Available from <https://portfolio.sotamaa.net/Intencities> (accessed 2018-12-12).

INFORMED WALKABLE CITY MODEL

Developing A Multi-Objective Optimization Model for Evaluating Walkability Concept

ASWIN INDRAPRASTHA[1] and BIMA DWI PRANATA PUTRA[2]
[1,2]*School of Architecture, Planning and Policy Development, Institut Teknologi Bandung*
[1]*aswin@itb.ac.id* [2]*bimaputrapranata@gmail.com*

Abstract. This study presents an informed city analysis methodology as a tool for evaluating the concept of walkability for the existing urban area. The aim of this study was to propose an integrative approaches enable optimization of urban design element and walkability amenities under certain walkability performance criteria. The parametric methods are being developed in three stages of modeling: 1) City data modeling; 2) Walkability scores and indicators modeling; 3) Optimization model of the urban area. In the walk score algorithm, we modified three elements that determine walk score result: Walk Score Categories, Distance Decay Function and Pedestrian Friendliness Metric. We developed the customized algorithm based on the data gathered from field observation and sample interviews to normalize and define values in the walk score algorithm. The result is a parametric model to evaluate walkability concept in a certain urban area considering quantified factors that determine walkability scores. The model furthermore seeks to optimize walkability score by assessing new amenities on an existing urban area using multi-objective optimization method that produces an integrative method of urban analysis.

Keywords. Walkability; walk score; parametric models; multi-objective optimization; informed city analysis.

1. Background

Walkability is an urban design concept at the beginning of the modern era that been considered as a key factor for the vibrancy of the city (Jacobs, 1961). This concept is part of the new urbanism agenda as a response to the existence of modernism theory that leads to the vehicle-oriented city. Recent concept of Transit-oriented Development, Mixed Use and Walkability are promoted to increase the quality of life of the city dwellers (Duany, et al., 2000). Big cities and metropolitan area in the emerging country such as Indonesia apparently suffer from the dominance of vehicle-orientation transportation system that contributes impact to air quality, severe traffic congestion and urban sprawls among other issues. Walkability

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 161-170. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

concept, therefore, is still relevant to offer a better approach for urban analysis and design particularly on promoting pedestrians and decreasing the use of vehicles in the city area. Manheim (1979) advised that a model of macro transportation can generate iterative correlation among activity system, transportation system, and movement pattern. A movement pattern will influence transportation system and vice versa, the current pattern of movement will stimulate and determine the demand for the transportation system in the future. Meanwhile, researches in the field of urban transportation system mostly try to tackle the issues on vehicle-based transportation and transit journey and put aside the significant factor of the pedestrian as a key aspect of a livable city (Jacobs, 1961, Litman, 2007).

This study presents the urban analysis methodology and a tool for evaluating the concept of walkability for the existing urban area. The area of research has been studied by several scholars for contributing a method for walkability analysis (Pak and Verbeke, 2013, Cichocka, 2015) in various urban settings (Lwin & Murayama, 2011, Rathnasiri, et al., 2015, Ozbil, et al., 2015) among others. To fill the gap on walkability model and simulation, the aim of our study is to propose an integrative and scalable approach in the creation of what-if scenarios that enable optimization of urban design elements and walkability amenities under walkability performance criteria. We developed the customized algorithm based on the data gathered from field observation and sample interviews that became our justification to normalize and define values in the walk score algorithm.

2. Framework

This study seeks to support better city analysis that would be followed by a decision-making process on urban planning and design by proposing a parametric and data-informed method based on the concept of walkability. The methodology can be used to evaluate multiple scenarios based on data-set combinations and rules through a parametric and iterative generation of solutions. The following diagram shows our flowchart of the study (Figure 1).

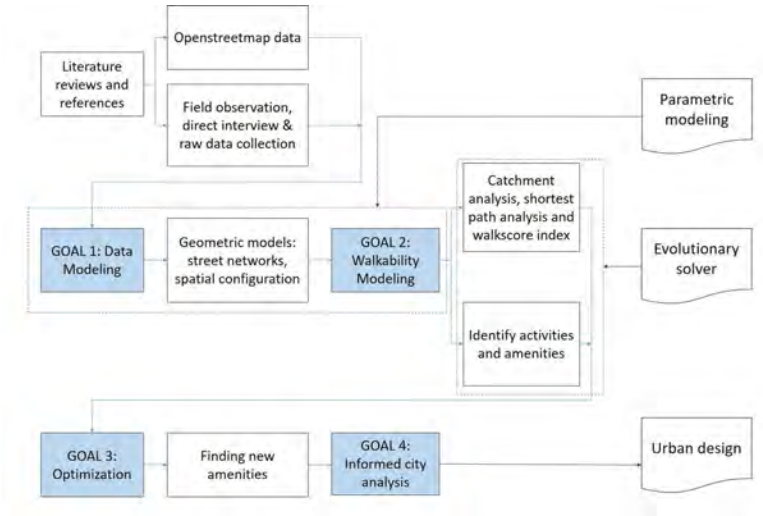


Figure 1. Flowchart of the Proposed Framework.

3. Case Study

The proposed methodology is implemented and tested in the case study of Bogor city. The City of Bogor is situated in the western part of Java island, Indonesia, located about 53 km south of Jakarta and about 85 km northwest of Bandung city, the capital of West Java province. The city area occupied about 11.85 sq km with 59.45% is built environment with 1.050 million inhabitants. The case study is located in the city center in the surrounding area of Bogor Train Station with about 104 ha. The designated area is considered as one of the economic districts of the city center with commercial areas, public spaces alongside its main streets. The train station which is located at the center the district historically became the main hub of the transportation and now still generates main traffic congestion along the city's corridor. For the purpose of the study to analyze the relation between street configuration and finding an area of amenities to increase Walkability score, the area of the case study is divided into two zones based on its main activity characteristics (Figure 2).

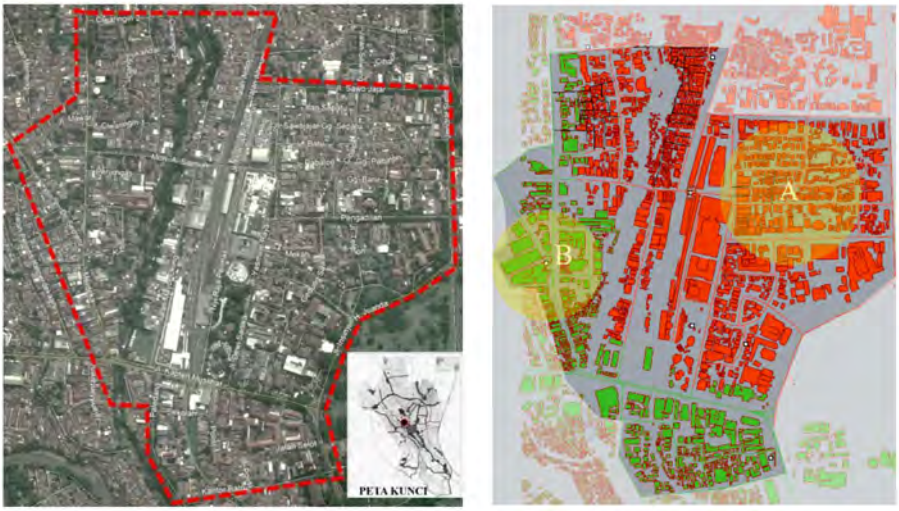


Figure 2. (Left) Delineation of the Area of Study; (Right) Two Zones as Unit of Analysis.

Zone A characterized by three main functions: commercials, public facilities, and houses. The commercial area typically located along main streets, the public services such as train station, governmental offices are located in the designated area while houses and settlements reside at the northern side of the zone. Whereas zone B typically characterized by commercial corridors with Dutch architectural style that historically had been the main commercial district of the city. The public services facility such as school and hospital, as well as houses, are located on the Southeast side of the zone. Based on the walkability score using amenities factors, we determined amenity categories of each of the zone adjusted by their actual and existing condition as depicted in the Table1 below:

Table 1. Categories of Amenities at the Zones of the Case Study.

Walkscore's amenities	Zone A	Zone B	Minimum Amount	Maximum Weight (W)	Weight of Nearest Amenities (w_i)
Groceries	Grocery stores	Transportation hub	1	3	[3]
Restaurant	Restaurant	Restaurant	10	3	[.75,.45,.25,.25,.225,.225,.225,.225,.2,.2]
Shopping	Restaurant	Bicycle parks	5	2	[.5,.45,.4,.35,.3]
Small shops	Food stall	Coffee shop	2	2	[1.25,.75]
Bank	Bank	Bank	1	1	[1]
Park	Health facility	Health facility	1	1	[1]
School	School	School	1	1	[1]
Book	Bookshop/library	Shopping mall	1	1	[1]
Entertainment	Public park	Public park	1	1	[1]

While by analyzing using Pedestrian Friendliness Metrics parameters: the average length of the block and number of street intersections, the result of each zone is calculated and depicted as follows (Table 2).

Table 2. Pedestrian Friendliness Metric of the Zones.

Walkscore's Pedestrian Friendliness Metrics	Zone A	Zone B
Average length of the block	52 blocks/134 m	11 blocks/ 130.8 m
Number of street intersections	93/0.74 sq km	23/0.3 sq km

4. Data Analysis and Modelling

City map data obtained from Openstreetmap.org that later on elaborated into multi-attributes geometric data in Rhinoceros using Grasshopper. The Elk add-on by Timothy Logan (2015) was used to convert OpenStreetMap data (.osm) into significant attribute points of physical properties such as building outlines, street outlines, river outlines, railways outlines. The parametric process through algorithm development had been used to compile these points into closed polylines that represent buildings, streets, rivers, railways, and others (Figure 3).

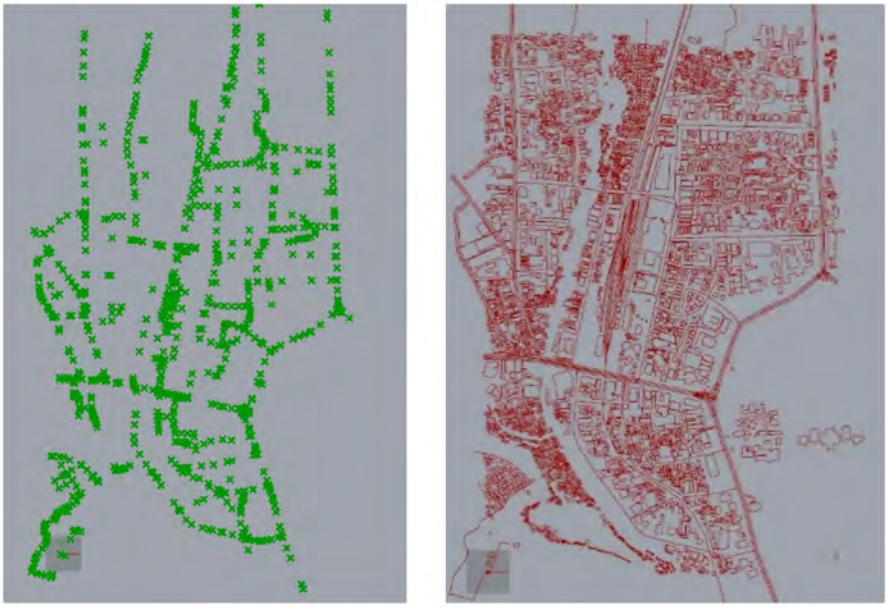


Figure 3. Development of Point-based Data into Polygon.

5. Subdivision of Unit Analysis

Following geometry preparation, we develop a mechanism to subdivide unit analysis of each zone by employing principles of the influence of serviceability using Voronoi closed curves. Each of the zones has two significant attractors that we defined based on field observation: Zone A: commercial center and public parks; Zone B: commercial center and transportation hub. The Cheetah add-on for Grasshopper had been used for subdividing the zones based on

the attractor's location, the influence of serviceability and street configuration (Figure 4). Cheetah_the Configurbanist by Nourian, et al. (2015) is a tool for configurational analysis in the urban design project, developed by Pirouz Nourian et al., at TU Delft. As seen in the Figure, Zone A is subdivided into three zones (A1, A2, A3 respectively) and Zone B is subdivided into two zones (B1 and B2, respectively).



Figure 4. Zones for Unit of Analysis and Derivative Units of Each Zone after Subdivision.

6. Walkability Analysis and Modelling

6.1. CATCHMENT ANALYSIS AND SHORTEST PATH ANALYSIS

The goal of catchment analysis is to seek maximum serviceability of each amenity by means of walking at 5 km/s. This analysis takes account of the street networks, the location of amenities as well as the location of other facilities such as houses, schools, parks, hospitals. The output of this analysis is a maximum distance of amenity's serviceability relative to the other city's facilities based on the shortest walking time (in minutes). The method of analysis is based on Walkscore methodology where the ranking of particular amenities is calculated by its capacity to reach the number of people by walking. By this analysis, we can map out the impact of each amenities from each zone based on their spatial configuration. We employed the shortest path analysis to seek and map out the walking shortest path from origin to destination of each unit analysis from each zone.

6.2. CUSTOMIZED WALK SCORE ALGORITHM

6.2.1. Customized Walkability Amenities

Our study of Walk Score modeling and analysis is based on the work of Urban Modeling Interface (UMI) by Sustainable Design Lab, MIT. We modified the

algorithm that allowing additional parameters such as local-based amenities and adjustments of the study area to be included in the model. As in the original algorithm, there are 9 amenity categories take into account for calculating the Walk Score with respect to the walking distance. In our model, we previously determined and weighing 9 amenities from each zone that can be included or having similar attributes to the Walk Score 9 amenities.

6.2.2. Distance Decay Function

Based on Walk Score algorithm, it is determined the percentage of a full score a category will receive based on the distance between the origin and an amenity's location. The use of this function is well accepted to depict the correlation between distance from the location of interest/origin and a full score that an amenity will receive. The polynomial function depicted that after a certain distance, amenity scores decrease less quickly with greater distance until it reaches certain distances. We employed a normalized factor for the metric used in this study.

6.2.3. Pedestrian Friendliness Metrics (PFM) and Its Penalty

We used two measures of (PFM) as mentioned in the previous section: average block length and street intersection density that are commonly used in walkability research. In addition, there are certain penalty scores of both measures that up to 10% of the total scores. With the principle of Walk Score that at a point of origin will receive: 20% score from grocery/public transport; 20% from 10 points of shops/restaurants; 13% from 5 points of restaurant/bicycle parking; 13% from 2 points of bicycle rental/coffee shop and 6% each from 1 point of bank, healthcare/school, bookshop/shophouse and entertainment/park respectively, we determined the penalty scores using the following formula:

$$P(n) = \frac{W - \sum_{i=1}^{n} w(i)}{15} \cdot 100 \qquad (1)$$

n= amount of amenities and its weight at n; P(n)= Penalty at n amount of amenities; W= weight value of amenity type; w(i)= partial weight value of particular amenity type.

As result, the determination of penalty score based on the number of amenities and normalized penalty score by the number of street intersections are as follows (Table 3 and Table 4):

Table 3. Penalty Score Based on Number of Amenities.

Walkscore's amenities	Zone A	Zone B	Amount of Amenity	Penalty Score
Groceries	Grocery stores	Transportation hub	0	20
Restaurant	Restaurant	Restaurant	0,1,2,3,4,5,6,7,8,9	20,15,12,10,8,7,5,4,2,1
Shopping	Restaurant	Bicyle parks	0,1,2,3,4	13,10,7,4,2
Small shops	Food stall	Coffee shop	0,1	13,5
Bank	Bank	Bank	0	6
Park	Health facility	Health facility	0	6
School	School	School	0	6
Book	Bookshop/library	Shopping mall	0	6
Entertainment	Public park	Public park	0	6

Table 4. Penalty Scores Percentage Based on Area.

Analysis Area (Y-axis) x 77 points	Number of Points in the area of Y sqkm	Penalty Score (%)
x point	>(x *100%)	0
	x * 75%	1
	x * 60%	2
	x * 45%	3
	x * 30%	4
	< (x * 30%)	5

7. Optimization Model

Following modified walkability model, we developed a method to optimize the walkability score by seeking new amenity for a certain area. The parametric method is based on the walk score algorithm with modification on new data set from each determined amenity categories, obtained from a set of origin points. We determined a new set of these points as a potential point for a new amenity that assigned on some existing urban elements such as residential, vacant lot, demolished an abandoned building and other similar types. By this hypothetical and potential points, in principle, the modified algorithm works by generating and evaluating each new points to the Walkscore algorithm of each zone utilizing evolutionary solver-Octopus to seek average maximum value from 9 parameters by means of genetic algorithm (Goldberg, 1989). The important aspect of this method is through a parametric model, we can generate multiple scenarios of evaluating new optimum location with specific function based on Walkscore categories at any given designated area. The algorithm for the optimization model for a new amenity location is given in the diagram below (Figure 6).

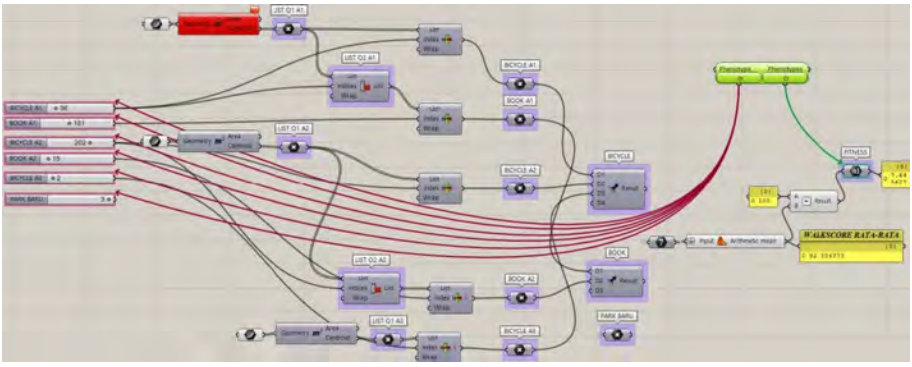


Figure 5. Algorithm for New Amenity Location.

For Zone A, the priority for new amenity categories are food stall, bookshop/library, and public park, while for Zone B, the priority amenities are: coffee shops, bicycle park, and transportation hub. The determination of new amenities is based on field observation and direct interview with locals that had been conducted during site surveys



Figure 6. Result of Optimization Method to Seek New Location for Amenities in Zone A (Above) and Zone B (Below).

As depicted in Figure 7, the result of the simulation shows that when new amenities are located at those areas the walkability score for Zone A is improved from 57.9 to 92.3 while for Zone B, the average walkability score is improved from 53.4% to 93.4%.

8. Conclusion and Future Direction

This study proposed an experimental applied method and model of the walkability principles as a tool for city and urban analysis coupled with a mechanism of what-if scenarios to increase its score by a multi-objective optimization process. The study contributes to the better urban analysis that led to a better decision-making process for the final planning and design output. The most valuable finding of the methodology is the potential to be used as a part of the tools for regulators and local authority on analyzing and planning for urban regeneration projects. The dataset gathered from direct observation and interview are used as part of the algorithm and refine simulation result. The modified walkability algorithms are necessarily made to allow an open-ended and adaptive strategy based dynamic context of the city. We made some adjustments and judgments for categories as well as normalization of the scores based on the local conditions. Our walk score

algorithms that divided into five clusters namely: data modeling (street networks, amenity points, and building attributes), shortest path of origin-destination, Distance Decay Function, weighting of amenities and penalty scores based on Pedestrian Friendliness Metrics contributes to improving UMI (Urban Modeling Interface) methodology by its flexibility and scalability on maximum of analysis area and modification of amenity parameters. In the end, the finding of this study presents a data-informed and multi-objective optimization method that may help to analyze and allocating public facilities that are methodologically relevant to the local context and conditions. The open-source and parametric method enabling extensible features of urban analysis such as Sky View factor, Urban Thermal Comfort and others in an integrated urban evaluation toolkit for a better informed urban design proposal. Future research would encompass further Walkability variables and parameters based on the local condition, elaboration on human movement factor in correlation with the level of service of the pedestrian walkways to determine and evaluate optimum dimension of the pedestrian path and networks.

References

Besser, L. and Dannenberg, A.: 2005, Walking to public transit: Steps to help meet physical activity requirements, *American Journal of Preventative Medicine*, **29**, 273-281.

Burak, P. and Verbeke, J.: 2013, Walkability as a Performance Indicator for Urban Spaces, *eCAADe 2013*.

Cerin, E.s.t.e.r., Leslie, E.v.a., du Lorinne, O.w.e.n., Neville, F.r.a.n.k. and Lawrence, D.: 2006, Destinations that matter: Associations with walking for transport, *Health and Place*, **13**, 713-724.

Cervero, R. and Duncan, M.: 2003, Walking, Bicycling, and Urban Landscapes: Evidence From the San Francisco Bay Area, *American Journal of Public Health*, **93**, 1478-1483.

Cichocka, J.: 2015, Generative design optimization in urban planning: walkability-optimized city concept, *Architectus*, **10**, 119-128.

Duany, A., Plater-Zyberk, E. and Speck, J.: 2000, *The rise of sprawl suburb and the decline of nation*, North Point Press, New York.

Goldberg, D.: 1989, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison Wesley, New Jersey.

Jacobs, J.: 1961, *The Death and Life of Great American Cities*, Random House, New York.

Kocher, J. and Lerner, M.: 2011, "Walk Score Methodology" . Available from <walkscore.com> (accessed January 2018).

Litman, T.: 2007, *The Economic Value of Walkability*, Victoria Transport Policy Institute, Victoria.

Logan, T.: 2015, "Elk Mapping Plugin for Grasshopper" . Available from <http://www.hksinc.com/hksline/2015/10/26/elk-mapping-plugin> (accessed March 2018).

Lwin, K. and Murayama, Y.: 2011, Modelling of urban green space walkability: Eco-friendly walk score calculator, *Computers, Environment and Urban Systems*, **35**(5), 408-420.

Manheim, M.L.: 1979, *Fundamentals of Transportation Systems Analysis*, MIT Press, Massachussett.

Nourian, P., Rezvani, S. and Sariyildz, S.: 2015, Configurbanist Urban Configuration Analysis for Walking and Cycling via Easiest Paths, *eCAADe 2015*, 553-564.

Ozbil, A., Yesiltepe, D. and Argin, G.: 2015, Modeling walkability: Te efects of street design, street-network confguration and land-use on pedestrian movement, *ITU*, **12**(3), 189-207.

Rathnasiri, S., Amarawickrama, S., Ranasinghe, G. and Ratnayake, R.: 2015, A Model for Assessing the Level of Walkability in Urban Neighborhoods in Sri Lanka, *International Journal of Built Environment and Sustainability*, **2**(4), 292-300.

HUMAN-BUILDING COLLABORATION

A Pedagogical Framework for Smart Building Design

DANIEL ROSENBERG[1] and ALEXANDROS TSAMIS[2]
[1,2]*Rensselaer Polytechnic Institute, CASE, School of Architecture*
[1,2]*{rosend9|tsamis}@rpi.edu*

Abstract. We introduce Human-Building Collaboration (HBC), a pedagogical framework for the design of next-generation smart buildings in architecture. Using the framework's philosophy, model, and tools we show designers how to enhance smart building performance by increasing and diversifying the ways humans have to share their intelligence with that of the building. We apply this framework through design exercises and present the result of two projects: (1) a tangible wall interface for lighting co-optimization and (2) a shape display facade interface for rainwater purification and reuse. Preliminary findings demonstrate that the framework helped designers proposing new means for humans to collaborate with smart buildings.

Keywords. Smart Buildings; Artificial Intelligence; Tangible Interfaces; Human-Building Interaction; User Experience Design.

1. Introduction

In 2016, an AI computer program, AlphaGo, beat a top-ranking professional player in the ancient game of GO (Silver et al. 2017). An achievement that demonstrates how artificial intelligence is getting closer and closer to reach our human intelligence. The excitement for this great feat, however, has been so large that AI researchers and enthusiasts have missed an important fact. While Lee Se-dol, the player, needed only his brain and a cup of coffee to perform the task, AlphaGo required 1,202 CPUs and 176 GPUs, consuming more than 350 kilowatts of energy. Yes, the human lost. The machine won at a well defined *closed* type of complex problem and in order to do so, it consumed 3000 times more energy than its opponent.

We do not have to look into complex problem-solving, such as playing GO, to understand AI's intensive energetic needs. Let us consider a simpler task, like recognizing an object in a room. For example, recognizing a cat. A task that does not require a top-rank professional and that any three-year-old child could perform easily in a fraction of a second. This task took Google's most advanced lab and 16,000 computer processors to perform (Le et al. 2012). We call this the *cat recognition problem*, demonstrating a broader context of efficiency and effectiveness of AI: in the current approach, the *smarter* the system the more energy and material resources it will require.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 171-180. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

We claim that this intensive energetic requirement could become an obstacle to AI being integrated into our broader built environment, precisely because of its high energy cost. Today, *smart buildings* are integrating AI capabilities with the purpose of optimizing energy consumption and increase the sustainability of the built environment (Lorenzo-Eiroa and Sprecher 2013; Sinopoli 2009). State-of-art propositions track occupancy and environmental conditions and then respond by adjusting their internal lighting and mechanical systems and/or actuating their facades (Kolarevic and Parlac 2015; Klooster 2009). Yet, similar to what is happening with AlphaGO, the practitioners and researchers on the smart building industry are missing a key fact: the *smarter* the building that they develop, the more energy and material resources it will require.

We propose an alternative framework towards next-generation smart building design. We call this framework Human-Building Collaboration (HBC). We claim that if we had to design a truly intelligent built environment, the notion of smart buildings needs to be expanded in order to include an effective way for AI to collaborate with humans (Licklider 1960). We can no longer afford to separate processing intelligence from energy intelligence. Smart buildings cannot pretend to be intelligent if they require much energy to reduce the energy of their regular use and operation. For us, the *cat recognition problem*, as a collaborative framework for building intelligence, is a shift from being one of autonomous intelligence to be one of *collaborative intelligence* (Daugherty and Wilson 2018). The question should not be limited to how can the smart building recognize the cat but instead how can a three-year-old transmit the location of the cat in an effective way to the building. It is our working assumption that intelligence should not be limited to individual processing intelligence but instead on active, bi-directional communication intelligence. That is what we mean by *collaboration*, human and building working together to obtain an intelligent result.

Our strategy to formulate the HBC framework is two-fold. First, we focus on the interaction between the human and the building. We are neither focusing on the AI nor the human intelligence but on the *interface* between the two. i.e., the means for human and building to communicate with one another. We want to expand and diversify the ways humans have to interact with these increasingly more intelligent and informed building systems. In this context, we align our work with human-building interaction (HBI) (Nembrini and Lalanne 2017), a research domain within human-computer interaction (HCI). While HBI investigates how to integrate HCI technologies into buildings, our model addresses smart building design from a pedagogical perspective. This difference with HBI constitutes our second strategy. The objective of our framework is to provide guidelines for practitioners, students, and researchers engaging in the actual design and development of smart buildings. Instead of proposing a specific technological solution, we introduce a framework that is meant to be taught, learned, and practiced in design.

In this paper, we introduce the foundations for HBC, including a philosophy, a model, and a set of tools. The philosophy corresponds to a new way of thinking about *interaction* in the context of a *collaboration* between humans and smart buildings. The model turns this philosophy into a set of design guidelines, through

a diagram describing the relational interactions and opportunities for collaboration between human and building. The tools apply the model through materials, examples, and techniques to be used in hands-on design practice.

Finally, we show a preliminary application of this framework through the design work of students at the Center for Architecture Science and Ecology (CASE). We found that the framework helped these students design smart building solutions with diverse interactions and collaboration modes. We conclude by elaborating on these findings and describing next steps. Future work involves specifying HBC functionality types, integrating new AI software techniques and implementations, and extending HCI towards new architectural methods.

2. How the (Smart) Building Sees Us

In 2004, Dan O‘ Sullivan and Tom Igoe, HCI professors, used an illustration of “how the computer sees us” to assess the interaction of their current digital technologies (O’ Sullivan and Igoe 2004). In the illustration, the human is represented as a hand with one finger, two ears, and one eye (Fig.1, Left). This depiction of the human is relevant because it exposed the limited means we had to interact with the computer at that time.

This illustration shows how the computer saw us in 2004. Today, 14 years later, HCI applications have somewhat progressed. We now have multi-touch screens and voice user interfaces (VUI). Therefore, today we have two fingers and a mouth. This updated depiction, however, is only valid for computers embedded in *devices*, such as personal computers, smartphones, wearables, tablets, and the IoTs. These are objects located *inside* our spaces. HCI has not yet been integrated within our spaces, as part of walls, floors, ceilings, doors, windows, and facades.

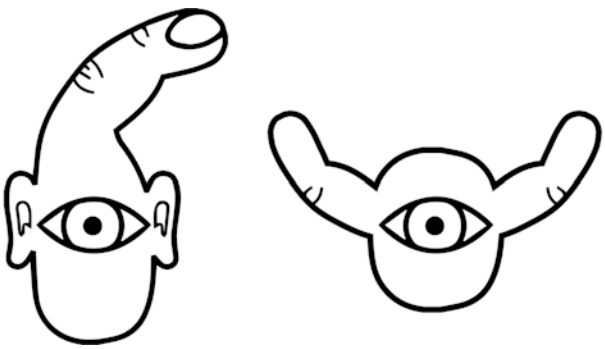


Figure 1. How the Computer Sees Us (Left). How the (Smart) Building Sees Us (Right).

We want to propose a new illustration of “how the (smart) building sees us.” In this depiction, the building is smart when it integrates computers, sensors, and effectors responding to environmental changes and user needs. In the illustration, we represent the human as a blob with two extensions (or arms) and one eye. This blob can move in a two-dimensional plane and can produce and feel temperature (Fig.1, Right). This illustration exposes the limited ways that humans have to

communicate and collaborate with smart buildings today.

In most smart building applications, not even interaction is considered, and the building systems or facades respond automatically to environmental changes by adjusting lighting and heating conditions (Sinopoli, 2016). In other cases, the building tracks position and number of people and optimize lighting and heating in response to occupancy (Kolarevic and Parlac 2015; Klooster 2009). In exceptional cases, facades or walls respond to the human movement in space and arm movements or gestures in real-time (Fox 2016; Krietemeyer et al. 2015).

For O' Sullivan and Igoe, "the human being as seen through the computer's input devices is a sad creature" (O' Sullivan and Igoe 2004). We claim the same for the current state of human-building interaction: the human being as seen through the smart building's input devices is still a sad creature. Humans do not have hands, fingers, feet, bodies. In sum, in current smart building solutions, humans have limited means to *act* on the building and *sense* a response coming from the building. We argue that this limitation constitutes an obstacle for human-buildings collaboration. We need to reframe interaction in this context, from a simple action-response relationship to a communicative process allowing the human and the building to work together: increasing and diversifying the ways humans have to share their intelligence with that of the building.

3. The Model

The model turns the philosophy into a set of design guidelines, through a diagram (Fig.2) describing the relational interactions and opportunities for collaboration between *human factors* (senses and actions) and *building factors* (detectors and responses). Using these factors and their relationships, the designer can explore the multiple and rich ways in which humans can interact, communicate, and thus collaborate with smart buildings. For example, a designer can choose *touch* for human action, and then *sound* for the building response to that action.

In the diagram, we illustrate a person inside a room. Next to the person, we describe the human *actions* and *senses*. In the top of the diagram, we note the building *detectors* and *responses*. The interaction takes place through a loop that we represent with one arrow connecting human actions to building detectors, and with a second arrow connecting building responses to human senses.

This is how the interaction between human and building unfolds: The human *acts* directly on the building by walking around, speaking, gesturing, or touching the building directly. All these actions are basically movements, i.e. the coordinated motion of body parts (limbs, hands, fingers, head, face, mouth, tongue, eyes). Even speaking could be described as the coordinated movement of mouth and tongue while breathing (Rosenberg 2015). The building *detects* these actions using sensors embedded in any of its material elements, namely points, lines, surfaces, and volumes. These elements can take the form of corners (points), railings (lines), walls (surfaces), and rooms (volumes). Then, the building, using embedded computers with AI capabilities, process this data and *responds* by adjusting and actuating any of its material elements. The building could open the facade, turn on the lights, increase the heat of an HVAC system, modify the surface

of a wall to display information. Finally, in the model, the loop is completed by the human *feeling* this response using the body senses.

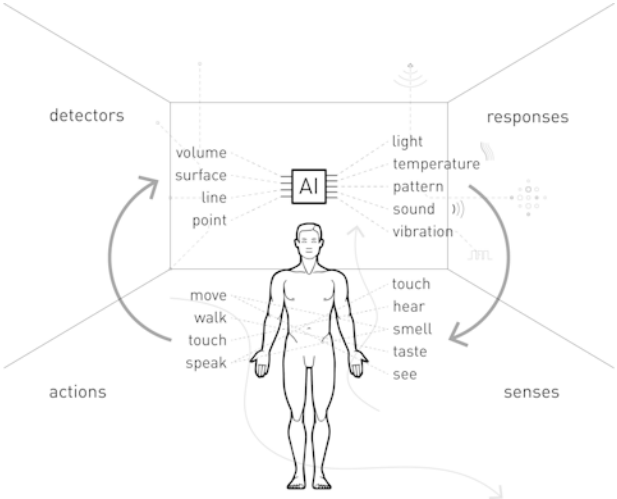


Figure 2. The HBC Model.

This model not only shows all these factors and their relationships but also organizes them as a continuous loop of chronological and sequential interactions. Most of the current propositions have focused on one unique moment of interaction, and have emphasized the building side of the loop–the building sensing and then responding. Our model shows the flow of interactions between both sides of the loop: a person acts, the building detects and responds, and then the person senses and acts again, as the loop starts over. This interaction flow becomes the means for communication and collaboration between two intelligent systems, the human and the building. The human can act on the building to provide solutions that could be complemented by the smart building system. For example, the human can touch the wall to tell the building where and how to increase the light of a room.

Finally, the model is a diagram to be used in design. We are demonstrating the whole range of human and building factors and their relationships in order to show all the options that designers can use for their designs. The model explains how humans could use the full range of their body capabilities for both, acting and sensing. Also, it shows how buildings could use any of their material elements, for both detecting and responding. Most of the current propositions have incorporated a limited set of human senses, mostly sight. They have also relied on an interaction mediated by smart devices (smartphones, wearables, touchscreens, IoTs). Through this model, we are proposing an unmediated way of achieving intelligent outcomes. Instead of using devices as a means of collaboration, the model shows how the actual buildings' elements can become the interface between the human and the machine.

4. Tools

While the model provides the guidelines to direct the design process, the tools translate the model into materials, practical examples, and techniques to be applied in hands-on design practice. These tools include an electronic toolkit and a set of representational techniques. Using these tools, designers can learn electronics, prototype working demos, research supporting technologies for their designs, and represent their designs as systems and sequential moments of interaction and collaboration.

The Toolkit corresponds to a set of electronic components and supporting technical exercises. The primary objective of this toolkit is to provide a palette of materials to be used by designers developing smart buildings. Using this toolkit, designers can comprehend the basics of analog and digital electronics and can prototype and explore initial HBC propositions.

We selected sensors and effectors according to the HBC model, with sensors that could detect a wide range of human actions; and effectors that could be sensed by humans using all their senses. These sensors and effectors are connected and controlled using microcontrollers (Arduino) programmed using the personal computer. The sensors include capacitance (touch), knock, switch, pressure, sonar (distance), accelerometer (movement). The effectors include vibration motor, buzzer (speaker), DC and servo motors, and LED strips. This toolkit also includes a set of *active materials* that can be used as inputs or outputs. The input materials include graphite-based (resistive) materials, steel grids, magnets, and organic (capacitive) materials. The output materials include photochromic and thermochromic paint, fiber-optics, and transducers.

Finally, the toolkit introduces technical examples from next-generation interfaces, namely tangible interfaces, ambient media, and shape displays (Ishii 2008). These applications go beyond the current Graphic User Interface (GUI) paradigm, showing research and solutions in the field of material, physical, and spatial HCI. In our toolkit, we use these HCI applications as technical references and investigate how to expand them into architectural HBC solutions.

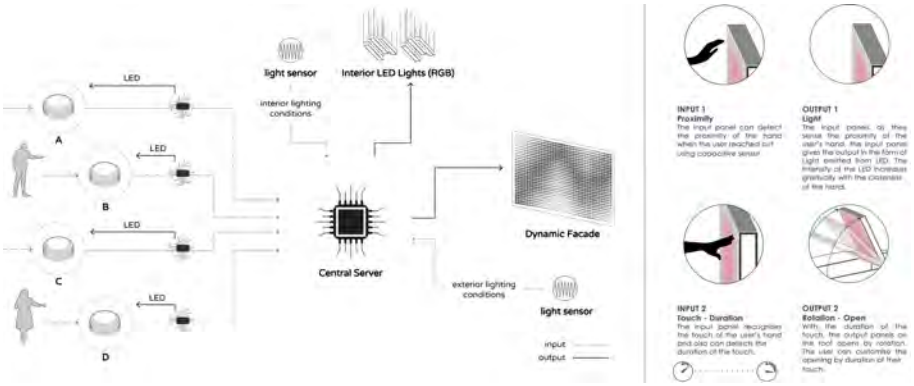


Figure 3. Information Architecture Diagram (Left) and Communication Map (Right).

The Representational Techniques constitute the medium for designers to represent, think, and develop their HBC designs visually. We adapted techniques from computer science and user-experience design (UX) and combined them with architectural 2D and 3D modeling and rendering. Our representational techniques include information architecture (IA) diagrams, communication maps, and experience-based storyboards.

The information architecture diagrams (Fig.3, Left) are network-graphs showing the different computational components, their relationship, and the flow of digital information. This visualization tool helps designers address complex computational systems, by focusing on the interactive components (inputs and outputs) and the role they play within the whole infrastructure. On the other hand, the communication maps (Fig.3, Right) are table-charts that describe the rules for interaction, connecting inputs and outputs. Using this tool, designers specify a *language*, i.e. a set of rules for explicit communication between the human and the building. This language helps designers map out the different human actions and how they trigger particular building responses, and vice-versa.

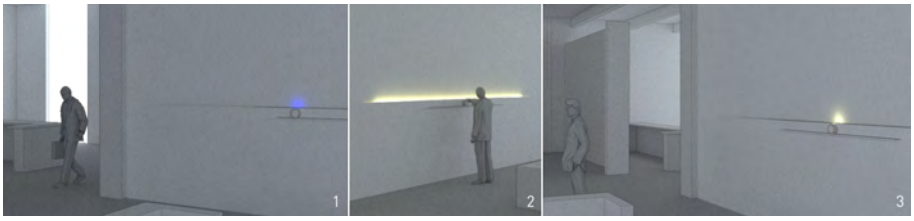


Figure 4. Experience-based Storyboards.

Finally, the experience-based storyboards (Fig.4) are 3D visualizations expressing the sequential experiential moments of a user interacting with a smart system. Each moment, or frame, can illustrate how the human collaborates with the building by acting on the building and sensing its response. Since the collaboration takes place in time and space, this visualization aids designers to explore how the sequence of human actions and building responses relate and unfold from moment to moment (Rosenberg 2015).

5. Design Application

We have conducted preliminary design exercises to put our framework into practice. Students were introduced to the model, background, and tools through a design process in an architectural studio environment at CASE. As in any design studio, we also facilitated their process and helped them explore specific HBC opportunities. We present the result of two projects, were students investigated different collaboration modes through tangible and spatial ways for people and building to interact with one another.

The First Project explores a cooperative way to optimize interior lighting. In this case, the collaboration is initiated by the human. The user tells the building *where* and *how* to adjust the light of the space. The AI senses interior and exterior light and combines natural and artificial light to reach the user goal. For the

mechanical output, the students used an adaptive facade system already developed at CASE (Krietemeyer et al. 2015).

This interface is comprised of a set of magnetic tokens attached to the building's surfaces or walls (Fig.5). The tokens are magnetic yet passive devices that do not need power, all sensors and computing capabilities are embedded in the building's surfaces (walls). There are multiple tokens in the space, which are tracked by the building in real-time. The users can place, move, and rotate these tokens to delimit specific areas for which they define their desired lighting conditions. By moving the tokens from left to right, the user can define the temperature of the light. By rotating the tokens the user can define the intensity of the light. While the user places and moves the tokens, the building computes interior and exterior light and adapts facade and lighting in response.

In this project, the *human intelligence* is about deciding lighting location (where) and lighting qualities (how). The *artificial intelligence* is about optimizing interior and exterior light, providing the required qualities for the specified locations. By optimizing energy, the building does not provide a predictable lighting result but suggests an approximation. The user can modify the tokens until a satisfactory result is produced. The building learns from the user actions, the user learns from the building responses. The lighting solution is co-created between the human and the building.

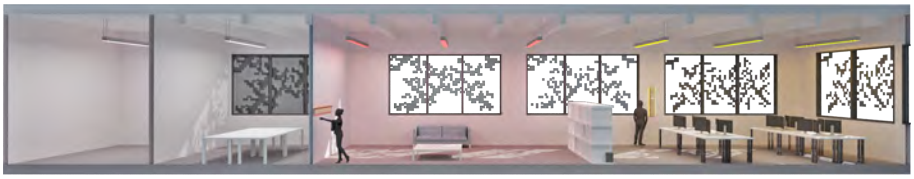


Figure 5. Tangible Walls for Lighting Co-optimization.

The Second Project explores a cooperative way to capture, purify, and reuse rainwater. In this case, the collaboration is initiated by the building. The building filters rainwater using green algae and then displays information inviting people to release this water for irrigation (Fig.6).

This interface is composed of a shape display facade connecting the roof of the building to a garden on the street level. On the roof, a pool collects rainwater and uses algae as a renewable purification method. Between roof and garden, the facade, made of transparent pipes, brings the water to the street level while displaying patterns and messages using digitally-controlled air bubbles. Through these messages, the smart building informs people about the state of purification and invites them to participate when the water is ready to use.

The facade then becomes a tangible interface that people can touch directly to activate the irrigation system. Using the water as a capacitive sensor, these pipes can sense human touch and can open and close to release filtered water in response. The channels between the tiles in the pavement system connect the water coming from the pipes to specific areas and plants in the garden.

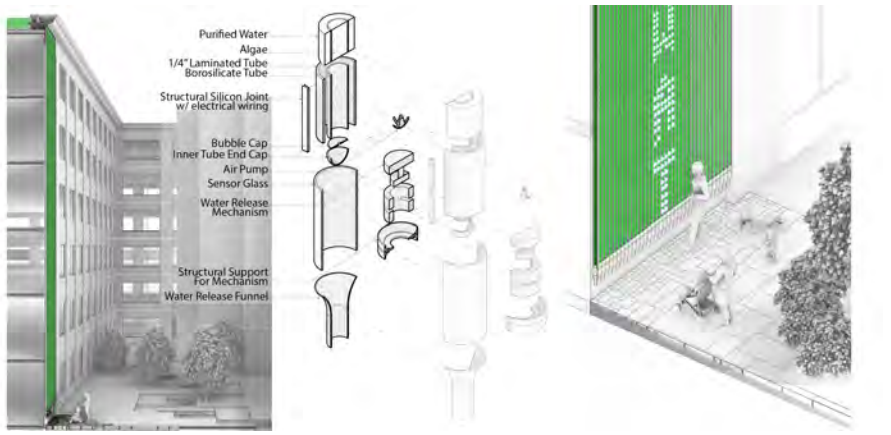


Figure 6. Shape Display Facade for Water Filtering and Irrigation.

In this project, the *artificial intelligence* is about cleaning the water and then communicating when the water is ready to use. The *human intelligence* is about deciding *when* and *where* to irrigate the garden. The user chooses a specific area for irrigation by touching the pipes that would direct the flow towards that selected area. After the user releases the pipes, the building suggests other areas for irrigation by opening untouched pipes. The user can accept or reject. A playful communication emerges between the user and the building. Ultimately, human and building have cleaned the water and irrigated the garden, *together*.

6. Conclusions

This paper introduced a new pedagogical framework for smart building design. The objective is to contribute to smart buildings development by expanding and diversifying the way humans and buildings have to interact and collaborate with one another. We have presented the framework's philosophy, model, and tools, and we have tested this framework through preliminary design exercises.

We have found that the framework helped students to envision and prototype smart building systems with interfaces that incorporate new means for human-building collaboration. They developed building systems that detect various types of human actions (walk, move, tap) and that respond through multiple sensory channels (see, hear, touch). These interfaces were embedded within the actual buildings' material elements, including walls, floors, facades, and ceilings/roofs. They applied these diverse interaction modes to foster collaborative intelligence, in which building and human worked together to (1) optimize lighting and (2) purify and reuse rainwater. Therefore, we conclude that through these projects, we are demonstrating how our framework can begin contributing to the development of next-generation smart buildings.

Regarding next steps, we have observed how these design applications defined different functionalities for human-building collaboration. For example, the functionality of the first project was optimizing environmental conditions and the second resource reuse. More functionalities could be explored and generalized

to help guide the HBC design process. Future research will also incorporate AI software into our pedagogical framework. Particularly, we will integrate machine learning algorithms as a means for the building to gain intelligence, as well as to grow and evolve the collaboration between the building and the human over time. Finally, some additional work will explore the boundaries between HCI and Architecture. Through HBC, we will explore and propose the appropriate scale, materiality, functionality, and interaction modalities for a spatial and material HCI integrated into architecture. Our goal is to identify modes of thought and practice that enable effective *collaborative intelligence* within our built environment.

Acknowledgments

This research was supported by Rensselaer Polytechnic Institute (RPI) and the Center for Architecture Science and Ecology (CASE). We acknowledge and thank the work of our students. The first project was developed by Daniel Polgreen, Mikaela Naval, and William Zaleskiewicz. The second project was developed by David Kitchen, Richard Markgraf, and Qinglan Luo. Luo.

References

Daugherty, P.R. and Wilson, H.J.: 2018, *Human + Machine: Reimagining Work in the Age of AI*, Harvard Business Review Press, Boston, MA.

Fox, M.: 2016, *Interactive Architecture: Adaptive World*, Princeton Architectural Press, New York, NY.

Ishii, H.: 2008, Tangible Bits: Beyond Pixels, *Proceedings of the Second International Conference on Tangible and Embedded Interaction*, Germany, 15-26.

Klooster, T.: 2009, *Smart Surfaces and Their Application in Architecture and Design*, Birkhäuser Architecture, Boston, MA.

Kolarevic, B. and Parlac, V.: 2015, *Building Dynamics: Exploring Architecture of Change*, Routledge, New York, NY.

Krietemeyer, B., Andow, B. and Dyson, A.: 2015, A Computational Design Framework Supporting Human Interaction with Environmentally-Responsive Building Envelopes, *International Journal of Architectural Computing*, **13**, 1-24.

Le, Q.V., Ranzato, M.A., Monga, R., Devin, M., Chen, K., Corrado, G.S., Dean, J. and Ng, A.Y.: 2012, Building High-Level Features Using Large Scale Unsupervised Learning, *Proceedings of the 29th International Conference on International Conference on Machine Learning*, USA, 507-514.

Licklider, J.C.R.: 1960, Man-Computer Symbiosis, *IRE Transactions on Human Factors in Electronics*, **1**, 4-11.

Lorenzo-Eiroa, P. and Sprecher, A.: 2013, *Architecture in Formation: On the Nature of Information in Digital Architecture*, Routledge, New York, NY.

Nembrini, J. and Lalanne, D.: 2017, Human-Building Interaction: When the Machine Becomes a Building, *Human-Computer Interaction - INTERACT 2017*, India, 348-369.

O'Sullivan, D. and Igoe, T.: 2004, *hysical Computing: Sensing and Controlling the Physical World with Computers*, Thomson, Boston, MA.

Rosenberg, D.: 2015, *Transformational Design: A Mindful Practice for Experience-Driven Design*, Ph.D. Thesis, Massachusetts Institute of Technology.

Sinopoli, J.M.: 2012, *Smart Buildings Systems for Architects, Owners and Builders*, Butterworth-Heinemann, Boston, MA.

AN URBAN FORM-FINDING PARAMETRIC MODEL BASED ON THE STUDY OF SPONTANEOUS URBAN TISSUES

MOHAMMED AQIL CHEDDADI[1], KENSUKE HOTTA[2] and YASUSHI IKEDA[3]
[1,2,3]*Keio University, Fujisawa, Japan*
[1,3]*{aqil|yasushi}@sfc.keio.ac.jp* [2]*hottakensuke@keio.jp*

Abstract. This research paper investigates the peculiarities of unplanned urban fabrics known for developing in a spontaneous way. By studying the characteristics of their urban form, a set of rules, functions, and objectives used for an experimental urban form-finding model are explored. Based on these features, the development of a parametric model seeks to grasp certain characteristics of spontaneous urban tissues in old Islamic cities and incorporate them into an experimental social housing proposal. By the use of genetic algorithms, the model aims to offer better adaptability and more diversification which will be to while still keeping a degree of preservation to the distinctive aspects that define those settlements. The use of a genetic solver is expected to be a problem-solving method that can simulate and offer a wide range of objective-based spatial that are considerably adaptive to particular urban contexts. In this study, we discuss the defining aspects and constituents of the urban form of these settings before interpreting them into algorithmic components to be incorporated in a parametric model.

Keywords. Spontaneous Urban tissues; Urban form-finding; Genetic algorithms; Islamic cities; Multiple-objective optimization.

1. INTRODUCTION

An urban fabric could be considered as being similar to a living organism that is made up of an aggregation of intertwined and consolidated spatial components: It finds its morphological expression in its spatial layout, road networks, the typology of buildings, and the relationship between its public and private spaces. This research finds its footing on the basis of observations of unplanned urban developments in old North African Islamic cities, namely in Morocco. In the case of Moroccan medinas (historic North African quarters enclosed by a wall), these spontaneous urban tissues are characterized by their adaptability and incremental evolution through time without the intervention of any formal urban design as it is known today. Even though Moroccan medinas such as the medina of Fez City is nowadays mostly constituted of old and saturated urban tissues, its space is a historic telltale of city growth that reflects a local social and cultural identity to north African settlements (Bianca, 2000). While at first glance, the medina

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 181-190. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

of Fez may seem as simply like a manifestation of a chaotic and disorganized development that echoes an apparently aimless labyrinth, but a set of fundamental principles of Islamic culture actually defines its space, consequently making it more representative of an organizational logic to which its urban space abides by. This is especially evident when considering that north African countries, which share mostly the same socio-cultural and environmental setting, and hence the same set of spatial organization principles, have an essentially similar urban morphology (O'Meara, 2007).

1.1. BACKGROUND

The spaces that are produced by different types of societies follow different types of organizational logic, which in turn lead to the creation of distinct spatial patterns (Hillier et al, 1984). This assertion is especially relevant in the case of spontaneous urban settings, which are composed of the incremental aggregation of physical elements in a scalable sense. Accordingly, the medina-type city is produced in an intuitive albeit procedural manner. Describing a Moroccan medina is no easy task considering its morphological dimension is deeply entangled with a set of fundamental political, religious and cultural guidelines, that define the logic of its space (Duarte et al, 2006). Indeed, This type of traditional urban fabric reflects a living style that is ordered around the spatial interpretation of Islam, and the adaptation to local environmental and social factors. Blocks can be described as being of irregular shapes yet very compact in nature; they are also open on the inside through the use of interior courtyards that play a double role of preserving privacy and moderating the environmental comfort inside buildings. In this way, the individual and collective elements that compose the city are carefully articulated around locations of key interests, of which places of worship or of political power play a prominent role. The aggregation of other vital quarters that contain places of commercial and craft activities is also given certain close attention. For example, according to sanitary concerns, there can be a requirement for a degree of disconnect between areas that harbor certain types of commercial or manufacturing activities (e.g tanneries) and places of worship (see Figure 1).



Figure 1. Typical organization of a medina-type city (Left); High-density courtyard morphology of the medina of Rabat (Right).

The seemingly labyrinthine urban morphology of Moroccan medinas is established with an organizational layout that is essentially characterized by bare, continuous walls (see Figure 2). This physical separation is in its turn defined by the basic element that is the housing unit, or "dar" in Arabic, which can be considered as being the fundamental unit or cell that in its aggregation defines the urban morphology. Coupled with a variety of other units such as alleys, neighborhood types of facilities etc. a diversification of shapes and functionality can be achieved. The interaction between these basic elements on a smaller scale is what allows for enough complexity for a larger scale urban coherence (Nikos, 2000).

1.2. STATE OF THE ART

In recent years, a number of researches discussed the subject of urban-form definition through the use of objective-based algorithms. One of the first projects to consider an urban form-finding model through an objective function algorithm is the Induction Cities project's "Sun God City" (Watanabe, 2002) where an algorithm generates a cityscape that is optimized for sun exposure. A later study established an urban shape grammar that encapsulates the street layout structure and the patio-type housing units of the medina of Marrakech (Duarte et al, 2006). While the outcome was to develop an algorithmic model for housing in Islamic contexts which synthesizes the medina's morphology, the focus was mostly on reproducing the said morphological structure rather than creating a model that interprets it for adapting to different conditions. Another study focusing on self-organized Architecture for housing (Ikeda et al., 2006) relied on the use of 3D cell-automaton to analyze and rearrange generated self-organized geometrical components. This form-finding methodology evaluates and optimizes the urban shape in the face of changing factors. It is also important to note recent research that focuses more on the methodology of genetic algorithms in the exploitation of objective fitness and the exploration of variation in urban form generation (Mekki et al., 2018) while taking into account a superblock of the ancient city of Fez as a base generic module for variations. While being part of this continuity of researches that approach the urban form question through genetic algorithms, our research takes the context for Moroccan traditional cities as its main focus. Thus, it explores context-specific characteristics to be incorporated into an adaptive methodology for the definition of the urban form.

1.3. PROPOSED APPROACH

Nowadays, cityscapes are often designed in a way that leaves little room for adaptability and diversification, though cities are still intrinsically a spatial expression of an evolving social complexity that manifests differently through time. Consequently, this research defines its main purpose as developing an approach for conceiving a city that can take into account dynamism and changeability. Indeed, one of the main features that can be observed when studying intuitive urban tissues is that they are highly adaptive to the evolution of social needs and environmental constraints. Such an approach, by offering a degree of flexibility, will allow users, to find, through a trial and error process, solutions

that address their issues by self-organizing and changing the usage typologies of the urban space. This process is done while always keeping in mind a number of social and functional directives that could be considered as flexible rules.

Although experimental, the use of self-organized models in architecture has thus far allowed for the development of rule-based forms that can allow for bottom-up design (Narahara, 2008). The application of such methods allows decentralization of the organizing system that favors the creation of spontaneously generated structures by way of feedback loops. This system can be especially fitting for our case, considering that our study is based on spontaneously developed urban tissues that have a tendency to build up from local interactions to form a global structure. Through the simulation, the algorithmic model should consequently show a suitable degree of responsivity in a dynamic setting. This capacity for the system to self-organize is described with three typical features.

- Adaptability; it reflects the ability of the system to be resilient in the face of both context-specific constraints and dynamic change. This proves the system strength as it allows to achieve the objectives in a variety of conditions.
- Flexibility; it expresses an intrinsic allowance for transformation which grants the system enough stability against complex constraints.
- Diversification; it indicates the capacity of the system to offer substantial variation in its spatial solutions. This capacity can not only increase the other characteristics but also ensure that there is enough interactivity between components of the system on a lower level to allow for the objectives to be attained on the whole.

1.4. RENDITION AND USE

On the basis of all of the above, the simulation will adopt a construction method that allows for diversification through standardized components. This can be achieved with the use of prefabricated modules that can be arranged in different possible combinations to form a variety of urban entities, thus aiming to create diversity through different forms of aggregation of the same basic unit (cf. cell and tissue). By being the smallest component of the system, those modules will be an interpretation of the dar, that when assembled together show a capacity for the system to adapt through bottom-upping. As for the plot definition method, it will have to allow for urban geometries with patterns that reinterpret the contiguous configuration of the medinas.

However, in order to refute any arbitrariness, it is necessary to evaluate the system behavior to assess the solutions adaptability. Accordingly, for our case, the use of an algorithm that applies a multi-agent genetic solver is deemed relevant to simulate an urban form-finding model for high-density, module-based housing.

2. THE EXPERIMENT

2.1. CASE STUDY

The use of genetic algorithms has shown itself to be a promising way to solve constraints related to social housing layouts (Aksoy et al., 2014). For this research

to be practical, the model was applied to a case scenario of social housing which provides a set of specific social, environmental and spatial constraints to be taken into account. This case takes place in the slum known as "Douar Al Garaa" in Rabat, Morocco. The reason for choosing this specific site is threefold. First, the slum is well integrated into its surrounding urban fabric that is comprised of the "Habitat Marocain" type of housing (Navez-Bouchanine, 2000), which is a modern economic housing typology. Second, by observing the spatial morphology of slums in Morocco, parallels can be drawn between its urban morphology (see Figure 2) and that of traditional medinas; although it was initially planned in a modern way, the organic nature by which urban growth is achieved in a spontaneous way, as well as the high density and intricacy that result from the incremental nature of its buildings, are some of the key points of analogy. Finally, strong demand for an on-site rehousing solution has been expressed by the inhabitants; in this way making it a fitting scenario for our experiment (Cheddadi, 2018).



Figure 2. Street in Douar Al Garaa (Left); Bare-walled street in the medina of Marrakech (Right).

2.2. SPECIFIC CONSTRAINTS AND PROSPECTS

For this case study, the solutions would have to guarantee a minimum degree of spatial comfort when compared to the surrounding urban fabric (cf. Habitat Marocain). Compared to the current situation, the improvements that this model aims to offer consist of a better ratio of public space per inhabitant, better accessibility for emergencies, both of which can be created by having a better-defined plot subdivision; an urban morphology that offers enough room for scalability since by relying on a modular and heterogeneously shaped construction approach; and also an improved environmental condition by equalization of sun exposure per housing unit.

Achieving these objectives supposes that some of the current characteristics of the site would have to be changed and others kept. The features that are kept include the locations of neighborhood equipment are landmarks for the population and also play an important role in social cohesion (i.e Mosques, public baths, water fountains etc.). Offering to house all the inhabitants also means that it will be

necessary to keep a least the same population density per surface area while also reaching for higher construction heights. However, street and plot subdivision will be changed in order to allow the algorithm enough flexibility to vary the output, as it is also an element of experimentation.

2.3. THE TOOLS

The simulation algorithm was developed with the use of Rhinoceros 3D (Rhino) and its visual parametric plugin Grasshopper (GH). Rhino was used for the CAD data whereas GH was used to establish the algorithmic workflow for the form-finding simulation by way of using a number of add-ons. The form-finding algorithm was carried out by the use of Octopus, the multi-objective solver add-on for GH, the environmental data (sun vectors) was incorporated by using the Ladybug add-on. On the basis of multiple-objectives evaluation functions, Octopus carries out an optimization algorithm that looks for the best combination of inputs to generate a best-fitting geometry (phenotype) and establishes a Pareto ranking.

2.4. SIMULATION METHOD

On the basis of the previously mentioned points, the parametric design algorithm is set to develop a self-organized model based on a number of factors including exposure to sunlight, physical accessibility, the number of floors, the urban population density and the randomness factor.

A number of GH components, which will be described in the workflow, are established as genes and coupled together with objective functions in order for Octopus to operate. The genes that are input include the random reduction seeds, the random 2D point population for plot subdivision, an integer range for plot subdivisions. As for the fixed input in the algorithm, which includes: the maximum building heights, the weather data; An integer range of population density; an integer number of fixed 2D population for plot subdivisions.

2.5. WORKFLOW OF THE ALGORITHM

Based on the aforementioned input, the GH model definition connects a number of components. We can divide these components into the following categories:

2.5.1. Plot subdivision

To subdivide the site into smaller plots, the algorithm takes its geometry as a reference before populating it with 2D points. A certain number of points are fixed as to refer to on-site neighborhood types of equipment, the rest of the points are randomly populated with a maximum cap. To ensure an organic shape, a Voronoi GH component is used to divide the plot, coupled with a surface offset that creates width for the streets (see Figure 3).

2.5.2. Grid definition

A 2D grid is mapped into the plot surfaces, its dimensions can be modified to suit different scenarios. Then, the 2D grid is coupled as an input with a height component in Z-direction that converts it to a 3D component. These represent the dimensions of prefabricated modules that are used for construction (see Figure 3).

2.5.3. Density definition

The 3D grid is connected to a Random Reduce component that deduces modules from it. It runs on two variable types of input: The rate of reduction which is the percentage of boxes to be reduced; A random seed that generates a number of user-set random factors for the random reduce component. For defining the density, two factors are taken into account. The first is the number of floors and the second is the reduction factor. The latter is relative to each floor and is not a global factor (see Figure 3).

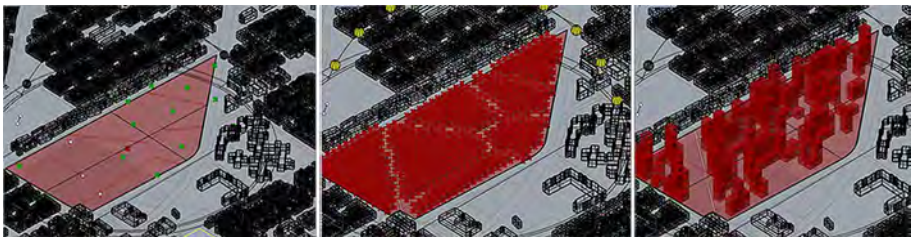


Figure 3. From left to right: Plot subdivision; Grid definition; Density definition.

2.5.4. Sun vectors definition

For defining the sun exposure (SE) data, the "Ladybug" environmental plugin within GH was used. The geographic weather profile for Rabat city is loaded into the GH definition in order to represent, depending on the scenarios, the sun vectors and sun path for the winter or the summer solstice.

2.5.5. Meshing and Color Mapping

To visualize SE, the resulting modules are merged and put together with a Mesh Union component (see Figure 4). The resulting meshes are then color-mapped by using a gradient component that visualizes SE by representing the exposure on any module surface throughout the day. The color gradient expresses values in a linear way by going from 1 to 10 hours of daily exposure.

2.5.6. Solver and fitness objectives

On the basis of two objective fitness functions that seek to maximize SE and accessibility (see Figure 4), in addition to its built-in diversification function, Octopus evaluates each phenotype of 3D geometry in order to seek better fitness. For this simulation, Octopus is set to a maximum of 50 generations with a population of 50 with the history option turned on.

The first fitness objective aims for better accessibility, its objective function calculates the distance between each module and the nearest street (shorter distance is better), thus evaluating the physical accessibility of each module and favoring the creation of open interior spaces. As for the SE objective function, it is set to reward the algorithm if the optimization results are equalized in a range that goes from 3 to 6 hours of sun exposure.

In order to check the reliability of the design algorithm, different scenarios (see Figure 5) were run to assess it in changeable conditions. These scenarios include different sets of density, different maximum heights and unit volumes (5x5 and 7x7 grid) and different plot numbers.

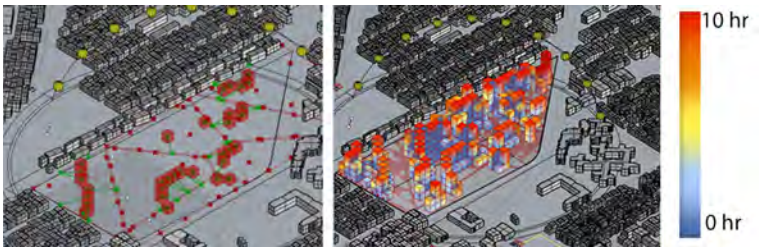


Figure 4. Accessibility fitness (Left); Meshing and Color Mapping (Right).

2.6. FINDINGS AND DISCUSSION

Inspection of the generation data of the Pareto front for the scenarios results (see Figure 5) indicates that the genetic solver has shown an overall potential for optimizing the urban form. As seen in the different scenarios, the generation number by which the solver reaches a stable Pareto front varies from situation to another. Judging by the nature of the genetic solver and the initial random condition by which the fitness landscape is explored, this could be considered as typical.

As was expected, higher SE scores are observed during summer, especially with a 5x5 grid. This might be due to the more intricate nature of a form generated by smaller volumes. Under similar settings, the results of simulations in which there were no fixed Voronoi points show better scores than those that do. this would suggest that more Voronoi points be dispatched by the algorithm, and subsequently, more subdivisions could be factored into having better SE and accessibility results. For the SE distribution, it seems that the result is close to expectations with a distribution approaching the bell curve in the most SE optimized phenotypes when compared with baseline results outside the Pareto front.

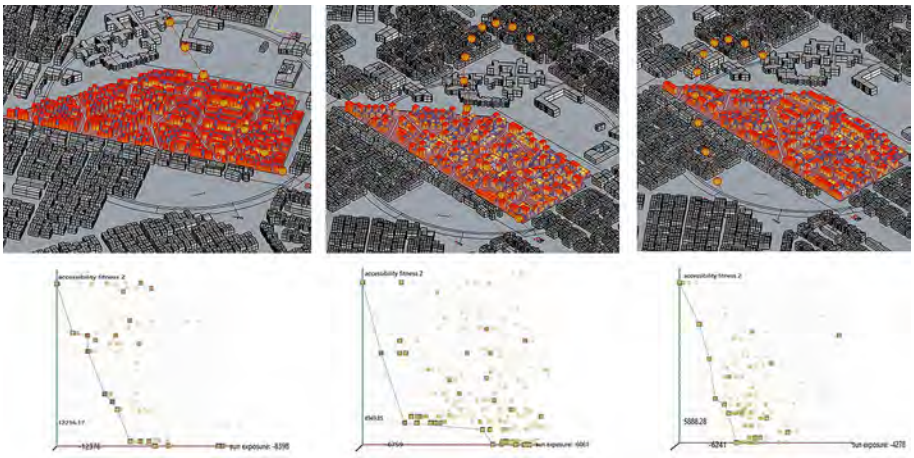


Figure 5. Examples of dominant phenotypes from three scenarios (Top); Pareto fronts corresponding to the scenarios (Bottom).

Analysis of the data shows that the algorithm is capable of sacrificing the global SE score for a better SE equalization result. As for the accessibility, in some cases, the algorithm might score better because there are simply fewer modules to take into account. In order to fix this issue, it would be more interesting to consider using an average score by the number of modules instead. The model has also shown a capability for resilience by withstanding unexpected changes in the results, a number of most optimized accessibility phenotypes in the earlier generations show up as empty surfaces where a Voronoi surface was not established. Although this could be considered as a limitation, Octopus has shown that it can recognize it as a non-viable solution on the Pareto front in later generations.

Overall, current results show that there is a certain lack of balance between exploration and exploitation of solutions. Indeed, the algorithm quickly favors the exploitation of better objectively fit results rather than more design variations, thus rapidly reaching its end results. This presents a certain challenge in the problem definition of the objective function in which a certain balance between exploration and exploitation should be aimed for. Although the methodology by which the simulation was approached does not necessarily reach a target solution as it continues to generate new, better-fitting phenotypes. it does show that there is potential in researching a high-density, self-organized model if the objectives of the algorithm and the variables are better defined and evaluated.

3. CONCLUSION

The use of an evolutionary problem-solving as a methodology in architecture and urban design became more prevalent in recent years. The present study follows on from these works and while not pretending to be completely groundbreaking, it finds its originality in contextualizing the problem-solving process with a cultural background study and a concrete footing in social issues. Through this experiment, contextualizing the issue meant that it was relevant to make a model inspired by

the traditional Islamic tissues, in all their intricacy and apparent randomness, while still taking into account the characteristics of modern economic Moroccan housing. Approaching the solution through a genetic solver in the form of a self-organized simulation has shown to have the advantage of offering enough adaptability and exploring a diversity of urban forms that break from the architectural redundancy of social housing. Potentially speaking, the use of modules can be a step towards achieving a balance between parametric diversity and mass production.

To better refine results, this experiment shows that further optimizations of the algorithm and studies of its behaviors under different constraints are necessary. Understanding how the algorithm works can allow for the integration of other environmental objectives such as airflow or heat island effect, thus making it more broadly adaptable. In the end, the study of self-organized architecture is more about the system-design of resilient and adaptive algorithms than it is about formulating a planning methodology.

One of the shortcomings of this research is not being able to fully take into account more of the social benefit factor of this approach, and not being able to measure it. Keeping social cohesion after rehousing the slums is what could be considered the most important factor to be taken into account besides the political ones. In future iterations of this model, we should look into methods that can keep local neighborhoods well-articulated and organized even after redefining structural subdivision factors such as the streets layout or facilities locations. In later iterations of the model, better defining the algorithm objectives also means to maximize social interactions through the connection between private and public space, while still keeping a certain degree of privacy that defines the principles of Islamic housing.

References

Aksoy, Y. and Cağdaş, G.: 2014, A Model for Sustainable Site Layout Design with Pareto Genetic Algorithm: SSPM, *Proceedings of eCAADe 2014*, Newcastle upon Tyne, 227-238.

Bianca, S.: 2000, *Urban Form in the Arab World - Past and Present.*, vdf, zurich.

Cheddadi, M.A.: 2018, *Towards a Digital Design Approach For Rehousing Slums: The Case Of Douar Al Garaa in Morocco*, Master's Thesis, Graduate school of Media and Governance, Keio University, Tokyo.

Duarte, J.P.: 2006, An Urban Grammar For The Medina Of Marrakech, *Design Computing and Cognition '06*, 483-502.

Ikeda, Y.: 2006, A study on construction method for self-organized architecture, *International Journal for Housing Science and Its Applications.*, **30**(4), p. 257-266 .

Makki, M. and Showkatbakhsh, M.: 2018, Control Of Morphological Variation Through Population Based Fitness Criteria, *Proceedings of CAADRIA 2018*, Beijing, 153-162.

Narahara, T.: 2008, New Methodologies in Architectural Design inspired by Self-Organization, *Proceedings of ACADIA*, University of Minnesota, 324-331.

Navez-Bouchanine, F. 2003, Urban Slums Reports The case of Rabat - Salé, Morocco, *in* D.P.U. University College London (ed.), *UNDERSTANDING SLUMS: Case Studies for the Global Report on Human Settlements*, UN-Habitat.

Nikos, A.S.: 2000, Complexity and Urban Coherence, *Journal of Urban Design*, **5**(3), 291-316.

O'Meara, S.: 2007, *Space and Muslim Urban Life: At the Limits of the Labyrinth of Fez*, Routledge, London; New York.

Watanabe, M.S.: 2002, *Induction Design: A Method for Evolutionary Design*, Birkhauser .

BIM-BASED LIVE SENSOR DATA VISUALIZATION USING VIRTUAL REALITY FOR MONITORING INDOOR CONDITIONS

WORAWAN NATEPHRA[1] and ALI MOTAMEDI[2]
[1]*Department of Architecture, Faculty of Architecture Urban Design and Creative Arts, Mahasarakham University, Mahasarakham, Thailand*
[1]*worawan.ne@msu.ac.th*
[2]*Department of Construction Engineering, École de technologie supérieure, Montreal, Quebec, Canada*
[2]*ali.motamedi@etsmtl.ca*

Abstract. This paper proposes a method for an automated live sensor data visualization of building indoor environment conditions using a VR system. The proposed method is based on the integration of environmental sensors, BIM, and VR technology. Such integration provides an opportunity to utilize an immersive and live sensing technology for improving data visualization. In our case study, the environmental data, such as indoor air temperature, humidity, and light level are captured by sensors connected to Arduino microcontrollers. The data output of sensors obtained from Arduino units are stored onto the BIM model and transferred to the developed VR system. The developed system simultaneously visualizes numerical values of sensors' reading together with the virtual model of the building in a VR headset. The result of the case study showed that the developed system is capable of visualizing various indoor environmental information of the building with the VR technology. It can provide users with useful information to help monitoring indoor thermal comfort conditions of the building in real-time, while performing the walkthrough in the virtual environment.

Keywords. Building Information Modeling (BIM); environmental sensor; thermal comfort; Virtual Reality (VR); Arduino; IoT.

1. Introduction

Environmental sensors have been widely used to monitor indoor comfort parameters, such as air temperature, humidity, and light level. They are used for the purpose of providing real-time feedback for occupants regarding their current comfort-related parameters. Using an efficient data visualization method for sensor data is important as it helps users understand and work with the data faster and easier (Richter, 2009). Traditionally, 2D data visualization techniques (e.g., charts, graphs, bar graphs, scatter plots, and maps) are utilized to help understanding and interpreting the meaning of the captured data. Although such

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 191-200. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

static visualizations provide users with tools to extract meanings from data more effectively, they have significant limitations. For example, such visualizations can only present certain data types and they are inefficient in presenting the real-time sensor data, such as air temperature, indoor air quality, and wind velocity that is needed for making quick decisions and actions to solve problems. With the growing size of datasets and the complexity of existing data, static information visualization methods become less helpful and such method needs to be improved (Kim et al., 2017; Olshannikova et al., 2015). In addition, interactive tasks cannot be done using static visualizations (Kim et al., 2017).

Recently, various new visualization methods have been developed to enable faster representation of data and to provide interaction. For example, Sicat et al. (2018) developed DXR, a toolkit for building immersive data visualizations. Pre-defined visualizations, such as scatter plots, bar charts, and flow visualizations were connected through filtering and linking. This system enabled users to make their data engaging and insightful in immersive environments. Kim et al. (2017) proposed VisAR system that integrated interactivity to static data visualization using Augmented Reality (AR). Hosokawa et al. (2016) developed a system for visualizing air flow rate of air-conditioner using virtual reality (VR). In addition, efforts to develop methods to improve data visualization have been proposed to support decisions throughout the building life cycle. For example, Natephra et al. (2017) developed a method to integrate Building Information Modeling (BIM), thermal images, and environment sensors to visualize thermal information of building surfaces and support indoor thermal comfort assessment. Motamedi et al. (2014) investigated a knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in facilities management (FM). This study proposed a method to integrate BIM visualization capabilities and sensors to support FM technicians with visualizations that allow them to utilize their cognitive and perceptual reasoning for problem-solving. Based on the previous studies, data preparation stage is required before incorporating with virtual environment. They also lack a capability to integrate real-time data with immersive environments.

On the other hand, real-time sensor readings and enhance data analysis are being increasingly used. Similarly, the Internet of Things (IoT) has been applied in various platforms to enhance the quality of life (Chang et al., 2018), such as air quality, living comfort, work productivity, and traffic control. Vaccari (2015) stated that IoT enables data from network-connected devices to be delivered and transformed into other types of information to be included in virtual simulation.

A large amount of effort has been proposed methods for integrating IoT and BIM to facilitate in various processes in architecture, engineering, and construction and facilities management (AEC/FM) industry. However, previous research on the integration of BIM and IoT is limited and it is mainly focused on the automation of the transfer of sensor information to BIM models (Chang et al., 2018). BIM refers to a digital transformation of information throughout the building lifecycle (Eastman et al., 2008). The integration of BIM and real-time sensor readings, such as environmental condition of workers, can be considered as state of art that can provide further benefits to the operation management (Teizer et al., 2017). Although the integration of BIM and sensor data has the potential for

assessing indoor thermal condition, the lack of real-time connections between live sensor information, BIM, and other building-related information sources prevents such assessment. This also prevents effectively analyzing indoor conditions, due to the difficulty in comprehending the correlation between time and changes of indoor condition.

The above-mentioned research gaps encourage investigating a BIM-based live sensor data visualization method that utilizes a non-static visualization technology such as VR for indoor comfort condition monitoring. The immersive experience offered by VR can be used for monitoring and visualizing real-time data of IoT sensors (Eastman et al., 2008). However, there is no research to date that investigates the integration of IoT, BIM and VR visualization for monitoring indoor environment.

This paper presents a framework for integrating BIM geometry information and environmental sensor data to create a live sensor data visualization in a serious game environment. The proposed method defines a system which uses an immersive and interactive VR environment for visualizing indoor comfort parameters. Arduino environmental sensors (e.g., temperature, humidity, light sensors) are used to capture real-time values for related comfort parameters. The sensor data obtained from Arduino units are stored in the BIM file using visual programming environment provided by the authoring software. The data is simultaneously transferred to the virtual environment using the Application Programming Interface (API) of the game engine. The developed dashboard is a tool to provide user with a real-time display of the sensors' readings in the VR environment as the user navigate in the BIM environment. Tools such as Autodesk Revit, Unreal Engine, and its scripting environment were used in our proposed system. The applicability of the proposed method is verified in a real-world case study.

2. Proposed methodology

The BIM-based live sensor data visualization is an integrated framework, which uses a BIM model, sensor data, and VR environment for monitoring indoor conditions. The proposed system helps identifying issues and examine different variables that influence indoor comfort for occupants. The proposed system visualizes the measured values of environmental conditions to provide an initial assessment of parameters related to comfort. It creates a user experience of being in an immersive computer-generated environment that is fed by real-time sensing data gathered through a seamless connection between the systems and the sensors. The proposed methodology comprises three main steps (as shown in Figure 1). The first step is to capture different environmental variables that influence on indoor comfort (e.g., air temperature, humidity level, and light intensity level) utilizing IoT sensors connected to a controller. Sensor readings are then transmitted by the controller to the BIM server and are stored in the model. In this step, BIM model is enriched by live environment data. Geometry information together with sensor data are transferred to the serious game environment (e.g., a game engine) using its Application Programming Interface (API). The visualization of the geometry and sensor data then be performed through VR headsets.

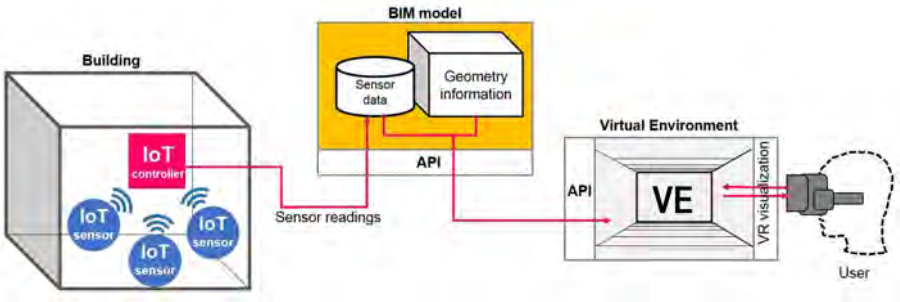


Figure 1. Overview of the proposed framework.

3. Prototype system

The developed prototype system follows the process flowchart shown in Figure 2. The process consists of five main steps. The first step is to create the BIM model and to collect environmental data. In this step, a BIM model of an existing building, which includes geometry information (e.g., walls, ceiling, floors, boundaries of rooms) is created using a BIM authoring software. Autodesk Revit (Version 2017) has been used in our prototype implementation. Environmental data (e.g., indoor air temperature, relative humidity, and light intensity level) is also captured using environmental sensors compatible with Arduino microcontrollers (Figure 2a). The sensors readings are linked to BIM objects and are stored in the BIM model using software tools developed by visual programming (e.g., Dynamo). Consequently, the BIM model is enriched by the environment data (Figure 2b). The third step is to transfer BIM data (e.g., geometry information and sensor data) to the game engine (Figure 2c). For transferring the geometry, a static mesh is generated after transferring FBX files from Revit to Autodesk 3ds Max. Unreal Engine is used as the game authoring environment in our prototype implementation.

In this step, sensor data is also linked to the game environment using visual scripting feature of Unreal Engine. The sensors data is constantly updated using the developed tool to maintain the live stream of data. In the fourth step, the sensor data and the geometry are visualized in the VR environment. For that, a user interface is developed to simultaneously display sensor data and to support interactions with users (Figure 2d). The BIM model with its geometry and information together with real-time numerical values of sensor data are displayed in VR environment. The created virtual environment allows users to perform walkthrough in a building. The user utilizes the immersive visualization provided in the fourth step to monitor the condition in real-time and to identify the indoor comfort level (Figure 2e). The user can also quantitatively analyze the environmental condition by viewing the sensor readings and calculated parameters in the virtual environment.

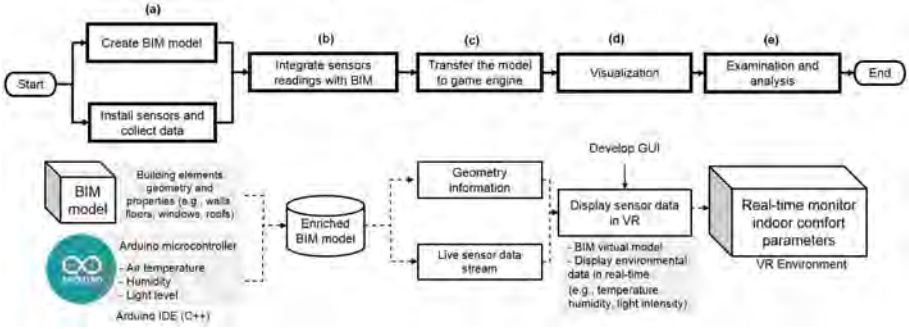


Figure 2. Process flow for integrating IoT sensors and BIM with VR.

The user interface is consisted of three main components that are available on the display screen: (a) First-person player view to give users a first-person perspective when they are moving in the virtual space; (b) Sensor data dashboard to show numerical values of air temperature, relative humidity level, and light level; (c) Minimap to aid users orienting themselves within the virtual model. Figure 3 shows the GUI interface of our developed system.



Figure 3. Screenshot of the main interface of the prototype system.

4. Case study

An apartment on the 7th floor of an existing residential building at Mahasarakham University, Thailand was chosen as an experimentation area. The apartment has two bedrooms with shared living and kitchen area, as shown in Figure 4. The environmental data was captured in the winter (November) from 9 a.m. to 6 p.m.

4.1. BIM MODELING AND INSTALLATION OF ENVIRONMENTAL SENSORS

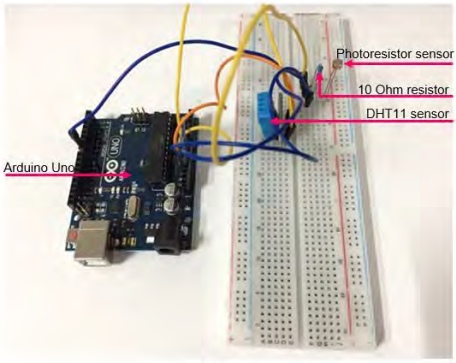
The BIM model of the case study was created using Autodesk Revit Architecture 2017 (Figures 4a and 4b). The placement of environmental sensors is shown in Figure 4b. The placement height of sensors was 1.20m from the floor. Indoor air temperature and the percentage of relative humidity were captured using Arduino compatible sensors (i.e., DHT 11). Temperature range of sensor is from 0 to 50 °C, with ±2°C accuracy. Humidity range of the sensor is 20-90% RH, with ±5% RH accuracy. Photoresistor sensors are used to measure light level in the room. Sensors were set to collect data with time intervals of 1 second.



Figure 4. Experimentation room.

Environmental-sensors are DHT11 sensor modules, which were connected to Arduino Uno microprocessors (Figure 5a). Arduino Integrated Development Environment (IDE) was used for programming the physical board. DHTLib library was installed to measure humidity and temperature readings. In this experiment, pin signal of the sensor was connected to a digital port of the Arduino board to read data output from the sensor. To measure ambient light, photoresistor sensor modules are installed on Arduino boards. Analog pin A0 was used to read value of lighting level.

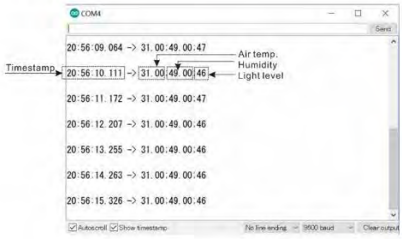
Once the developed code is uploaded to Arduino boards, sensors start to capture readings. The setup code to run sensors and measure the specified comfort parameters is showed in Figure 5b. The outputs of temperature, humidity, and light intensity level readings were in Celsius (C), percentage (%) and Lux (lx), respectively. Figure 5c shows serial monitor reading of sensors.



(a) Arduino setup

```
int chk = DHT.read11(DHT11_PIN);
float temperature, humidity, light;
//getTemperature, Humidity (&temperature, &humidity);
//Serial.print("Temperature = ");
Serial.println ();
Serial.print(DHT.temperature);
Serial.print(";");
//Serial.print("Humidity = ");
Serial.print(DHT.humidity);
Serial.print(";");
Serial.println(int(Light(analogRead(0))));
```

(b) Processing code



(c) Screenshot of serial monitor readings

Figure 5. Circuit board setup, processing code, and sensor reading outputs.

4.2. SENSOR READING, BIM, AND GAME ENGINE INTEGRATION

The workflow of transferring sensor reading to BIM is shown in Figure 6. First, DHT11 and photoresistor sensors were installed on Arduino board (Figure 6a). After uploading the developed coded to the board, air temperature, humidity, and light intensity level were captured and the outputs of sensor data were displayed on serial monitor console (Figure 6b). In order to store sensor readings from Arduino Uno to BIM, Firefly plugin provided in Dynamo (a BIM visual programming) was used (Figures 6c and 6d). To link Arduino sensor outputs with Unreal Engine, UE4Duino2 was used (Figure 6e). This plugin helps Unreal Engine to directly retrieve data from Arduino. Consequently, live data visualization using VR in Unreal Engine can be performed (Figure 6f). Figure 7 shows the visual scripting that enable Unreal Engine to receive sensor readings from Arduino.

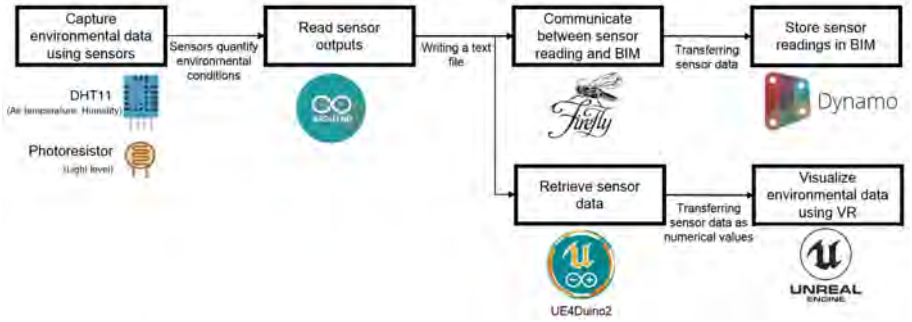


Figure 6. Sensor readings transfer to BIM.



Figure 7. An example of visual scripting to communicate with Arduino (Blueprint).

4.3. STORING DATA IN BIM AND DATA VISUALIZATION IN VR

To store sensor data in BIM, readings were retrieved using Firefly visual programming. Figure 8 shows sensor readings in Dynamo. Sensor readings along with their timestamp were saved as text file (Figure 9a), which can be used for tracking operation history for further indoor condition analytics. Figure 9b shows an example of the environmental data output visualization using the developed system. Numerical values obtained from sensors are displayed on the scene. A user can visually monitor the value of comfort parameters in real-time while navigating the VR environment. Monitoring the comfort parameters in real-time provides users with indoor conditions while having an immerse virtual experience of navigating in the building.

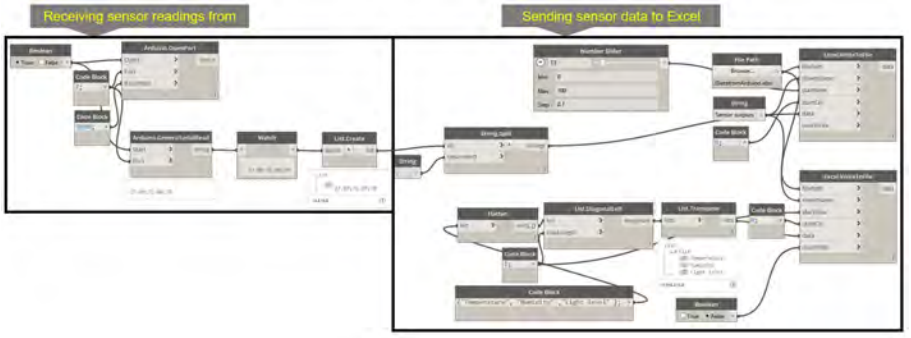


Figure 8. Screenshot of visual script for connecting sensor reading to BIM.

	Temperature	Humidity	Light level
2	27.00	72	79
3	27.00	72	81
4	27.00	72	80
5	27.00	72	79
6	27.00	72	77
7	27.00	72	81
8	27.00	72	79

(a) Transferring sensor data from BIM to store in Excel



(b) Data visualization in VR

Figure 9. Example of sensor outputs.

5. Results and discussion

There are limitations and challenges in using BIM-based live sensor data visualization using VR for monitoring indoor comfort parameters.

- Although the developed system provides an ability to connect sensor with BIM and VR, and enables the user to examine air temperature, humidity, and light level through an HMD, only digital numerical values can be visualized. In order to help users easily understand comfort conditions, presenting sensor readings in virtual charts and graphs in VR should be developed.
- In our case study, although visual programming tool of a BIM authoring software (i.e., Dynamo) and its plug in (i.e., Firefly) were successfully used to retrieve sensor readings from Arduino, a full integration of sensor data and BIM to directly store sensor data in BIM should be developed.
- The proposed system enables storing comfort parameters in .xlsx file. However, storing such data using IFC resources to support BIM data exchange is desirable.
- The analysis of the thermal comfort condition of the building is limited only temperature and humidity through digital values retrieve from the sensors. Air-flow rate and mean radiant temperature can also be integrated with our developed system.

6. Conclusions and future works

This paper presented a method for creating a BIM-based live sensor data visualization using VR for real-time monitoring of indoor comfort of an existing building. The advantages of integrating BIM, sensor data, and VR for operation and maintenance included providing the opportunity to support and track indoor conditions in real-time, proactive management of indoor environment, better monitoring and storing of sensing data, and identifying the measured parameters that could affect indoor comfort conditions. By utilizing VR, users were enabled to visualize and monitor the current condition of the room and detect possible issues in real-time. The VR headset is used in this study for maximum immersion, however, the developed application supports non-immersive VR visualizations, such as on a computer screen.The proposed method has been verified in an apartment building in a campus. Air temperature and humidity were captured by DTH11 sensor and a photoresistor sensor was used to measure light intensity level.

Arduino Uno was used to read sensor outputs. In order to transfer sensor readings to BIM and a game engine, tools such as Firefly for Dynamo and UEDuino2 for Unreal Engine were used. Our initial results revealed that the sensor data from Arduino can be successfully transferred to BIM and sensor readings were also successfully integrated with the VR environment. In order to better understand the actual characteristics of the space, which influences the indoor condition, integrating an interactive sensor data visualization with Augmented Reality (AR) can be also explored. Some challenges must be addressed in our future works, such as developing a method to store environmental sensor reading to IFC file, and developing a direct integration between sensor reading and BIM for assessing thermal comfort based on ASHRAE standard. We also intend to investigate a method to integrate other sensors, such as infrared sensors, air flow sensors, and air quality sensors with our system to support an automatic assessment of indoor thermal comfort. Integrating noise sensors in our system can facilitate the assessment of acoustic comfort by visualizing noise level data.

References

Chang, K.M., Dzeng, R.J. and Wu, Y.J.: 2018, An automated IoT visualization BIM platform for decision support in facilities management, *Applied Sciences*, **8**, 1086.

Eastman, C., Teicholz, P., Rafael, S. and Liston, K.: 2008, *BIM Handbook*, John Wiley & Sons, Inc., New Jersey.

Hosokawa, M., Fukuda, T., Yabuki, N., Michikawa, T. and Motamedi, A.: 2016, Integrating CFD and VR for indoor thermal environment design feedback, *Proceeding of the 21st CAADRIA 2016*, Hong Kong.

Kim, T., Saket, B., Endert, A. and MacIntyre, B.: 2017, VisAR: Bringing Interactivity to Static Data Visualizations through Augmented Reality, *arXiv:1708.01377*.

Motamedi, A., Hammad, A. and Asen, Y.: 2014, Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management, *Automation in Construction*, **43**, 73–83.

Natephra, W., Motamedi, A., Yabuki, N. and Fukuda, T.: 2017, Integrating 4D thermal information with BIM for building envelope thermal performance analysis and thermal comfort evaluation in naturally ventilated environments, *Building and Environment*, **124**, 194–208.

Olshannikova, E., Ometov, A., Koucheryavy, Y. and Olsson, T.: 2015, Visualizing Big Data with augmented and virtual reality: challenges and research agenda, *Journal of Big Data*, **2(1)**, 1–27.

Richter, C.: 2009, Visualizing Sensor Data, *Media Informatics Advanced Seminar on Information Visualization*, Munich.

Sicat, R., Li, J., Choi, J. Y., Cordeil, M., Jeong, W. K., Bach, B. and Pfister, H.: 2018, DXR: A Toolkit for Building Immersive Data Visualizations, *IEEE Transactions on Visualization and Computer Graphics, (c)*.

Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Propach, M., Neges, M. and König, M.: 2017, Internet of Things (IoT) for integrating environmental and localization data in Building Information Modeling (BIM), *Proceeding of the 34th ISARC 2017*, 603–609.

Vaccari, A.: 2015, How Virtual Reality Meets the Industrial IoT, *https://wiki.aalto.fi/download/attachments/109392027/How-VR-meets-IIoT.pdf*.

ENHANCED BUILDING SERVICES

Smart fixture case studies

ANDRZEJ ZARZYCKI
[1]*New jersey Institute of Technology*
[1]*andrzej.zarzycki@njit.edu*

Abstract. This paper reviews strategies for embedded systems for product development and research prototyping. It focuses on the open-source and open-access technologies that can be applied into wiring smart cities, smart buildings, and smart building components. The paper contextualizes this discussion through two smart product case studies deploying microcontrollers and Raspberry Pi with Node-RED and publish-subscribe messaging services. The value of these case studies lies in identifying approaches for enhancing user-focused building services and in demonstrating new qualitative characteristics these services would provide. The studies presented here exemplify effective research pipelines into embedded technologies and smart building systems.

Keywords. Smart devices; Internet of Things; User tracking; Embedded systems; Smart buildings.

1. Introduction

Embedded and interconnected devices facilitate new responsive buildings with adaptive façades and with context- and user-aware behaviors. Autonomous spaces engage users in an interactive dialogue, allow for public-domain authoring, and are critical factors in sustainable designs where buildings monitor their own performance and respond to environmental factors (Coen 1998, Akkaya et al. 2015). Intelligent environments integrate information technologies with distributed sensing, change users‘ expectations toward building behaviors, and address emerging resiliency and zero-energy needs (Gorbil et al. 2011, Klippel et al. 2006, Kobes et al. 2010). They start to redefine the role buildings play as active co-participants within the built environment, facilitating occupants' safety, comfort, and well-being (Schwartz 2013, Li 2012, Corna et al. 2015). These emerging directions not only point to new opportunities for the built environment but also set new design and research agendas for architects.

This paper discusses the smart product development, user controls, and occupancy-tracking strategies in the context of building products. It looks at conceptual underpinnings combined with technology development and implementation. The paper demonstrates how building components

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 201-210. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

and assemblies can be interconnected into a network of data sharing and cross-actualization agents. It also looks at opportunities for current low-level building sensing and automation technologies to be upgraded with effective migration paths toward more intelligent buildings. To contextualize these points, two case studies are presented showcasing the smart technology implementation with a building assembly integration to produce coherent and user-friendly designs. The discussion is intended as an "under the hood" look at technologies that power a number of smart interactions and building-component research projects and are generally considered as the primary Internet of Things (IoT) prototyping tool sets. An open-source framework and a relatively low entry point of technological expertise make these tools highly effective in architectural research and prototype development. These tool sets can be seen in a number of academic research projects with active student engagement, such as the Sensing Wall (Zarzycki 2017), which developed a sensing building skin for real-time building performance monitoring. Mom's Tray, a real-time dietary monitoring system-user interaction and experience research project (Jung et al. 2017), builds upon a similar IoT framework and expends it with a smartphone app.

2. Smart Device Communication Protocols

Device communication is a critical feature of smart technologies. IoT implementations rely on distributed networks of sensors and actuators, usually with a large number of interconnected components and scarce network resources. Maintaining such a broad network of devices that interact in real time requires sophisticated, reliable, and lightweight protocols, such as Message Queue Telemetry Transport (MQTT), which take advantage of scarce network resources (Zarzycki 2018).

3. Node-RED

Node-RED is an event-processing engine and an open-source visual editor for wiring the IoT, which integrates wide range of online services, APIs, and hardware devices. It utilizes a dashboard-like overlay and connects to already existing components (Raspberry Pi, smart thermostat, or smartphone) and web services without an in-depth understanding of protocols. The web-based dashboard simplifies tasks of interfacing between multiple outside technologies by providing readymade components and API tools.

4. Case Studies: Smart Closet

The Smart Closet utilizes embedded IoT framework, with an additional focus on user experience (UX) and user interactions (UI) facilitated by mobile phone applications.

4.1. PROJECT INTENT

The Smart Closet project investigates ways to automate a daily outfit selection routine (Fig.1 left). It builds on the observation that certain activities, while they significantly contribute to our image or effectiveness, do not need to take energy or

time away from other core pursuits. This is echoed by choices many high-visibility personalities make when choosing how they dress. Mark Zuckerberg is well known for always wearing the same gray T-shirt. When asked about it, he responded that he would rather focus his energy on work-related decisions than on clothing (Saul 2016, Trotman 2014). Similarly, Steve Jobs was known for his unvarying signature look of a black mock turtleneck and blue jeans (Smith 2012). This attitude of simplifying a daily outfit selection routine resonates with many people. It is also an activity that could be streamlined and designed to keep track of outfits used at various times, occasions, and contexts. Consequently, the Smart Closet project and associated mobile app integrate aspects of the home automation system with the calendar and task scheduling to provide an easy-to-use solution for wardrobe management.



Figure 1. Smart Closet concept diagram (left) and the mobile app interaction tree (right).

4.2. USER INTERACTIONS AND EXPERIENCE

The Smart Closet mobile app is the primary interface between clothing automation and users. The app facilitates prearranged selection of clothes and matching outfits. In the setting mode, users can correlate various pieces of their wardrobe and assign them into categories, such as formal, casual, or practical, as well as neutral or bright colors. In the outfit selection mode, the app will start by giving users the choice to select one of the outfit categories set up initially. Then the app will guide a user through other choices and make the final outfit selection. Once the selection is made, the message will be sent to appropriate hangers, which will illuminate to indicate the final outfit's readiness (Fig.1 right).

4.3. TECHNOLOGICAL IMPLEMENTATION

The key to effective deployment of the Smart Closet was the real-time tracking of clothes and their locations in the closet. This allowed for having a current inventory of all clothes, knowing which assets are available, and understanding their hanger assignments by localizing them with a specific hanger. This was achieved with RFID technology. Each piece of garment was equipped with a passive RIFD tag integrated with the clothing label. Since the project used passive tags, there was no power needed for this side of the sensor interactions.

On the data-reading and receiving side, hangers were equipped with an RFID sensor shield (reader) connected to a small and low-energy Wi-Fi-capable microcontroller (ESP8266) by Espressif Systems. The placement of each tag

aligned with the location of sensor shields in cloth hangers. This provided enough proximity for each tag to be registered with a dedicated sensor but at the same time allowed for enough spacing so individual pieces of garments would not be read by multiple sensors. However, in rare cases it was possible for multiple (2 or 3, but mostly 2) items be read by a single hanger. For this reason, collision and false positive strategies were identified to eliminate this condition (Fig.2). The strategies relied on comparing and filtering various database fields for duplicate entries and eliminating those cloth tags that registered with multiple hangers.

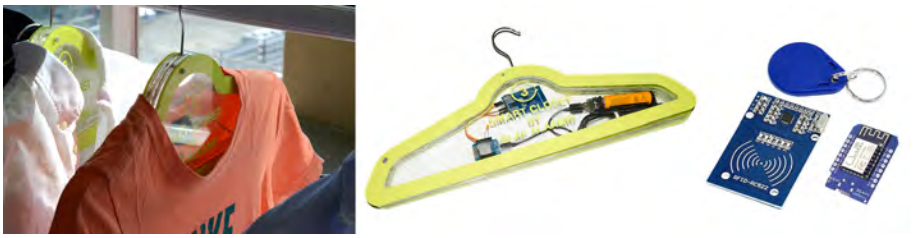


Figure 2. Smart hanger design with ESP8266 microcontroller (left and center), electronic components: ESP8266, RFID shield and tag (right).

A product design solution proposed modified hanger-rod indents or a spiral profile that would allow hangers to be placed only in district location spaces every 4 cm. This is a common solution for many automated clothing and laundry systems that require keeping each piece of garment separate (untouched by surrounding items). In addition, a software solution (algorithm) was developed to keep track of overlap readings and provide an informed guess as to what hanger the piece of clothing belongs to.

4.4. POWER CONSIDERATIONS

Hangers were the only component of the Smart Closet that required direct power to operate and as such were equipped with a rechargeable battery. While the microcontroller and RFID shield were not a significant draw on the electrical battery, at the times of Wi-Fi activities, the use of electricity would go up significantly. For this reason, the optimal solution would require microcontroller chip hibernation with periodic awake states for system checking. The hibernation approach significantly extended the life of the battery-operated hanger, but it also removed real-time interactions and controls. Depending on an individual user's lifestyle, the hangers could reawake every minute or every few minutes. This would extend the battery time to a couple of months. An alternative and/or complementary approach, tested as a separate test case, would involve remote charging of the hanger with the use of the same technologies as are currently used for mobile devices. This approach was found to be feasible from a technological point of view, but the actual design integrating it into a product was not developed.

4.5. COMMUNICATION PROTOCOL

The Smart Closet app and automation project were the first in a series of mobile-device-to-IoT-asset interactions. As such, it followed a relatively safe and narrow system integration pipeline. It was fully custom designed, without utilization of any APIs for their party software. Specifically, for the hardware, it used ESP8266 chip architecture with the connected Mifare RC522 RFID/NFC (13.56MHz) shield and corresponding passive tag. The ESP8266 microcontroller is Wi-Fi enabled and can be programmed with the Arduino integrated development environment (IDE). It uses HTTP requests to communicate with an outside MySQL database. The database holds information regarding outfit matching and selections. The communication with the database is bidirectional, which allows for each microcontroller (hanger) to report its status, including the tag ID, to the database (push) and to listen to the database server for commands associated with the selected outfits (pull). The Android mobile app uses a similar route for sending and receiving communications via the MySQL server.

This approach, while reliable and effective, is close to but not quite real-time, particularly considering the power-saving strategies discussed in the previous section. The database approach, as a clearinghouse for all communications, prevents a mobile app and individual hangers from pushing messages between each other and requires pull on either side to retrieve information from the database.

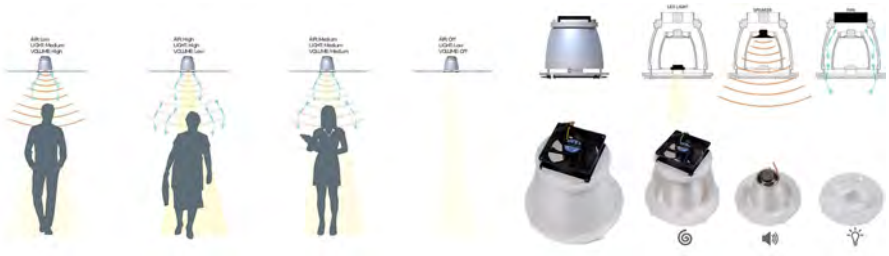


Figure 3. LSA Smart Fixture user diagram (left) and fixture components: concentric shells (top right) and 3D-printed prototypes (bottom right).

5. Case Studies: Adaptive Fixture

Light-Sounds-Air (LSA) is a smart fixture that functions as an element of the broader building-user interface by allowing occupants to control room environmental conditions and set their preferences. The LSA fixture prototypes focus on three aspects of building environmental controls: light (intensity and hue), ambient sound (music, radio), and air supply (cooling and heating) (Fig.3 left). They provide a single localized control point for all three environmental factors. While moving through a building, occupants register with individual LSA fixtures located in their immediate proximity, with the fixtures responding to occupants by adjusting their illumination, ambient sounds, and air flow to individual preferences.

The intended applications of this fixture include office buildings, hospitality and exhibition areas, and possibly retail spaces. The design allows for personalization of shared and collectively occupiable spaces without negatively impacting the comfort of coinhabitants. At the same time, it affords opportunities for energy savings by adjusting thermal and lighting levels in unoccupied areas with much higher spatial granularity (on the sub-room scale).

5.1. MODULE DESIGN

The fixture was designed as a set of concentrically embedded shells to take an advantage of the geometric shapes for the light, sounds, and air distribution (Fig.3 right). The size and round shape mimic typical recessed lighting, with an additional light diffuser placed slightly below the bottom rim of the fixture. The light diffuser also functions as the air supply diffuser.

The LSA design was conceived as a modular element that could fit, and potentially replace, existing acoustical tiles used in the suspended ceiling systems common in the building types mentioned earlier. One of the product design strategies relied on the development of a universal (power) connection that would allow for LSA fixtures placed in the tiles to be powered with low-voltage DC current via the ceiling mounting grid. The other strategy relied on the interstitial space between the ceiling and the upper slab to form the plenum for HVAC systems providing air for individual fixtures. This would eliminate the need for for ductwork separately connected to each fixture. Both strategies, while not essential from the smart- appliance perspective, would significantly lower the installation and maintenance costs.

Additionally, two alternative designs were developed for the LSA fixture, one with the fixed light position and the other with adjustable lights controlled by user location via a wearable wrist device and via the smartphone. The reason for the wrist controller is to use the fixture in the task light mode, where the light focus would follow and illuminate activities associated with hand locations.

5.2. TECHNOLOGICAL IMPLEMENTATION

The implementation of smart fixtures relies on a number of interconnected IoT technologies, including the Raspberry Pi-based MQTT broker-server and NodeMCU WiFi-enabled ESP 8266 microcontrollers (compatible with Arduino IDE) connected with Bluetooth HC-06 modules (Fig.4).

Unlike in the previous example, where mobile phone communication was achieved via MySQL databases, in the LSA implementation the phone talks directly with the IoT assets, either with MQTT server or individually with each fixture client. Mobile phone integration is achieved via Bluetooth and user tracking with RFID technology. The RFID tags can be associated with users' phones (similarly to digital wallet platforms) or be integrated with other wearable technologies like personal ID cards and hand bracelets.

The benefit of this approach is that communication can only happen if the mobile device is in relatively close proximity (up to 25 m, but real-world factors usually limit it to 10-15 m) to IoT assets. This short range functions as a

location-awareness feature and provides an additional level of security. Moreover, the direct communication with IoT assets makes this implementation resilient to Internet loss and could function as an intranet. The limitation of this approach is the need to reconnect a mobile device with new IoT assets when moving large distances within a building. Another drawback of Bluetooth technology is lower bandwidth as compared to Wi-Fi. However, in smartphone control applications, higher bandwidth is not needed.

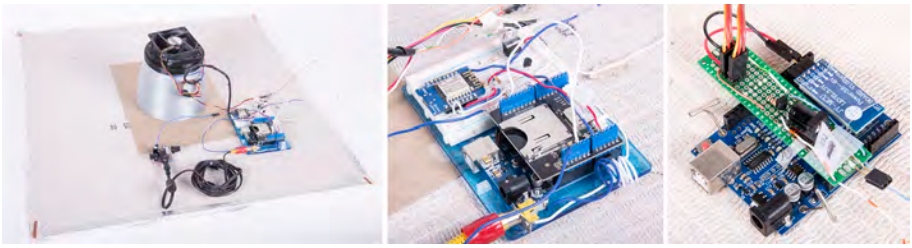


Figure 4. LSA Fixture placed into the ceiling tile: top view (left), microcontrollers with electronic components (center), and Bluetooth module with custom servo shield and microcontroller.

In addition to the smartphone control interface (Fig.5), occupants can use a designated wall controller that allows for RFID tag registrations along with conventional dimmer, switch, and motion actuation (RCWL-0516 microwave radar sensor) functions. RFID tag registration facilitates the execution of custom LSA fixture profiles, as each tag serves the role of an ID card. The user profiles reside with the MQTT broker and Node-RED server and can be changed with the same wall controller by pushing the sync button and setting up desired levels of air, light, and sound.

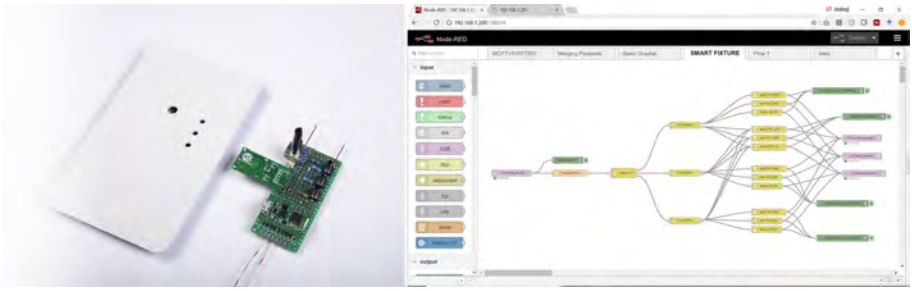


Figure 5. Wall controller utilizing ESP module and microwave motion sensor (left) and Node-RED web dashboard (right).

5.3. COMMUNICATION PROTOCOL

Critical parts of the LSA fixture interactions and operability are the programing logic and data flows. Node-RED serves as a browser-based flow editor to set up

and control payload flows between various IoT assets. All communications are deployed via MQTT protocol with Node-RED passing subscribed and published messages in JavaScript Object Notation (JSON) format. For example, when the RFID tag is registered with the sensor module (e.g., wall controller), the tag's ID is passed by a local microcontroller to the MQTT broker with Node-RED server. Node-RED matches the user ID with the corresponding device settings and passes these values via MQTT to surrounding LSA fixtures. The customization of LSA settings follows a similar workflow, with the exception that the update request appends an additional header to the tag ID with new values. When the message reaches the Node-RED environment, the payload is parsed into ID and new setting objects, and new settings are used to update a local database (Fig.6).

5.4. ADDITIONAL POINTS

The project was designed to provide light, air, and sound services to individual occupants by relying on a large number of relatively low-power and low-load fixtures uniformly distributed throughout the space. Therefore, consideration was given to integrating these fixtures with the suspended acoustical tile ceiling to enable broad distribution of individualized environmental controls with high levels of customization. The delivery of light, air, and sound is synergistic in the way they serve users and connect to building systems, so combining these three environmental controls into a single fixture would provide opportunities for construction cost reduction (i.e., labor and components) while associating like services.

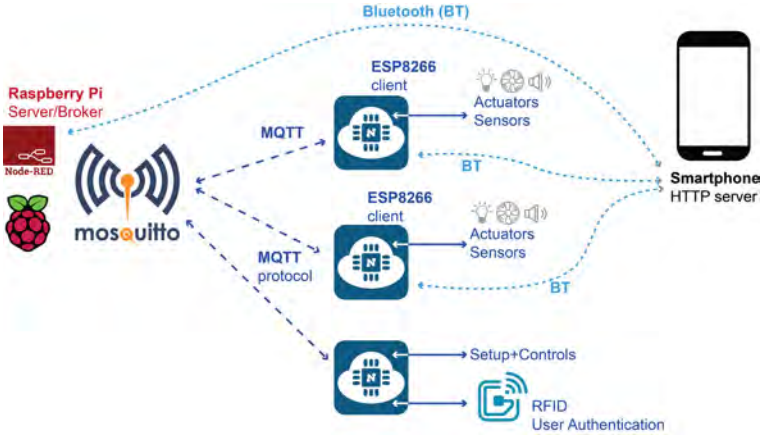


Figure 6. LSA fixture communication framework.

While light typically requires a solid translucent diffuser to reduce or eliminate glare, forced air and sound distribution generally benefit from perforated or slotted grill diffusers. The proposed design integrates both features in the form of a partially perforated diffuser (Fig. 7 left and center). However, since the diffuser is separated from the fixture housing and the plane of the ceiling, a completely solid diffuser would also allow for proper air circulation when associated with

a low-pressure distributed HVAC system. This approach would be consistent with HVAC diffuser designs that are commonly used in spaces with low ceilings and when located directly above workstations. Solid diffusers, such as the one in Figure 7 (right), eliminate the undesirable vertical drafts often experienced with grill-based diffusers. Fabric-based diffusers were additionally considered as a method to improve sound transmittance from the internal speakers while also maintaining glare reduction.



Figure 7. Light and forced air diffuser design (left and center) and conventional HVAC diffuser (right).

5.5. CURRENT LIMITATIONS AND FUTURE DIRECTIONS

The initial prototypes were developed utilizing RFID technology for tracking users. While it is an effective and reliable approach, it comes with a relatively small registration distance. It also requires constant possession of authenticating tokens or keys. While this is typical of all remote-sensing technologies, such as magnetic card access, the general trend is toward limiting a number of the separate authenticating keys with the use of a universal "remote"-the smartphone. The next step in the user tracking and fixture matching would involve the use of WiFi- or Bluetooth-based localization. This would provide more fluid registration with smart fixtures and the ability to more effectively interpolate custom settings between a larger set of fixtures and to develop strategies for multiuser customizations and preference negotiations.

6. Final Points

While very different seen from design and user perspectives, the projects presented in this paper demonstrate a wide range of architectural and building technology applications of embedded smart systems. Both case studies follow similar data-sharing protocols and technological implementation approaches, which demonstrates a certain commonality of IoT practice strategies in the context of the built environment. Many designs and building systems can operate using the same software and hardware logic, since they ultimately respond to users and control comparable IoT assets with many shared characteristics.

The future developments for these projects, particularly the LSA fixture, would involve remote over-the-air (OTA) programming and possibly interfacing it with the IoT App Store for firmware updates. This would facilitate development versatility, lowering the technology adoption threshold, and gaining flexibility on

the end-user side. It would also allow mass-produced building products to become mass-customizable with or without end-user involvement.

Acknowledgments

The Smart Closet project was developed by Elaf Al-Aamri, (NJIT) and the LSA Fixture by Antony Avila, Christian Guzman, and Karl Kroner (NJIT). Both projects were done under the author's guidance utilizing software frameworks implemented by the author. See these links for additional information:

andrzejzarzycki.com/smart-fixtures

andrzejzarzycki.com/smart-closet

References

Akkaya, K., Guvenc, I., Aygun, R., Pala, N. and Kadri, A.: 2015, IoT-based occupancy monitoring techniques for energy-efficient smart buildings, *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*, 58-63.

Berry, J. and Park, K.: 2017, A Passive System for Quantifying Indoor Space Utilization, *ACADIA 2017: DISCIPLINES & DISRUPTIO*, Cambridge, MA, 138-145.

Coen, M.H.: 1998, Design principles for intelligent environments, *AAAI/IAAI*, 547-554.

Corna, A., Fontana, L., Nacci, A. and Sciuto, D.: 2015, Occupancy detection via iBeacon on Android devices for smart building management, *Proceedings of the 2015 Design, Automation \& Test in Europe Conference \& Exhibition*, 629-632.

Jung, G., Zarzycki, A. and Lee, J.H.: 2017, Mom's tray: real-time dietary monitoring system, *SA '17 SIGGRAPH Asia 2017 Mobile Graphics & Interactive Applications*, Bangkok, Thailand.

Li, N., Gulben, C. and Becerik-Gerber, B.: 2012, Measuring and monitoring occupancy with an RFID based system for demand-driven HVAC operations., *Automation in Construction*, **24**, 89-99.

Saul, H.: 2016, "Why Mark Zuckerberg wears the same clothes to work everyday, Independent;" . Available from <https://www.independent.co.uk/news/people/why-mark-zuckerberg-wears-the-same-clothes-to-work-everyday-a6834161.html> (accessed December 1, 2018).

Schwartz, M.: 2013, Collaborative and human based performance analysis, *Proceedings of eCAADe 2013: Computation and Performance*, Delft, The Netherlands.

Smith, J.: 2012, "Steve Jobs Always Dressed Exactly the Same. Here" . Available from <https://www.forbes.com/sites/jacquelynsmith/2012/10/05/steve-jobs-always-dressed-exactly-the-same-heres-who-else-does/#6dcef9e65f53> (accessed December 1, 2018).

Trotman, A.: 2014, "Facebook" . Available from <https://www.telegraph.co.uk/technology/facebook/11217273/Facebooks-Mark-Zuckerberg-Why-I-wear-the-same-T-shirt-every-day.html> (accessed December 1, 2018).

Zarzycki, A.: 2017, Embedded Building Components - Prototyping with Emerging Technologies, *Proceedings of the 35th eCAADe Conference*, Rome, Italy, 337-344.

Zarzycki, A.: 2018, Strategies for the Integration of Smart Technologies into Buildings and Construction Assemblies, *Proceedings of eCAADe 2018 Conference*, Lodz, Poland, 631-640.

CLASSIFICATION AND REVIEW OF SOFTWARE APPLICATIONS IN THE CONTEXT OF URBAN DESIGN PROCESSES

HOSSEIN BEHMANESH[1] and ANDRÉ G.P. BROWN[2]
[1,2]*Victoria University of Wellington*
[1,2]*{hossein.behmanesh|andre.brown}@vuw.ac.nz*

Abstract. We have seen increasing expectations from our cities: as we aim to enable them to become smarter, more efficient and more sustainable. Having these goals makes the urban designing process increasingly complex. Undertaking contemporary urban design and analysis requires a rounded and inclusive approach. In the discussion relating to the smart city there has been attention to infrastructure technology solutions. But ways of estimating the success of more comprehensive urban design interventions is also extremely important. In response to these needs, digital urban design simulation and analysis software packages have been developed to help urban designers model and evaluate their designs before they take shape in the real world. We analyse, and reflect on the current aids available, classifying the urban design software packages which were used in the body of knowledge. In addition, more influential urban design software packages have been reviewed to figure out in which stages of the urban design process, they have applied. This review also helpful for software developer to understand which software packages more useful and which ones need to be developed in future.

Keywords. Smart city; Urban Design Process; software application; classification.

1. Introduction

In some ways, contemporary urban design (UD) and ideas of 'new urbanism' take us back to 1960s ideas (Moudon, 1992). Karimi (2012) suggests that, at this time, urban designers principally relied on personal knowledge and experience; and consequently often considered limited subsets of relevant factors that might prevail. For instance, (Araabi, 2016) noted that concern might focus on visual aspects or on establishing a particular identity.

But Cities are now considered to be complex organisms with both organisation and interplay of factors seen as more important and challenging than before (Cuthbert, 2008, Al-Douri, 2013). This complexity partly explains the emergence of the concept of the Smart City. Pardo and Nam (2011) structure the smart city ideas into three conceptual dimensions: the technology dimension, the human dimension and the institutional dimension (Cocchia, 2014). Computer-mediated approaches have a role in all these three dimensions. We use computational means

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 211-220. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

for collecting and analysing the data besides representing, engaging with and visualising the design alternatives. The overarching aim being that the quality of our decisions would be enhanced.

Broadly speaking research suggests that computational tools have not been used for urban design as extensively as they might be (Al-Douri, 2013, Fraser and Bjornsson, 2004, Billger et al., 2017). We could look at this contention from two perspectives: one view could be to say there is a need for more flexible and capable computer programs - ones that allow urban designers to employ different processes in their designs. The other aspect could be related to the nature of the urban design issue. As UD is a multidisciplinary field, it takes in a range of architecture and urban planning views. So, urban designers might use computer applications to satisfy a range of needs. As a result, the importance of software application development in this area is undeniable (Brown, 2016). And it, therefore, becomes important to understand which computer programs, could be employed and enhanced in each phase of an urban design process. To address this, we have undertaken and analysis, aimed at understanding and reporting on the position of UD software applications within the broader disciplinary body of knowledge.

The scope of applications that can fall into consideration ranges from plugins, such as those developed for ArcGIS and Rhinoceros, to aid urban design, to other bespoke software, like CyberCity3D, CityEngine, Modelur, CityPlaneer and UrbanFootprint, which provide customised platforms for this field of study.

Consequently, the primary purpose of this paper is to answer a main question: what is the extent and frequency of computational tools used in the body of UD activity and knowledge? This then leads to two further sub-questions: firstly, in which phases of the UD process, are those computational tools used?, And secondly, whether research articles report on the development of such software applications, or do they focus on the application of existing tools to certain cases?

In order to respond to these questions, first, different approaches to the different UD processes are explained and the associated, different phases are explicated. Subsequently, software packages in the reported on in research contexts and then in commercial contexts are identified.

Our systematic review of digital techniques and technologies used in the urban design process is then presented. A key initial aim of this research is to review and classify software packages in the context of the urban design, prior to development and application. The focus of this paper is to classify and examine software applications used in different phases of the urban design process.

This research has been undertaken in three stages. First, the frequency of software packages reported in the body of discipline knowledge was extracted. As a second phase, the most recently published documents and the most influential ones (in terms of citation/adoption) were reviewed and these selected reports were classified according to the appropriate phase of the urban design process (data collection, data analysis, modelling, and visualisation; see below) to which they contributed.

2. Different Phases of Urban Design Process

Carmona (2014) described the urban design as a mongrel discipline; one that justified its theories derived from different intellectual roots, such as sociology and anthropology, as well as from professional theories of architecture, landscape architecture, planning. Such descriptions reveal the breadth of the field and emphasises the need for considering a range of contributors from various disciplines involved in urban design processes.

Researchers note that different genres of UD theory result in different UD process (Araabi, 2016, Bahrainy and Bakhtiar, 2016). So, one might expect that a particular UD theory links to a specific UD process as an outcome. Consequently, it might be further expected (Al-Douri, 2017), that each design process generates the need for a specific software application to deal with it.

From the literature, a number of different UD theories can be recognised. In a very useful oversight paper, Araabi (2016) classified UD theories into three types:

theories about the subject within UD,

theories about the object of UD, and

Theories about the knowledge of UD

theories about the subject of UD often start by explaining a spatial problem in the built environment. Key authors in this area include Hillier and Hanson (1989), Cullen (2012), Sitte and Stewart (1945), Rowe and Koetter (1978), Trancik (1986), Larkham and Conzen (2014), Lynch (1960). Such authors have defined different concepts dealing with aspects such as:

How to present physical forms of the city on the map,

Morphological debates,

Three-dimension design, and

the composition of new buildings within in their context (Araabi, 2016).

In order to analyse the application of computer-mediated applications in urban design it is useful to identify the stages, and operations within those stages, in urban design. Understanding the differences and nature of these processes and concepts in urban design processes is important. Different researchers have described the urban design processes as existing in various stages; and there are some differences, although inherently they may at first seem to be the same. The different stages and processes will require different digital tools.

Below we articulate some important but different articulations of the process in the context of urban design:

- Shirvani (1985) categorized the conceptual foundations of design methods by identifying six types: internalized, synoptic, incremental, fragmental, pluralistic and radical. He considered internalized and synoptic approaches to be the most common methods used by both designers and planners. The synoptic method is described as ‘comprehensive’ and is described as occurring in seven steps:

1. Data collection, the survey of existing conditions- natural, built and socioeconomic
2. Data analysis, identification of all opportunities and limitations

3. Formulation of goals and objectives
4. Generation of alternative concepts
5. Elaboration of each concept info workable solutions
6. Evaluation of alternative solutions
7. Translation of solutions into policies, plans, guidelines and programs

(Shirvani, 1985)

- In the RIBA practice and management handbook, the design process is divided into four phases as follows:

1. Assimilation: the accumulation of general information and information especially related to the problem.
2. General Study: the investigation of the nature of the problem, the investigation of possible solutions.
3. Development: the development of one or more solution.
4. Communication: the communication of the chosen solution/s to the client.

(Cuesta et al., 2012)

Other scholars have undertaken research, aimed at classifying computer-aided tools in the context of urban design; for instance, see (Brown, 2016).

- Brown emphasised the need for having a Design Information System applied to urban design. He refers back to the seminal work of Eastman (1979) and articulated five issues related to the development of a Design Information System:

1. Spatial modelling
2. Integration of attributes
3. Database management
4. Design development
5. Design coordination

(Brown, 2016)

Charlton et al. (2008) classified computer programs used in the UD process to six classes: 3D modelling, pedestrian modelling, noise mapping, thermal comfort software, wind analysis software, platform (VR engine). The focus of their survey was using software and computational tools for the design of a specific urban space; the design of a square.

- Al-Douri (2017) has undertaken research relating to the effectiveness of computational and modelling tools in urban design development processes. He characterised the different aspects in the urban design development process as having four functions:

1. Navigation-Visualisation,
2. Communication-Collaboration
3. Analytical functions
4. Simulation & Decision-Support function

(Al-Douri, 2017).

Examining the different design process analyses, it is clear that the different stages in the urban design process identified by each of the researchers have overlaps. In order to undertake our classification, we have looked for a broad

categorisation and have therefore used four unifying terms to describe the stages for the purpose of this paper:

1. Data Collection
2. Data Analysis
3. Modelling
4. Visualisation

In Table 1 we show how each term in our classification relates to the classifications by others. However, each is not a rigid classification, and each stage may have overlap with other stages. By having this simplified over-arching classification, we could then codify the position of software applications in the UD process. Subsequently, we could analyse the frequency of software packages used in different stages of the design process, in our empirical studies, in relation to this structure (see Table 1).

Clearly, there is not a perfect match between the terms used by other researchers and our terms. For instance, our term "visualisation", is intended in its broadest sense to incorporate the representation of analysis outcomes. Table 1 illustrates how our classification maps onto the classifications of four others.

Table 1. Different attitudes towards Urban Design Process classifications.

Table 1. Different Urban Design Process Classifications

In this paper	Al-Douri	Brown	The RIBA handbook	The synoptic design method
-Data Collection	-Navigation-Visualisation	-Database management	-Assimilation	-Data collection, the survey of existing conditions- natural, built and socioeconomic
-Data Analysis	-Analytical functions	-Integration of attributes	-General Study	-Data analysis, identification of all opportunities and limitations -Formulation of goals and objectives
-Modelling	-Simulation & Decision-Support function	-Spatial modelling -Design development	-Development	-Generation of alternative concepts -Elaboration of each concept into workable solutions -Evaluation of alternative solutions
-Visualisation	-Communication-Collaboration	-Design coordination	-Communication	-Translation of solutions into policies, plans, guidelines and programs

3. Urban Design Software Applications

In computer science, one type of specialized software is computer-aided design (CAD) applications, which are conventionally understood to be drawing, geometric modelling and rendered images of building and products. Hussain (2017) categorises urban design software applications as CAD applications, though this somewhat misses the point that as the discipline had become more sophisticated in the use of digital technologies, and the adoption of a wider base of computer-mediated techniques has become prevalent.

As there is no specific source that identifies urban design software applications, in this paper, we provide the lists of software applications which mentioned in the literature that relate to urban design.

Undertaking a review and analysis of academic and research references, we recognised seven applications that were evident: Esri CityEngine, CityPlanner,

Modelur, Space Syntax (DepthmapX & QGIS), Urban Modelling Interface (UMI), ArcGIS, and UrbanFootprint (see Figure 1).

The Capterra Software Catalogue (Capterra, 2018) is a database that we used that for identifying the UD software packages, from the commercial view. However, there is no UD related classification offered by Capterra. The four related key classifications presented by Capterra Software database were 3D Architecture Software, Architectural CAD Software, Architecture Software, and Landscape Software.Those software applications which can use only in the context of architecture or landscape architecture were eliminated. So, the results reduced to eight software applications (see Figure 1).

The processes described above thus produced Figure 2, which shows our analysis of applications found in practice focussed sources. Figure 1 shows the analysis of applications referred to in Urban Design Research sources. The size of the circle indicates the occurrence and application of the particular technique for each particular purpose.

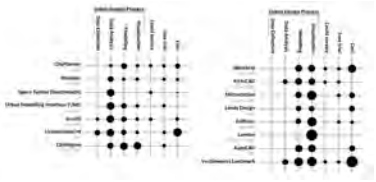


Figure 1. Urban Design software applications from the academic resources (Left), Urban Design software applications from the Capterra catalogue (Right).

4. Method

Empirical studies were undertaken to evaluate which software applications were most frequently adopted, and in which phases of the UD process. This was done by reference to reports, articles and papers readily available in the current body of knowledge (see stage 1 details below).

This research has been undertaken in three stages. First, the frequency of software packages in the body of UD knowledge has been extracted. Second, recently published papers and the most influential ones has been focussed on. Then, selected papers arising from the previous two stages, have been classified according to the urban design process to which they contributed. Finally, selected papers have been classified by their focus whether they have written:

- to report the development of software/code or
- to describe the application of a specific software package to a particular case/problem.

Stage 1: a list of software packages identified above in the section three of this paper, were searched for through databases. This took in eight databases including CumInCAD, ACM Digital Library, Scopus, Springer Links, Wiley Online Library, Web of Science, Science Direct, and ProQuest Central. In this research, only

articles published in English from 2008 to 2018 were considered. The articles not relevant to the urban design field were eliminated.

Stage 2 and 3: articles published in the last two years, 2017 and 2018, were assigned the designation 'recently published' and two papers with the highest citations were chosen as 'influential' ones. The citation of articles assessed in Google Scholar took place in November 2018. The software applications mentioned in articles, were classified by their contribution in the phases of the UD process. The classification of the UD phases which are described in section three of this paper were used for classifying the selected articles. The other criteria which were considered for sorting the articles involved ascertaining whether they focussed on the development of the software application or whether they present the application of the software.

5. Results

Figure 2 shows software packages which have been extracted from the commercial database. It reveals an expected dominance use for the purpose of modelling and visualisation, while the main focus of those which are derived from academic/research references (see Figure 1) are primarily focussed on the data analysis and modelling phases. Moreover, there are just two bespoke software packages that cover nearly all phases of the urban design process, ArcGIS and UrbanFootprint.

The result shows four software applications - Space Syntax (DepthmapX & QGIS), ArcGIS, SketchUp, and CityEngine - are the most used ones in the urban design process (see Figure 3). Space Syntax (DepthmapX & QGIS) and ArcGIS dominate so substantially compared to the other recognised software applications that a different y-axis scale is used in Figure 3. With the frequency less than 200, SketchUp and CityEngine are the next stages.

Figure 4 shows the distribution of academic references from 2008 to 2018, that have Space Syntax (DepthmapX & QGIS) and ArcGIS as the focal software. This shows that researchers have employed these software packages increasingly. What is interesting to note is the similar phenomenon on both graphs. For both Space Syntax (DepthmapX & QGIS) and ArcGIS there is a significant increase in citation and application from 2013 to 2018, compared to the frequency of citation from 2007 to 2013.

This is partly due to a general increase in the number of papers and citations but even given this, it is notable that there has been significantly increased interest and attention for both of these cases.

Table 2 adds more specific detail to the overall analysis summarised in Figures 3 and 4. Recent and most cited papers are analysed to evaluate their focus and attention. The final two columns indicate whether the attention was on using the software as a tool, or whether it was focussed on the enhancement of the software itself. In the case of the use as a tool to examine a particular problem the location of the application case is shown in the table.

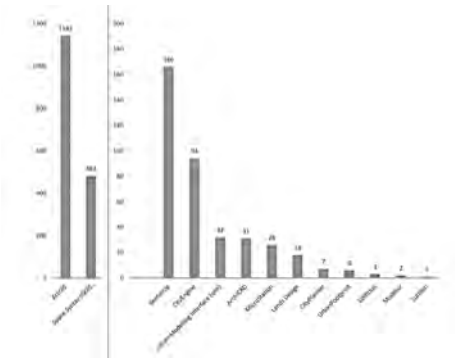


Figure 2. The frequency of software applications in the body of Urban Design Knowledge from 2008-2018.

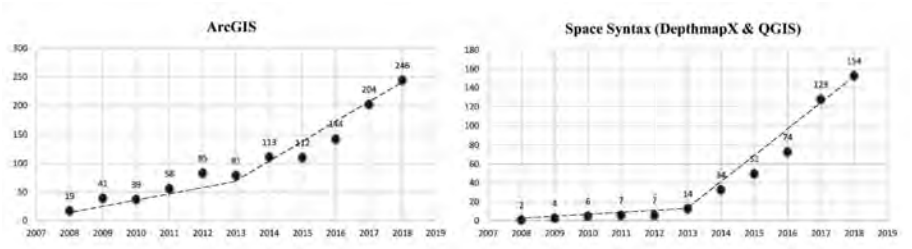


Figure 3. The frequency of ArcGIS and Space Syntax (DepthmapX & QGIS) in the body of Urban Design knowledge in each years between years 2008 to 2018.

Some comments can be made as a result of the study summarised in Table 2:

ARCGIS - This has most highly cited papers in recent years (2016-18). The primary use of the software has been in the application of the software via exploitation as a data analysis tool. However there is an interesting case (Omer and Kaplan, 2017) of a visualisation of the non-visual.

SPACE SYNTAX (DepthmapX & QGIS) - The main focus in the four papers here has been development of the software/code itself. And the most frequently cited occur in 2014 and 2015.

SKETCHUP - The references here focus entirely on using the software as a key part of an application process. The primary use if for data analysis and modelling.

CITY ENGINE - In the case of CityEngine the attention in published works is on modelling and visualisation applied to a particular problem. Easily the most heavily cited paper (Xu and Coors) was written in 2012.

6. Discussion

The results of this paper support the assertion about the lack of a comprehensive computer program for the Urban Design field; one that covers all phases of the urban design process (Gil, Beirão, Montenegro, & Duarte, 2010). However,

ArcGIS and UrbanFootprint appear to offer a comprehensive suite of possibilities. We should note that the introduction of the facility for accessing real-time data also adds to the broader scope and potential in the case of these two applications.

Table 2. Review of influential and recently published articles .

	Title of papers	Author(s)	Citation	Year	Primary Focus: Data collection	Data analysis	Modelling	Visualisation	A	D
ArcGIS	Urban function connectivity: Characterisation of functional urban streets with social media check-in data	Y Shen, K Karimi	27	2016	●	●●●	●	○	China	○
ArcGIS	"Form Syntax" as a contribution to geodesign: A morphological tool for urbanity-making in urban design	Yu Ye, A Yeh, Yu Zhuang, Avan Nes and J Liu	3	2017	○	●●●	●●	○	Netherland	D
ArcGIS	Filling the space between trams and place: Adapting the 'Movement & Place' framework to Melbourne's tram network	M J. Diemer, G Currie, C De Gruyter, I Hopkins	1	2018	●	●●●	○	○	Australia	○
ArcGIS	Using space syntax and agent-based approaches for modelling pedestrian volume at the urban scale	I Omer, N Kaplan	9	2017	○	●	●	●●●	Israel	○
Space Syntax (DepthmapX & QGIS)	Parametric modelling with GIS	P Janssen, R Stouffs, A Mohamed, E Tan, R Li	1	2016	○	●●	●●	●	○	D
Space Syntax (DepthmapX & QGIS)	Spatial Optimisations: Merging depthmapX, spatial graph networks and evolutionary design in Grasshopper Merging depthmapX, spatial graph networks and evolutionary design in Grasshopper	R Koenig, T Varoudis	1	2015	○	○	○	○	○	D
Space Syntax (DepthmapX & QGIS)	The space syntax toolkit: Integrating DepthmapX and exploratory spatial analysis workflows in QGIS	J Gil, T Varoudis, K Karimi, A Penn	12	2015	●	●	○	●	○	D
Space Syntax (DepthmapX & QGIS)	Using space syntax to model pedestrian movement in urban transportation planning	Y Lerman, Y Rofe, I Omer	39	2014	○	●●●	●	●	Israel	○
SketchUp	Evaluating procedural modelling for 3D models of informal settlements in urban design activities	V Rautenbach, Y Bevis, S Coetzee, C Combrinck	7	2015	○	●	●●●	●●	South Africa	○
SketchUp	Research and design for thermal comfort in Dutch urban squares	S Lenzholzer	27	2012	○	●●●	●●	○	Netherland	○
SketchUp	The study of the effects of building arrangement on microclimate and energy demand of CBD in Nanjing, China	JY Deng, NH Wong, X Zheng	4	2016	○	●●●	●●●	○	China	○
SketchUp	The numerical analysis of outdoor wind and thermal environment in a residential area in Liaocheng, China	L Zhang, Z Yu, J Liu, L Zhang	1	2018	○	○	●●●	○	China	○
CityEngine	Evaluating procedural modelling for 3D models of informal settlements in urban design activities	V Rautenbach, Y Bevis, S Coetzee, C Combrinck	7	2015	○	●	●●●	●●	South Africa	○
CityEngine	Using Parametric Modelling in Form-based Code Design for High-dense Cities	MA Schnabel, Y Zhang, S Aydin	2	2017	○	●●●	●●	●	Hong Kong	○
CityEngine	Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development	Z Xu, V Coors	107	2012	○	○	●●	●●●	Germany	○
CityEngine	iCity 3D: A geosimulation method and tool for three-dimensional modelling of vertical urban development	O Koziatek, S Dragićević	1	2017	○	○	●●●	●●	Canada	D

A. Application to a case study D. Development of the computer program

High ●●● Medium ●● Low ● None ○

The analysis in the sections above shows that in the research domain certain software is being developed in response to perceived need and that development is being reported on. In the commercial/practice field the focus is, as we would expect, on the application of the tools rather than the development of them.

As we aim to improve city design and associated processes with the aim of achieving the smart (intelligent?) city, one of the effective ways to support that is to develop our current Urban Design process by having more productive, capable and reliable computational tools. This paper analyses, and makes some consequent reflections on the development and exploitation of such tools over the past ten years or so.

References

"Software Categories" : 2018. Available from <https://www.capterra.com/categories>.
AL-DOURI, F.: 2013, Assessment of the methods and extents of the usage of urban modeling in urban design practice in US cities, *Environment and Planning B: Planning and Design*, **40**, 523-549.
AL-DOURI, F.: 2017, The Employment of Digital Simulation in the Planning Departments in US Cities, *eCAADe 36*.
ARAABI, H. F.: 2016, A typology of Urban Design theories and its application to the shared body of knowledge, *Urban Design International*, **21**, 11-24.
BAHRAINY, H. and BAKHTIAR, A.: 2016, *Toward an Integrative Theory of Urban Design*, Springer.
BASEER, H.: 2017, "Applications Platforms and different types of Software" . Available from <ApplicationsPlatformsanddifferenttypesofSoftware>.
BILLGER, M., THUVANDER, L. and WASTBERG, B. S.: 2017, In search of visualization challenges: The development and implementation of visualization tools for supporting dialogue in urban planning processes, *Environment and Planning B: Urban Analytics and City Science*, **44**, 1012-1035.
BROWN, J. L.: 2016, *Computer Modelling for Urban Design. Routledge Revivals: The Design Professions and the Built Environment (1988)*, ROUTLEDGE.
Carmona, M.: 2014, The place-shaping continuum: A theory of urban design process, *Journal of Urban Design*, **19**, 2-36.
CHARLTON, J., GIDDINGS, B. and HORNE, M.: 2008, A survey of computer software for the urban design process, *9th Design Decision Support Systems Conference*.
COCCHIA, A.: 2014, *Smart and Digital City: A Systematic Literature Review*, Springer International Publishing.
CUESTA, R., SARRIS, C., SIGNORETTA, P. and MOUGHTIN, J.: 2012, *Urban design: Method and techniques*, Routledge.
CULLEN, G.: 2012, *Concise townscape*, Routledge.
CUTHBERT, A. R.: 2008, *The form of cities: Political economy and urban design*, John Wiley & Sons.
EASTMAN, C. M.: 1979, *The computer as a design medium*, Department of Architecture, Carnegie-Mellon University.
FRASER, M. and BJORNSSON, H.: 2004, Real-time digital modelling in design education and practice, *Urban Design International*, **9**, 187-196.
GIL, J., BEIRAO, J., MONTENEGRO, N. and DUARTE, J.: 2010, Assessing computational tools for urban design, *eCAADe 2010 Conference: Future Cities*.
HILLIER, B. and HANSON, J.: 1989, *The social logic of space*, Cambridge university press.
KARIMI, K.: 2012, A configurational approach to analytical urban design:'Space syntax'methodology, *Urban Design International*, **17**, 297-318.
LARKHAM, P. J. and CONZEN, M. P.: 2014, *Shapers of urban form: explorations in morphological agency*, Routledge.
LYNCH, K.: 1960, *The image of the city*, Cambridge Massachussettes.
MOUDON, A. V.: 1992, A catholic approach to organizing what urban designers should know, *Journal of Planning Literature*, **6**, 331-349.
NAM, T. and PARDO, T. A.: 2011, Conceptualizing smart city with dimensions of technology, people, and institutions, *Proceedings of the 12th annual international digital government research conference: digital government innovation in challenging times*.
ROWE, C. and KOETTER, F.: 1978, *Collage city*, MIT Press.
SHIRVANI, H.: 1985, *The urban design process*, Van Nostrand Reinhold Company.
SITTE, C. and STEWART, C. T.: 1945, *The art of building cities: city building according to its artistic fundamentals*, Reinhold Publishing Corporation New York.
TRANCIK, R.: 1986, *Finding lost space: theories of urban design*, John Wiley & Sons.

COLLABORATIVE LARGE-SCALE URBAN DESIGN WITH THE FOCUS ON THE AGENT-BASED TRAFFIC SIMULATION

KATERYNA KONIEVA[1], KATJA KNECHT[2] and REINHARD KOENIG[3]
[1]*Singapore-ETH Centre, Singapore University of Technology and Design*
[1]*konieva@arch.ethz.ch*
[2]*Singapore-ETH Centre*
[2]*katja.knecht@arch.ethz.ch*
[3]*Singapore-ETH Centre, Austrian Institute Of Technology, Bauhaus-University Weimar*
[3]*reinhard.koenig@uni-weimar.de*

Abstract. The better integration of the knowledge and expertise from different disciplines into urban design and the creation of more interdisciplinary and collaborative work processes to accommodate this have been under discussion in related research for decades. Nevertheless, many barriers preventing a seamless collaborative work flow still persist. In this paper we present an experiment taking place under real-world conditions, which outlines an alternative way for more efficient collaboration by focusing on the design process rather than the result and thus providing additional insights for all parties involved. A parametric design approach was chosen to help mediate between the areas of expertise involved supporting the smooth transition of data, the mutual translation of design feedback and better informed design decisions as an outcome. The case study presented in this paper exemplifies the application of the approach in a design project on masterplan scale integrating inputs from urban design, economics and mobility experts; and shows the opportunity for transforming the formerly segregated design process into a platform for transparent negotiations.

Keywords. Parametric urban design; urban mobility; collaborative design.

1. Introduction

Rapid urbanization and climate change are the key challenges to urban design in the 21st century and add further to the complexity of urban design and decision-making processes. The better integration of knowledge from related areas of expertise has been hailed as a solution and increasingly as a necessity to create more sustainable and resilient urban environments and systems. However, the design and implementation of more collaborative, interdisciplinary urban design

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 221-230. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

processes as well as of methods and tools to support these have been slow and have been facing challenges of their own. In this paper we present the workflow and results of a collaboration between urban design, economics and mobility experts, which was devised as a 'save-to-fail' experiment taking place under real-world conditions. This set-up provided an alternative way to support collaboration from the technical perspective by focusing on the design process rather than the result.

The goal of the collaboration was to establish an integrated interdisciplinary workflow between urban design and transport planning to overcome the traditional sectoral approaches in urban design. The underlying assumption was that a better integration of transport planning expertise in the early stage of the design process would help to create more sustainable urban layouts by considering not only individual design proposals, but different scenarios of each depending on the transportation strategy. The advanced planning of the transportation system, preferred mobility types and the formulation of the mobility issue to address would open up many more opportunities compared to considering these only at the later design stages, as every aspect up to the built-up density and development phasing could still be manipulated and negotiated at this point. The 'safe-to-fail' experiment described in this paper, where several research teams with various expertise were working on a large-scale design project, allowed to set up and test the workflow between parametric design and agent-based simulation tools to support the necessary exploration and negotiation process among teams.

However, the interaction and communication between urban designers and transport planners, methods and tools as well as the establishment of a joint workflow was not free from challenges. In the following, we present the state of art in the field and the step-by-step documentation of our experiment. We describe the aims of the project, the expertise involved, as well as the detailed ways of exchanging information and evaluation results, which provided the subsequent opportunity for the informed adjustment of decisions.

2. Background

It has been argued that the challenges arising out of urbanization and climate change require a new, integrated approach to urban design, which ties together various disciplines and expertise that previously were only loosely connected in the design process (Gaffron et al. 2005, Ahern 2013). An integrated approach entails the collaboration between different practices allowing for knowledge transfer between teams with the aim to increase the sustainability and resilience of urban form by cross-validating methods and knowledge as well as to increase the transparency and deliberation of the process (Gil and Duarte 2013, Tennøy et al. 2016, Waddell et al. 2018). However, the actual implementations of successful interdisciplinary processes and the integration of disciplines in urban design remain scarce and are considered gaps in research still to be addressed (Wilson 2018). Risk averseness and fear of failure have been found to inhibit the implementation of an integrated approach (Ahern, 2013). To overcome some of the challenges affecting integrated urban design and its uptake, Kato and Ahern (2008) suggested to advance transdisciplinary collaborations in research through adaptive design in form of 'safe-to-fail' experiments.

Integrated computational urban design methods and tools are thereby seen as important means to help synergize expert knowledge and design integration (Wilson 2018). However, existing planning support systems (PSS) have been criticized to focus too much on technology to sufficiently support planning practice and as being primarily used to inform rather than to support design and decision-making and in consequence of lacking a lasting impact on the design process (Geertman 2006, Batty 2007, Al-Douri 2013). This has mainly been attributed to a lack of transparency and flexibility of the systems, as well as understanding of how they can be applied and best benefit the design process (Vonk et al. 2005, Al-Douri 2013).

Urban modeling techniques have been hailed as a way to overcome the limits of more traditional methods by helping to better address the complexity of modern, multidisciplinary projects, allowing to integrate new data sources and test alternative scenarios, and to thus improve the transparency and adaptability of the system (Al-Douri 2013, Wilson 2018). Modeling frameworks have tried to implement the idea of integrated, transdisciplinary work processes for real life use. For example, the modelling framework SIMULACRA allows planners to access complex urban models visually and to rapidly assess different urban scenarios, thus improving the user-friendliness and understandability for planners (Batty et al. 2013). Also, the Cognitive Design Computing framework, which proposes a modular strategy of design generation and analysis techniques based on the platforms Rhino and Grasshopper, addresses the aforementioned challenges and shortcomings (Koenig et al. 2017). The proposed framework connects design generation and analysis methods to create, evaluate, and optimize parametric urban master plans for projects on different scales and contexts (Dennemark et al. 2017, Konieva et al. 2018).

Despite the support of digital tools, the role of the designer to lead, negotiate and synergize inputs from different disciplines and stakeholders in the design and decision-making process remains. In empirical studies, Tennøy et al. (2016) found that the lack of access to and accessibility of expert knowledge for designers and the lack of understanding of the results and ability to translate expert recommendations into action can inhibit their integration. In particular, methods used by planners to analyze transport and traffic related aspects and to assess design decisions have been found to be very often based on so-called 'tacit knowledge' (Tennøy et al. 2016, p. 8), which stems from previously acquired knowledge and experience rather than strategic relevant domain knowledge. Alternatively, if related expertise is sought to assess the impact of design decisions, it has been found that this usually is done after a proposal has already been agreed on. However, due to the close relationship and the interdependency between urban layout, land-use, density and transport, the better integration of transport planning expertise is a requisite for sustainable urban development (Dempsey et al. 2010, Tennøy et al. 2016).

In the following we describe and discuss the results of a 'safe-to-fail' experiment, which allowed to test an integrated approach to urban design as a collaboration between experts in urban design and parametric design, transport planning and economics in the scope of an experimental case study.

3. Case study description

Waterfront Tanjong Pagar was launched as a synergy project in 2016 to bring together the multiple disciplines involved in the Future Cities Laboratory (FCL) in the design of a sustainable redevelopment strategy for the port area of Tanjong Pagar, Singapore. The container terminal at Tanjong Pagar will be relocated by 2027 freeing up 400 ha of land close to the waterfront and the central business district. The aim of the synergy project was to integrate and synergize research findings from different research teams into a design-based proposal for the site.

A scenario was developed based on assumptions on the future economic and demographic development, and expected changes in future mobility, advancements in technology, and challenges arising out of climate change. The guiding design principles and concepts were developed by the urban designers of the Grand Projet team in form of a master plan proposal, which provided the basis for the integration of other planning expertise. The initial design brief was created based on the economic predictions and synthetic population model, which provided the expected population number, percentage of the land uses, density limits, and distribution between private and public residential developments.

The workflow between the teams took different shapes during the development of the project. Largely, it consisted of multiple small iterative loops, in which experts from different teams gave feedback on the proposed design and provided recommendations for modification. Our Cognitive Design Computing work stream provided technical assistance in form of the translation of the design proposal with assisting CAD drawings, Excel sheets and sketches into a parametric urban model to incorporate contributions from various teams. A workflow between the parametric urban design framework and the agent-based traffic simulation software MATSim (MATSim Community 2019) was developed in collaboration with the Engaging Mobility team. The smooth design and evaluation data exchange was supposed to support integrated mobility related design-decision-making, which would trigger the necessary design adjustments at an early stage.

4. Mobility module

The mobility integration in the current experiment was regarded as an integral part of the initial conceptual proposals which contained necessary data for the meaningful simulation results. The simulation required the data sets summarized in Table 1. Several datasets were provided by the Engaging Mobility team, including existing public transport information and vehicle capacities, characteristics of autonomous vehicles (AVs), and car ownership statistics.

Other information, such as built-up area and type of land use, was generated based on the urban design concept. The master plan proposal divided the site into separate zones with distinct features for each (Figure 1). Parametric tools proportionally assigned the number of square meters for each land use type to each individual street block. The resulting information was geo-referenced and converted into csv file format that could be read and written in both Rhinoceros/Grasshopper and MATSim.

In Singapore, the road reserve types and characteristics are specified by the regulations of the Land Transport Authority (Land Transport Authority, 2018). The regulations specify the required buffer zones, as well as all other elements, including center median, carriageway and side tables (tree planting, verge and services, cycling path, footpath). The existing regulations were questioned by the Engaging Mobility group in the anticipation of the impact of AVs on street design. In particular, the implementation of AVs is expected to affect the need for parking space and the public transport fleet size (Soteropoulos et al., 2019; Zhang and Guhathakurta, 2017), which would have a direct impact on the road typology.

Table 1. Data required for the traffic simulation.

Element	Road network	Public Transport system (subway)	AV system	Mobility demand
Data required	- Nodes (lat/lon) - Links (from/to)	- Stops (lat/lon) - Lines (sequence of stops, sequence of roads, departure times) - Vehicle capacities (int)	- Fleet size (int) - Vehicles capacities (int) - Vehicles initial location (lat/lon) - Pick-up Drop-off locations (lat/lon)	- Building floor area by land use type (sqm) - Road flow by time of the day (veh/hour) - Public transport ridership by time of the day (passengers/hour)

Several new street typologies were developed, which also included revised policy measures, such as the design speed of each road type and restrictions on private vehicle usage. They were generalized and grouped into three street categories according to their total width, vehicle capacity and buffer requirements and then distributed across the site according to their role as local (category 3, 15m), main (category 2, 25m) or arterial road (category 1, 15m) (Figure 1). The road segments configuration and characteristics were similarly transferred into csv format in preparation for the MATSim simulation.



Figure 1. Left - site division into precincts with distinct land use mix and densities. Right - street typologies (15, 25 and 35 m) distribution. Dark purple corresponds to an underground tunnel. Credits: Grand Projet; Engaging Mobility with the use of streetmix.net.

5. Traffic Scenarios and Design Implications

In two iterations, we collaboratively developed and analyzed four different scenarios for comparison (Figure 4). In the first iteration, pick-up and drop-off points for vehicles were generated randomly in Grasshopper and two simulations

were executed: with the car access under present day mode share policies (scenario a); and with restrictions on private vehicle parking, pick-up and drop-off on the local streets (scenario b). In the second iteration, the predefined drop-off points were distributed in two ways: homogenously with an average distance of 400 m between each other (scenario c); and with their distribution frequency depending on the built-up density (400 m in areas with a Gross Plot Ratio below 5.0 and 200 m in areas with a GPR above this threshold - scenario d).

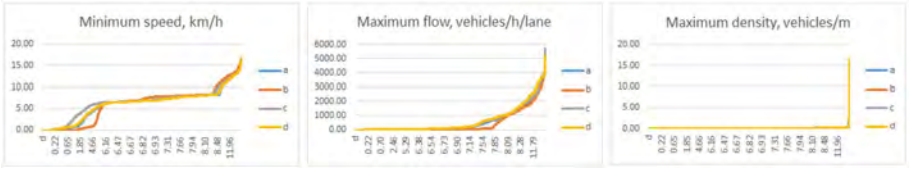


Figure 2. From left to right: minimum speed (km/h), maximum flow (vehicles/h/lane) and maximum density (vehicles/h) for four scenarios for each street segment. .

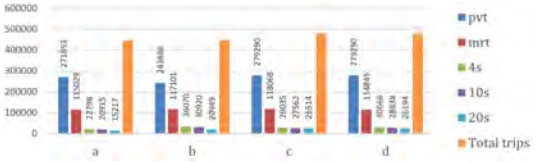


Figure 3. Mode share for four scenarios.

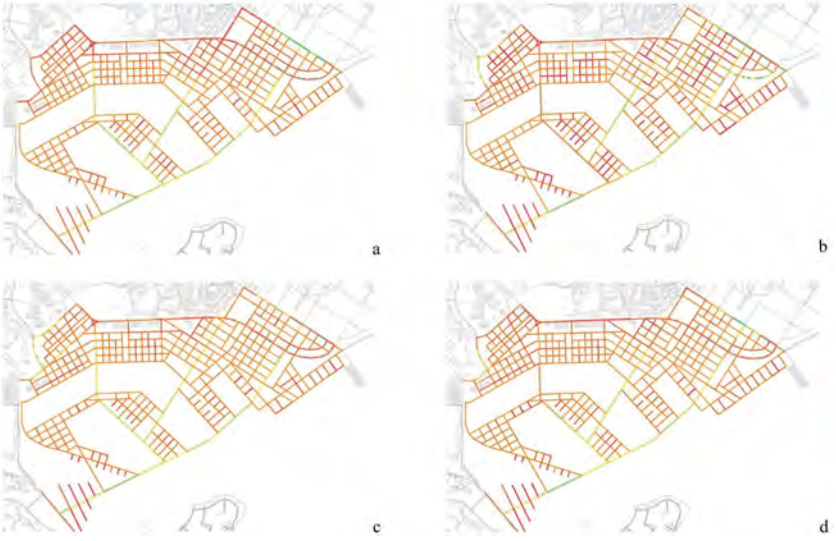


Figure 4. Minimum speed (km/h) in each street segment in each direction; warmer color represents a slower speed. MATSim simulation results visualised in Rhinoceros &Grasshopper .

We considered the following four criteria from the MATSim analysis for the evaluation of the design proposal: minimum speed (km/h), maximum flow (vehicles/h/lane), maximum density (vehicles/m of the road) for each street segment, and total number of trips per each mode share type (Figures 2, 3). The mode share indicated the number of trips made by private vehicles, MRT (subway) and 4, 10 and 20-seaters AVs.

A minimum speed parameter with a value equal to zero could either mean an extreme traffic jam with no possibility to move or a street with no vehicles passing through. Comparing the maximum flow with the full flow would indicate how much the actual number of vehicles varies from the expected number. Full density of traffic flow was defined as 1 vehicle per 7m (0.143 vehicles/m) on average, where a higher number indicates heavier traffic and zero indicates a vehicle-free road. No optimal values exist for any of these three parameters, but by combining them it is possible to find out, which points could be targeted and adjusted in the subsequent design iteration.

Comparison of the mode share revealed the lowest use of private vehicles in scenario b and the lowest total amount of trips in scenario a. Further we compared the simulation outcomes for each street category between different scenarios to establish the relationship between street network design and traffic-related aspects. A comparison of the minimum speed revealed for scenarios a, c, and d that the average minimum speed did not vary significantly between road categories 1 (arterial road) and 2 (main road). Values ranged between 6.6 and 7.6 km/h, although the assigned design speed for categories 1 and 2 were 50 and 30 km/h respectively (Table 2). In scenario b, however, the vehicle flow was significantly lower for category 2 indicating limited use of streets of this road type (Figure 6). The analysis of maximum flow for category 3 (local streets) returned low values in all scenarios, which meant vehicles were rarely passing through (Figure 6). The last parameter, maximum density, revealed that 30 to 44% of the streets of category 1 exceeded the threshold of 1 vehicle per 7 m and hence would experience traffic jams. The highest level of congestion occurred in scenarios a and d.

Several trajectories for design improvement could be laid out based on the evaluation of the simulation results. Pursuing a reduction in the usage of private vehicles as a general strategy, scenario b would constitute the most justified option, as the restriction of vehicle access in local streets impacted vehicle usage. In consequence, however, this scenario also showed a low rate of street usage indicating an unnecessary coverage of space with roads. A possible design response was a closure or repurposing of underused streets, which would create additional buildable area and reduce infrastructure cost. A disadvantage of this scenario was the limitation of car ownership for residents, which might not necessarily find favor among stakeholders in the decision-making process.

Scenarios a and d showed the highest load on the roads, with several streets prone to congestion. This could potentially be resolved by closing the most congested streets to redistribute traffic, which would need to be validated by an additional simulation. One of the biggest advantages of the scenario d, however, was the shortest average distance between pickup and drop-off points, which could be reached within 200 m in highly dense areas. This scenario would be the optimal

solution for a design concept focusing on walkability.

Scenario c had the highest total number of trips, especially by private vehicles. Nevertheless, it showed the lowest rate of congestion and second highest usage of the roads. As was illustrated, by testing various transportation strategies, one design proposal can have at least several development scenarios not only with regards to transport and mobility, but to the urban form and economic indicators.

Table 2. Average values of simulation outcome (not including the values for underground tunnel).

Road category	Design speed, km/h	Minimum speed, km/h				Maximum flow, vehicles/h/lane				Maximum density, vehicles/m			
		a	b	c	d	a	b	c	d	a	b	c	d
1	50	6.07	7.64	7.39	6.46	1568.65	1516.16	1685.78	1786.63	0.17	0.14	0.11	0.15
2	30	6.69	6.97	6.90	6.61	288.57	135.12	329.02	343.12	0.06	0.03	0.06	0.06
3	25	5.54	3.70	5.45	5.42	39.03	11.14	53.18	55.97	0.03	0.01	0.03	0.03



Figure 5. Maximum flow (vehicles/h/lane) value for road categories 2 (left) and 3 (right).

The adoption of each scenario would result in specific design and policy implications, which would require a number of compromises. In the experiment the Speckle open source platform (Stefanescu, 2015) was used to communicate the quantitative simulation outputs visually for further negotiation among the teams involved in the project. However, discussion about the results of the traffic simulation ended at the point at which a low congestion of streets could be interpreted as affirmation of the proposed street network. Although the aim was to support integrated and adaptive urban design, it ended up following traditional models. This suggests that deeply rooted behaviorisms and habits in the collaboration between experts in urban design process need to be addressed.

6. Conclusion

In this paper we presented the results of a collaborative, interdisciplinary project, which aimed at overcoming existing traditional sectoral approaches in urban planning and, in particular, the better integration of mobility expertise in the urban design process. To this effect, we established a workflow between the parametric urban design framework and the agent-based traffic simulation software MATSim, which simplified the analysis of urban design proposals and provided a basis for discussion of necessary design adjustments for more sustainable land-use and transport planning at an early stage. The presented experiment has shown the benefits of this approach, which allowed to transfer design and analysis data

between the two applications more fluently and flexibly compute and visualize different simulation scenarios.

The presented experiment has shown the opportunities of a parametric approach, which provided the basis for quick analysis of the design alternatives based both on the urban design concept and transportation strategy. The modular approach and the openness of the software platform also provided enough freedom to allow for the integration of expert tools in the design generation and analysis workflow, in this case MATSim. The experiment did not indicate the best design solution, neither did it merely inform the mobility experts on the required strategy. Instead, it provided a platform for negotiations, where all parties could interpret the analysis of the others and adjust its own strategy.

However, the implementation of a dynamic planning model and the integration of expertise-specific analysis and knowledge faced challenges stemming both from a lack of common computational platforms as well as a lack of understanding of the expert input and its implications. It applied to the expertise-exclusive decision making and adherence to traditional models of development which reflected that the uptake of computational methods in planning and education, which allows to better facilitate integrated, interdisciplinary planning, has remained slow. In the specific case, the simulation results from MatSim were initially taken as affirmation of the proposed street network design without requesting expert evaluation laying out further possibilities for improvement. Consequently, the project followed existing models of applying expertise in urban design rather than using it to help guide the development.

It has been argued that learning how to use and apply expert input through practice supports the wider dissemination of integrated planning. In as such, the synergy project as 'safe-to-fail' experiment provided the perfect framing and a real-world context for learning out of a mutual knowledge exchange as well as testing a workflow for better integrated urban design. This approach seems promising but that more research is needed in how to initiate discussion and negotiation to help overcome the deep rooted behaviorisms and habits of traditional urban design.

Acknowledgements

The presented research was discussing the process of the collaborative design project Waterfront Tanjong Pagar at the Future Cities Laboratory. The authors are grateful for all the participants for their valuable contributions and additional inputs for this paper.

References

"About MATSim." : 2019. Available from <https://matsim.org/about-matsim> (accessed February 8, 2019).

Ahern, J.: 2013, Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design, *Landscape Ecology*, **28**(6), 1203-1212.

Al-Douri, F.A.: 2013, Assessment of the Methods and Extents of the Usage of Urban Modeling in Urban Design Practice in US Cities, *Environment and Planning B: Planning and Design*, **40**(3), 523-549.

Land Transport Authority, (L.T.A.): 2018, "Circular to professional institutions" . Available from <https://www.corenet.gov.sg/media/2186957/a-revised-road-cross-section-details-of-safeguarded-roads-b-including-proposals-involving-2-landed-houses-in-the-development-control-lodgement-to-road-transport.pdf> (accessed 15 December 2018).

Batty, M.: 2007, "Planning Support Systems: Progress, Predictions and Speculations on the Shape of Things to Come" . Available from <http://discovery.ucl.ac.uk/15175/1/15175.pdf > (accessed 15 December 2018).

Batty, M., Vargas, C., Smith, D., Serras, J., Reades, J. and Johansson, A.: 2013, SIMULACRA: Fast Land-Use—Transportation Models for the Rapid Assessment of Urban Futures, *Environment and Planning B: Planning and Design*, **40**(6), 987-1002.

Dempsey, N., Brown, C., Raman, S., Porta, S., Jenks, M., Jones, C. and Bramley, G. 2008, Elements of Urban Form, *in* M. Jenks and C. Jones (eds.), *Sustainable City Form*, Springer Netherlands, Dordrecht, 21-51.

Dennemark, M., Schneider, S., Koenig, R., Abdulmawla, A. and Donath, D.: 2017, Towards a modular design strategy for urban masterplanning - Experiences from a parametric urban design studio on emerging cities in Ethiopia., *Proceedings of 35th eCAADe Conference*, Rome, 485-494.

P. Gaffron, G. Huismans and F. Skala (eds.): 2005, *Ecocity. Book I: A better place to live*, Facultas, Vienna.

Geertman, S.: 2006, Potentials for Planning Support: A Planning-Conceptual Approach, *Environment and Planning B: Planning and Design*, **33**(6), 863-880.

Kato, S. and Ahern, J.: 2008, 'Learning by doing': adaptive planning as a strategy to address uncertainty in planning, *Journal of Environmental Planning and Management*, **51**(4), 543-559.

Koenig, R., Schmitt, G., Standfest, M., Chirkin, A. and Klein, B. 2017, Cognitive computing for urban planning, *in* C. Yamu, A. Poplin, O. Devisch and G. de Roo (eds.), *The virtual and the real in planning and urban design : perspectives, practices and applications*, Routlege, 93-111.

Konieva, K., Knecht, K., Osintseva, I., Vesely, O. and Koenig, R.: 2018, Parametric assistance for complex urban planning processes: Three examples from Africa and South-East Asia, *Proceedings of ACE 2018*, Singapore.

Soteropoulos, A., Berger, M. and Ciari, F.: 2019, Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies, *Transport Reviews*, **39**(1), 29-49.

Stefanescu, D.: 2015, "Speckle: One digital infrastructure for designing, making and operating the built environment" . Available from <https://speckle.works/> (accessed 15 December 2018).

Tennøy, A., Hansson, L., Lissandrello, E. and Næss, P.: 2016, How planners' use and non-use of expert knowledge affect the goal achievement potential of plans: Experiences from strategic land-use and transport planning processes in three Scandinavian cities, *Progress in Planning*, **109**, 1-32.

Vonk, G., Geertman, S. and Schot, P.: 2005, Bottlenecks Blocking Widespread Usage of Planning Support Systems, *Environment and Planning A*, **37**(5), 909-924.

Waddell, P., Boeing, G., Gardner, M. and Porter, E.: 2018, "An Integrated Pipeline Architecture for Modeling Urban Land Use, Travel Demand, and Traffic Assignment" . Available from <https://arxiv.org/pdf/1802.09335.pdf> (accessed 15 December 2018).

Wilson, A.: 2018, The Future of Urban Modelling, *Applied Spatial Analysis and Policy*, **[online]**, 1-9.

Zhang, W. and Guhathakurta, S.: 2017, Parking Spaces in the Age of Shared Autonomous Vehicles: How Much Parking Will We Need and Where?, *Transportation Research Record: Journal of the Transportation Research Board*, **2651**(1), 80-91.

A GENERATIVE DESIGN METHOD FOR THE FUNCTIONAL LAYOUT OF TOWN PLANNING BASED ON MULTI-AGENT SYSTEM

RUOCHENG ZHANG[1], HANSHUANG TONG[2], WEIXIN HUANG[3] and RUNZHOU ZHANG[4]
[1,2] *Tsinghua University*
[1] *adamzhang46@outlook.com* [2] *tonghanshuang2018@163.com*
[3,4] *Tsinghua University*
[3] *huangwx@mail.tsinghua.edu.cn* [4] *jyuan@hzsusa.com*

Abstract. In recent years, with the development of artificial intelligence and digital architecture, more architects begin to wonder how to generate urban planning and urban design through computational method. For the purpose of generating urban planning digitally using computational algorithms, we design a series of algorithms to develop a system that evaluates initial features of the site such as the strength of sunlight, water, landscape. These parameters related to the function zoning of the town were determined based on the data extracted from case studies. These data were integrated into a Markov chain mathematical model for the sake of analyzing the function of grid points. Finally, an algorithm of a multi-agent system was used to optimize the function that could evaluate the grade of each raster point of the town, which could be used to decide the function of a specific region.

Keywords. Generative design, Town planning,Multi-agent system, Data analysis.

1. Introduction

In the field of traditional urban planning, planners use their own experience and some theories of urban planning to design cities. (Liu, Li, Tang 2017)However, this working mode is disconnected from reality due to careless mistakes and inaccurate judgment of reality. So far most generative design researches focus mostly on the architectural form(Peng, Yang, Bao,2016), optimization of the opening of a facade as well as the function zoning in a small range (GUO, Li, Tang,2017).

Therefore, this paper proposes a fully artificial intelligence system based on a multi-agent algorithm. The system can simulate the process that planners use to design cities. It can also support planners to think about design in an early conceptual stage. In addition, it can accurately integrate features of data of the environment, adjust parameters according to planners' intention to generate several different function zoning principles. The purpose of this system is to establish a set of methods and systems that can generate road network and function

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Paper 640 (Preprint). © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) in Hong Kong.

zoning intelligently by a computer, and relieve the pressure of planners and improve work efficiency by computer-aided architectural design. In addition, the digitally generated urban planning can be very well evaluated by the algorithm that integrates different factors and objectives, and if the evaluation algorithm is carefully planned, the outcomes could be more reasonable and reliable with variations that could be more heuristic for planners.

2. Research Methods

2.1. DIGITAL SITE MODELING

Function zoning plays an important role in the field of urban planning. We hope to establish a function zoning process based on site analysis. In order to better understand the features of the site, we generate a uniform mesh surface according to the topographic characteristics in the area of the town.



Figure 1. Modeling process diagram.

2.2. SITE FEATURE EXTRACTION AND SCORING SYSTEM

For the purpose of integrating features of the site into our model. We equally divided the site to get grid points of the site, which means that an evaluation grid containing a group of points is applied to evaluate all parts of the site. To quantify features of the site, we graded each grid point by analyzing different aspects of the site.

2.2.1. Centrality Score

The distance between a grid point and the center of the town is defined as centrality. It is worth mentioning that we provide an interface for changing the location of the center of the town manually. Because, for a small town, where the center is planned can be determined by planners through comprehensive analysis rather than by computers. In Qinglong town, we only set up one center. But more generally, if the size of the town is large enough, it can have multiple centers. For example, if there are n centers named $P_1, P_2, \ldots, P_n$, then the centrality score of point C_p should be the weighted sum of the inverse of the distance $D_{P1}, D_{P2}, \ldots, D_{Pn}$ from each center, where $t_1, t_2, \ldots, t_n$ represents the influence coefficient of each center.

$$C_P = \frac{1}{D_{P1}} \cdot t_1 + \frac{1}{D_{P2}} \cdot t_2 + \ldots + \frac{1}{D_{Pn}} \cdot t_n \tag{1}$$



Figure 2. Location Centrality Map.

2.2.2. Waterfront Score

The distance between a grid point and the nearest point in the river is defined as waterfront score in the research. If there are multiple rivers forming a water network, the shortest distance between grid points and each river is calculated, and then these values are weighted according to the distance to form a waterfront score. The formula is similar to the centrality.

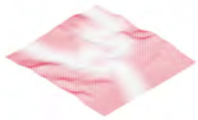


Figure 3. Location waterfront plan.

2.2.3. Topographic Slope Score

The slope of a triangular mesh face where a grid point locates is defined as the topographic slope score. For each triangular surface m, the normal vector n is calculated first, and the angle between the normal vector n and the z-axis is the slope of the triangular surface. Let's say that n_1, n_2 are any two unit vectors that are not collinear on triangle m, and the unit vector on the z-axis is N_z. Then the slope of the grid point is $n_1 \cdot n_2 \cdot N_z$. After calculating the radian value of the slope, set the slope value that greater than 15 to 0.



Figure 4. Mountain Slope Map.

2.2.4. Sunshine Condition Score

The length of time when sunshine has an effect on a house is affected by the house orientation and the angle of incidence of the sun. The evaluation of the sunshine

score here is an accumulation of insulation duration around the year considering the shadow cast by the surrounding mountains.



Figure 5. sunshine condition map.

2.2.5. Landscape View Score

With regard to the quality of the landscape view, we divided the landscape into discrete points with equal distance. Then we link each grid scenery point and the number of sight lines which could reach the scenery point is called the landscape score. The score could represent the area of scenery that could be seen from a certain location. To analyze it, we raster the landscape nodes into a series of equidistant points, and connect these points with grid points. The number of lines that do not cross the mountain grid is taken as the evaluation value.



Figure 6. landscape view map.

2.3. FUNCTION-SITE FITNESS EVALUATION

To generate a function zoning principle, we introduced 4 function categories into the generation system. They were residential areas, industrial areas, commercial areas and public parks. Since a site feature system was established, we now built a linear model using the scores of site features, to describe whether a particular point or area of the site was suitable for a particular function category, which was called function-site fitness (f). As shown below, the function-site fitness is described as a weighed average of all site feature scores ($[Grade]_i$), the weight (a_i) of which differs with function.

$$f_{residential} = \sum a_i \cdot [Grade]_i \quad (2)$$

3. Optimization algorithm of functional zoning

In order to solve the problems mentioned above, a dynamic iterative optimization algorithm based on Multi-agent System (MAS) is developed in this research.

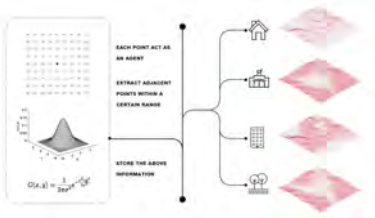


Figure 7. Diagram on function evaluation system.

3.1. THEORETICAL BASIS

A multi-agent system (MAS or "self-organized system") is a computerized system composed of multiple interacting intelligent agents. Consisting of agents and their environment, multi-agent systems can solve problems that are difficult or impossible for an individual agent or a monolithic system to solve. (WIKIPEDIA) Hereof, each grid point itself is an agent, while the functional category at each moment is its state. Under certain conditions, agents perceive the changes in the surrounding environment and decide future behaviors based on these changes.

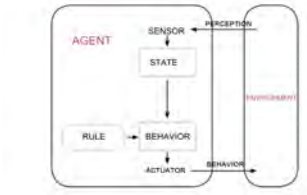


Figure 8. Multi-agent System.

3.2. OBJECTIVE OF THE INTERATIVE OPTIMIZATION ALGORITHM

Throughout the iteration, we expect the final function zoning to meet the following requirements. First, the functional category of each grid point should meet the higher function-site fitness, based on the results of chapter 3. Second, the mix ratio of the functional categories should satisfy with our pre-set ratio, which makes it possible for designers to control the size of each functional partition. To meet those requirements, we now introduce the following iterative optimization algorithm based on MAS. Third, the topological relationship between functional areas is complicated in town planning cases. A certain functional area may have a tendency of aggregation or separation from another area with the same or different functional category. Here, we use topological fitness to describe and quantify such property, which is not included in the previous operations.

3.3. OVERALL FITNESS

As shown below, overall fitness F is composed of two part: function-site fitness f and topological fitness T, while the b is the coefficient that indicates the strength of

influence between agents with the same or different functional categories, which will be discussed later in this passage.

$$F = f + b \cdot T \tag{3}$$

f is described and calculated in 2.3. And now we focus on the topological fitness. Topological fitness describes the coordination between an agent and its surrounding agents. For a certain agent containing its functional category C, its surrounding agents may have a positive or negative influence on this agent's fitness according to the relationship between functions. For example, residential areas tend to be adjacent to public parks and to be exclusive with industrial areas. The image on the right shows the relationship between each functional areas. According to their mutual relationships shown on the right, we have established a matrix on mutual relationships. For any of them, the other three functional areas can respectively have a positive or negative effect on its fitness, which is described as a positive or negative coefficient, shown as α on the image below. The absolute value of this coefficient α indicates the strength of this effect. For each agent, the sum of the influence of the surrounding agents is described as topological fitness.

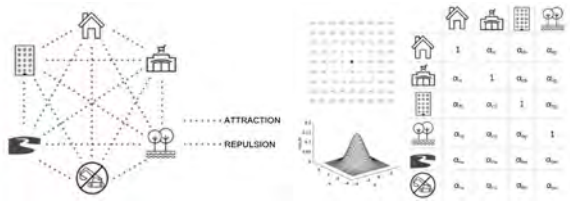


Figure 9. Topological fitness describes the coordination between an agent and its surrounding agents according to their functional categories.

It is worth mentioning that the mutual influence among agents is highly related to their distance. In other words, in addition to the coefficient α which is determined by agents' functional categories, there is a parameter or formation that describes how surrounding agents' influence on a certain agent changes with distance in the calculation of topological fitness.

Here, we introduce Gaussian filter function, which is commonly used in image processing. Its function is to calculate the influence of surrounding agents on certain agent in a more scientific way. A two-dimensional Gaussian function is as follows:

$$h(x, y) = \frac{1}{2\pi\delta^2} \cdot e^{-\frac{x^2+y^2}{2\delta^2}} \tag{4}$$

(x, y) is the coordinate for each agent, which is treated as an integer in conventional image processing; δ stands for the standard deviation. For the purpose of obtaining a Gaussian filter template, it is a reasonable choice to discretize the Gaussian function and take the value of the Gaussian function as the coefficient of the template.

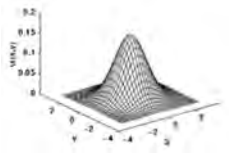


Figure 10. Two-dimensional Gaussian distribution.

In this case, we took a 15*15 Gaussian filter template. For each agent P, if its function category is classified as C, then the computer will go through agent P's all surrounding agents, and record each one's relative position in coordinates as (i, j), and its function category as C_2. Next, the computer will get an influence coefficient α according to C, C_2 and their relationship in Figure 9. The parameter k is related to the size of the Gaussian filter template. In this 15*15 Gaussian filter template, $k = 7$. The influence of each surrounding agent of a certain agent P is calculated as $H_{i,j}$ as shown below. Then the topological fitness can be calculated as the sum of all $H_{i,j}$ in the template. The bigger the result is, the higher the topological fitness T of a certain agent is, which means the mutual functional relationship between a certain agent and its surrounding environment is topologically reasonable.

$$H_{i,j} = \alpha \cdot \frac{1}{2\pi\delta^2} e^{-\frac{(i-k-1)^2+(j-k-1)^2}{2\delta^2}} \tag{5}$$

Now, as we finished determining the calculation of overall fitness, a iterative algorithm flow is necessary in reaching a scientific functional zoning.

3.4. MAS ALGORITHM FLOW

At the beginning of the MAS generative process, for a given site, the functional state of each point is randomly assigned to each grid point according to the pre-set mixing ratio, which ensures that the ratio of each function category always meets our requirement. Under this condition, the next step is to optimize the functional zoning to meet the requirement of higher global overall fitness through iteration based on MAS.

First, we need to calculate the distance matrix of each agent using Gaussian filter function. Then, based on the distance matrix, we could get the overall fitness scores through calculation of the overall fitness matrixes of all the agents, of which, we record each of the agents with relatively low overall fitness as P. As mentioned before, agent P has a certain functional category C. We now record the overall fitness of agent P under functional category C, for example, commercial area, as F_c (commercial). Also, agent P's overall fitness F_r (residential), F_i (industrial), F_p (public park) can be derived by the same methods. The maximum value among F_r, F_i, F_p could be easily calculated, recorded as $F_{\max}$, and the agent's functional category when reaching $F_{\max}$ is marked as $C_{\max}$. If $F_{\max} > F_c$, it shows that agent P is preferable with functional category $C_{\max}$ than with functional category C. Record $(C, C_{\max})$ as the permutation information of this agent. Now we traverse all agents with unqualified overall fitness using the same operations as above and get records for each agent, which comprise a permutation matrix of a two-dimensional

array.

Here, in this permutation matrix, if the permutation information $(C, C_{\max})$ of two different agents is exactly opposite, for example, the former is $(Commercial, Residential)$ when the latter is $(Residential, Commercial)$, then switch their functional category C. An iteration is finished when all functional category of the matching agents have been replaced. And the iterative loop ends calculated by the sum of all agents' overall fitness cannot be improved any more. Through this iterative process, an optimum functional zoning can be achieved.

4. Evaluation and discussion on multiple results of functional zoning

4.1. PARAMETERS TO BE DETERMINED

In the MAS iterative algorithm, there are two models that involve adjustable parameters. The first is the model that calculates the functional fitness according to the characteristics of the site, such as the calculation of the fitness of a certain residential area. Here, as shown below, the determination of each coefficient a_i is of vital importance, directly deciding whether the result is a scientific one.

$$f_{residential} = \sum a_i \cdot [Grade]_i \tag{6}$$

The second model, as mentioned before, is the one used to calculate the overall fitness.

$$F = f + b \cdot T \tag{7}$$

Where parameter T stands for topological fitness. As mentioned before, in calculating T, there is a coefficient b that indicates the strength of influence between agents with the same or different functional categories. Here, the parameters to be determined are this a_i and b which represents the weight between function-site fitness f and topological fitness T.

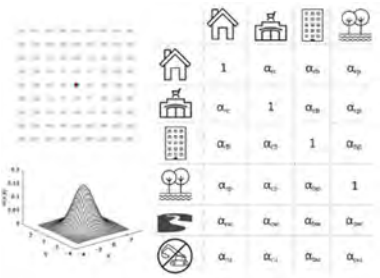


Figure 11. Parameters involved in the algorithm.

Actually, in determining those important coefficients, we would prefer a determination system or algorithm which adopts machine learning or some other methods of artificial intelligence, considering that there are multiple different types of town cases which could be databases for testing whether a set of coefficients make sense. However, considering the large amount of work which is difficult for us at the present stage. Therefore, we adopted a manual parameter adjustment

process which is based on our certain site- a place which could be a typical case for town planning with complex geographical environment.

4.2. PARAMETERS OPTIMIZATION AND DETERMINATION PROCESS

First, we used the method described above to optimize and determine the coefficient $a_i$in the function-site fitness model. a_i, representing the weight of each functional category in calculating a certain function-site fitness, differs from one functional category to another. Considering that commercial land use becomes increasingly important in urban planning, we first determined the weight of the fitness score of commercial areas a_c, which directly decides the priority of commercial land use among all functional category. The larger the value, the higher priority commercial land use possesses during operation. The image below shows how functional zoning varies with a_c.



Figure 12. Different functional zoning proposals with different values of a_c.

Then, considering that the relative weight between the function-site fitness and topological fitness may have a more significant influence on the global system, the determination process performed above is operated on the coefficient β. Larger β, greater impact topological fitness will have on the global evaluation system.

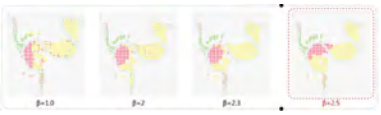


Figure 13. Different functional zoning proposals with different values of β.

It is shown on the image above that the approximate structure of the entire functional zoning is basically determined in a clear way, generally satisfying the requirements mentioned above. Now we can go back to the parameters which we have already optimized before, to perform further calibration. Fig. 15 shows the adjustment of a_{cp}, the relative priority weight between commercial land use and public green space.



Figure 14. Different functional zoning proposals with different values of a_{cp}.

The MAS system can generate multiple function zoning plan as the random seeds that are used for initiating the generation change. In order to select a

proper plan, we considered the relationship between functional areas and whether the generated functional zoning scheme fits the current site conditions. We chose the one with the best environmental adaptability, which is shown in the image below. In the functional zoning plan, the industrial area (brown) is located downstream of the river, minimizing its pollution to the whole town. Commercial areas (red) are distributed along the river, showing its high priority in selecting the city's best view. As for residential areas (yellow), they are mixed with a commercial part and public green spaces, creating livable communities. Generally speaking, this solution is in line with our expectations for the functional arrangement. As shown in Figure 16, there are several points with commercial function category scattered among residential areas, which displays a tendency of crossed function. Actually, considering that contemporary urban planning recommends mixed uses or functions, the result shown below should not be regarded as a final sharp function zoning result, but a referential result which shows a tendency of distribution of different functions. In other words, Figure 16 shows the distribution of function categories with greatest possibility for each part of the site.



Figure 15. Different functional zoning proposals with different values of a_{cp}.

5. Conclusion

In the whole process of using the set of algorithms to explore the generation of town planning, The Qinglong Town is selected as the test problem in this research. However, the system is not general enough.Thus when the system is applied to another town case, it may still need some manual adjustment of parameters in that functional zoning or other urban planning process depend on the state. Also, it is worth mentioning that the system lacks a clear logic for the computer to judge whether a solution or scheme meets our expectations for the moment. If possible, we would really like to explore machine learning's application in such area to help us to generate all those designs in a more intelligent way.

References

Dennemark, M.D., Schneider, S.S., Koenig, R.K., Abdulmawla, A.A. and Donath, D.D.: 2017, Towards A Modular Design Strategy For Urban Masterplanning, *eCAAD*, 15.

Guo, G.H., Li, L.B. and Tang, T.P.: 2017, An Exploration Of Rule-Based Generative Design Method Of Urban Design, *Proceedings of the 22nd International Conference*, 45-67.

Koenig, R.K., Miao, Y.M., Knecht, K.K., Buš, P.B. and Mei-Chih, C.M.: 2017, Computational Methods for Fast Prototyping of Urban Design Proposals, *Interactive Urban Synthesis*, 88-100.

Peng, C.P., Yang, Y.Y. and Bao, F.B.: 2016, Computational Network Design from Functional Specifications, *NLPR-CASIA*, 69.

NON-STANDARD HOUSING

Exploring Generative Design Strategies for Differentiated Residential Projects

JEROEN VAN AMEIJDE
[1]*School of Architecture, Chinese University of Hong Kong*
[1]*jeroen.vanameijde@cuhk.edu.hk*

Abstract. This paper presents arguments and experiences around generative design applied to housing, combining the potential of computational tools with an agenda to increase internal differentiation. It argues for a more varied and mixed approach to the clustering of apartment types and building typologies to increase the social diversity within projects and in relation to this, the sustainability and resilience of urban environments towards future societal changes. Through the discussion of two residential projects operating at different scales, it is shown how carefully calibrated complexity can be introduced in the design process, communicating with clients and collaborators and keeping the complexity of the workflow minimised. It is argued that this avenue of work points to significant opportunities to rethink how computational architectural and urban design processes can be linked to social sciences and a more human-centred approach within the understanding of performance of the built environment.

Keywords. Generative Design Methodologies; Urban Planning and Design; Housing; Generative Architectural Design.

1. Introduction

Housing is a topic where the requirements of many different inhabitants, as well as of the individual resident are being addressed. The are many contradictions between the interests of the individual and the interests of the collective, such as desire for space, privacy and flexibility versus the need for sustainable and economically productive urban density. Policies of optimisation, both in public housing as well as in private developments, often lead to suppression of individual differences, through homogeneity within urban clusters and repetition within building and apartment designs. In these types of neighbourhood, changes in life-style, career or family structure often force residents to move out of their building or area to find adequate housing. All these factors are counter to the widely accepted understanding that successful neighbourhoods contain medium and long-term residents that take responsibility for safety, social and cultural life of the area. As Jane Jacobs famously argued, successful city spaces are activated through a mixture of people of different ages and backgrounds, ensuring ‘’a feeling

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 241-250. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

for the public identity of people, a web of public respect and trust, and a resource in time of personal or neighbourhood need‘’ (Jacobs 1981, p56). She argued that the mixing of different types of programs and residents creates active public spaces, which in turn helps to create trust and collaboration amongst members of an urban community. These qualities of openness and resilience cannot occur in monocultural or gated communities, which feature either too much social control or social isolation:

The more common outcome in cities, where people are faced with the choice of sharing much or nothing, is nothing. In city areas that lack a natural and casual public life, it is common for residents to isolate themselves from each other to a fantastic degree. (...) As a practical result, the ordinary public jobs like keeping children in hand- for which people must take a little personal initiative, or those for which they must band together in limited common purposes, go undone. (Jacobs 1981, p65).

This paper explores the theoretical and pragmatic aspects of mixing different building and apartment typologies in residential neighbourhoods, to contribute to the social and economic resilience and sustainability of urban areas. A lack of governmental oversight, minimised regulations or emphasis on economic growth targets may lead to urban developments which within a short number of years will be out of touch with the demands of the ever-changing population. Within the planning and design of new residential projects, it is necessary to incorporate an understanding of life style changes and adaptation, incorporating a rich mixture of apartment typologies and supporting facilities such as public spaces, retail and leisure facilities.

An increasing interest by many local governments into a more human-centric approach to urban planning is apparent in the programmes being implemented by cities such as Barcelona, Shanghai, Singapore and New York, using programmes that refer to ‘citizen spaces’, ‘liveable cities’, ‘heartlands’ and ‘great public spaces’ (respectively), amongst many other initiatives aimed at increasing the quality of city life. However, as urbanist Jan Gehl points out, these improvement programmes seem to be most frequently occurring in established cities in developed countries, while the development of many new urban areas are still based on orthodox urban practices that involve the separation of functions and car-based infrastructure (Gehl 2010). New urban areas in China and the Middle East are still being developed through oversimplified land use planning, leading to monofunctional neighbourhoods or ‘mega-plots’ filled with repetitive housing.

Exploring the mixing of building typologies and apartment types within newly planned housing developments, this paper argues for social and cultural differentiation of urban neighbourhoods to promote mutual understanding and exchange between different segments of society. It examines the potential opportunities of addressing these issues through newly emerging strategies in computational design, exploring how the role of the architect could change from a single mastermind to that of a process designer, collaborating with stakeholders, consultants and computational tools. Different approaches to ‘generative design’ are discussed, using examples of housing projects developed by the author and collaborators in the context of several research and design commissions received

in China. The projects demonstrate how generative tools can help produce differentiation in residential projects at the scale of the urban block as well as at the building scale, while managing the complexity of each project in relation to their performance criteria and goals.

2. Housing Planning as Social Policy

The design and planning of mass housing is a complex process that has large-scale consequences as well as a direct effect on individuals' quality of life. Appearing in many different forms across the world, housing is a manifestation of the political frameworks prevalent in each society, showing various degrees of intervention in the organisation and supply of housing for its people.

Many developed countries are currently governed on neoliberal principles that favour market-driven mechanisms in the construction industry. Here, the meeting of demand for housing is left to private developers, with government setting out minimal regulations to determine the density and programming of newly available land, while the choice of type of apartments is left to the developers. The aims of maximising profit and minimising risk usually lead to the targeting of higher income home buyers, with very little internal variation in the apartment typologies or buildings types within developments. The result is that new residential projects are occupied by people of similar income level and life style preferences. Cities made up of isolated social enclaves contribute to a society characterised by a lack of interaction between of people of different cultures. Separated neighbourhoods by social class can contribute to decreased opportunities for its residents, including health, employment and other life opportunities (La Grange 2010), thus leading a self-reinforcing status of social segregation.

Policies to promote demographic mixing and social mobility could be enacted through public housing programmes, but a decreasing number of countries are operating these. The share and size of public housing has declined in the United Kingdom and The Netherlands and more rapidly in Eastern Europe and in China, where there have been radical changes in economic and political systems (Lau and Murie 2017). A few notable exceptions include the Hong Kong SAR and Singapore, which operate active and evolving programmes of public housing construction that serve large parts of the population. Forrest & Wu (2014) point out that public housing in these two areas are not associated with only marginal groups within society but with a range of income levels and cultural groups. In the case of Singapore, the public housing programme plays an important role in the harmonious coexistence of different religious groups within society.

In Hong Kong, most new public housing estates are designed under the management of the government's Housing Authority, who have developed an advanced expertise in the design and delivery of cost-effective estates that incorporate communal facilities and a range of apartment types for different family sizes. There may be further opportunities to incorporate flexibility of use or offer a range of apartment types, as Hong Kong's society is experiencing an increase of non-standard family structures and live-work patterns associated with the new forms of work of the post-industrial society. By offering a range of apartment types

suitable for single or sharing young professionals, young people could choose life and work priorities that suit their abilities and ambitions, rather than feeling forced into an idealised standard model for how to progress one's life and career.

Further opportunities can be identified for project in the private sector, where an abundance of supply might give rise to a need for differentiation in the appearance, programmatic mixing and cultural atmosphere of residential projects. Precedents such as the 'Linked Hybrid' in Beijing, '8 House' in Copenhagen and 'Interlace' in Singapore show private developments designed with boundary pushing architecture, to offer a greater variety of living conditions and priorities to a discerning clientele. In a competitive housing market context, differentiation from the standard development model and internal differentiation is used to attract residents seeking to associate themselves with housing that expresses individuality and sustainability and that offers novel ways of living, working and socialising.

3. Generative Design for Housing

This paper builds upon the author's earlier work exploring computational processes for programmatic and organisational design problems. The paper on data-driven urban porosity (Van Ameijde and Song, 2018) traces some of the recent academic publications on generative urban design and quotes Lima and Kós' assertion that "this form of algorithmic or parametric modelling transcends the understanding of the computational paradigm as a mere promoter of complex forms and contributes to processes capable of forming models that contemplate several parameters involved in the functional, environmental and of the cities and the buildings they contain" (Lima and Kós, 2014). This understanding builds on the theoretical framework introduced by pioneers such as Leslie Martin and Lionel March, Christopher Alexander and Bill Hillier, who developed 'configurational theories' of architecture and urbanism, offering mechanisms of abstraction of the built environment. Current software package such as Rhino and Grasshopper that offer a graphic interface for coding make these theories accessible to architects and urban designers, using a collaborate, iterative and partially intuitive work-flow rather than a fully autonomous or automated computational process.

In our 'East Gardens' residential development project, such as process of generative design was used to explore spatial distribution patterns of differentiated building typologies. Located within a new urban district for Changyuan, Henan province, China, the project is aimed at middle- and higher-income residents including elderly, so emphasis was placed on the socialising opportunities in semi-private courtyards and shared green spaces. The entire development has access to shared leisure facilities and internal gardens, while retail, healthcare and recreational facilities embedded in the porous perimeter of the project are accessible to the surrounding urban area as well.

Using a rule-based computational process, the distribution of buildings across the site was explored as a balance between the planning guidelines of the client brief and environmental criteria such as maximising sunlight access, views and privacy. The range of building typologies include residential towers, low-rise apartment blocks and townhouses with private access, offers a range of social

settings related to the open or more closed version of the ‘courtyard module’ that was used as a basic urban element (Figure 1). These modules were distributed across the site and varied according to their proximity to certain design drivers such as plot edges, main road intersections and the location of an internal attractor point that drove the opening up of the block typologies. In a second stage of the computational design process, sightlines from each semi-public courtyard at the outer zone of the project towards the centre were generated and used to cull intersecting apartment units, to increase the visual porosity of the project at ground level and improve orientation and social cohesion of the community within the project (Figure 2). After several stages of iteration and refinement, a final version of the design was visualised for client approval of the spatial qualities of the proposal (Figure 3).

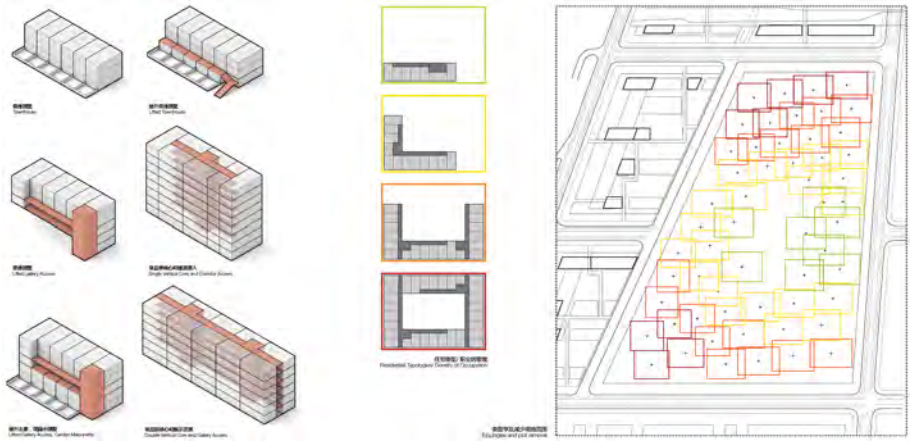


Figure 1. Catalogue of building typologies and access strategies, combined into courtyard modules distributed across the site.

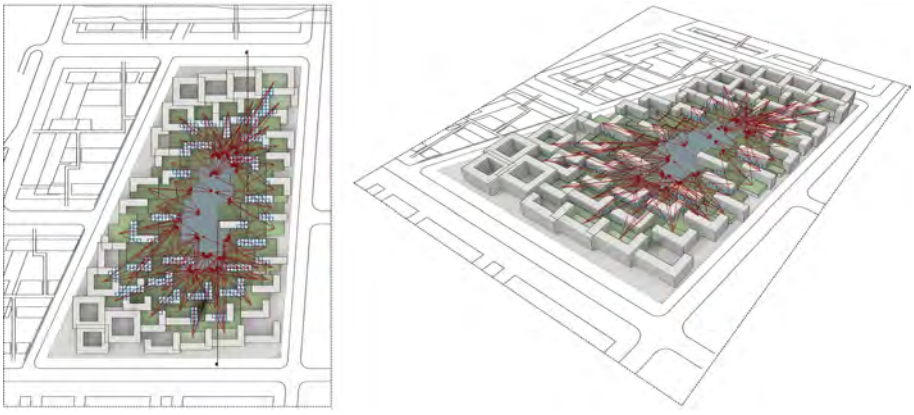


Figure 2. Projection of sight lines and culling of volumes to increase visual connectivity.



Figure 3. Eye level view within the project, testing the urban massing and visual connectivity.

4. Nesting Typologies

In a subsequent project located in the same new urban district, the author and collaborators developed a more detailed strategy for the materialisation of two residential towers, that included the organisation of internally differentiated apartment types and the automatic translation of this into the façade element arrangement. In a preliminary study, a range of apartment types was generated without specific building application but based on possibilities of the internal arrangement of rooms. The apartments were classified according to the social dynamics of the layout, distinguishing layouts more suitable for families who desire high internal social interaction versus people who prefer privacy (Figure 4). A connection between family size, life style and desired interaction with the surroundings was made, which could inform the placement of these apartments within a three-dimensional building envelope. Single elderly people for instance, or young people with an active social life could be located lower to the ground with sight lines to public spaces.

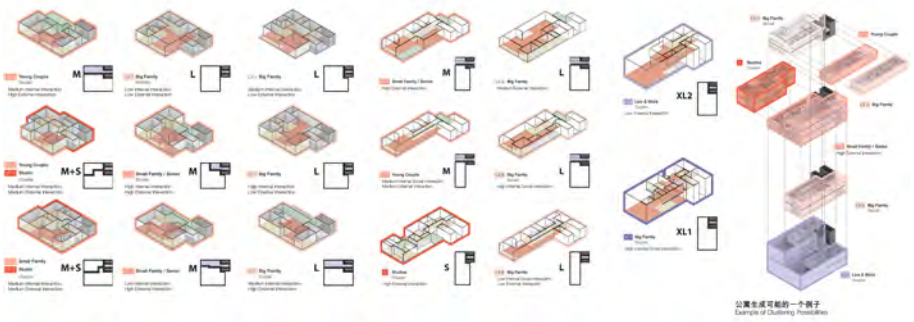


Figure 4. Range of apartment types classified by internal social interaction characteristics.

In a subsequent stage, a similar strategy of distributing different apartment types was applied to the design of two residential towers, using a customised generative process set up in Rhino/Grasshopper that created different nested apartment typologies based on the life style associations and spatial location criteria of each of the different apartment types (Figure 5). Different clustering combinations were arranged over the height of the towers to create a strategic mixing of apartment options and place the higher value units towards the top of the towers (Figure 6).



Figure 5. Possible clustering options of different apartment types within the building envelope.

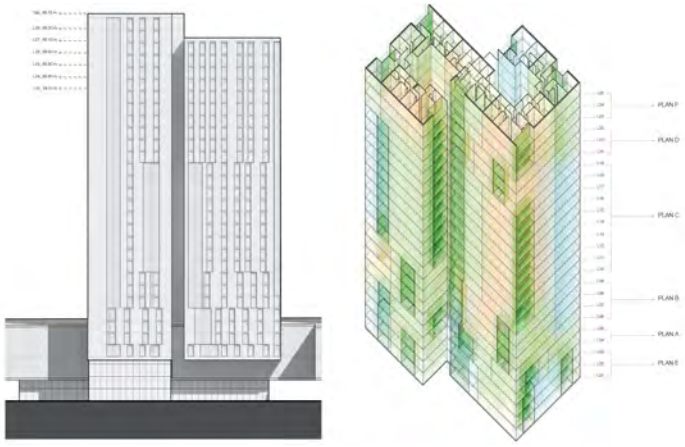


Figure 6. Distribution of apartment types throughout the building envelope based on access, views, sun and client market research.

In the development phase of this project, our generative design process was

expanded to include the automated generation of a Building Information Model (BIM) for the building including the façades, using a modular system with a limited number of elements (Figure 7). The relational nature of the workflow allowed for changes in apartment distribution to be made, as the BIM model could be automatically updated. This enabled the client to finalise the specific apartment ratios and distributions at a late stage during the project development, giving more time for market research and predictive calculations of development scenarios.

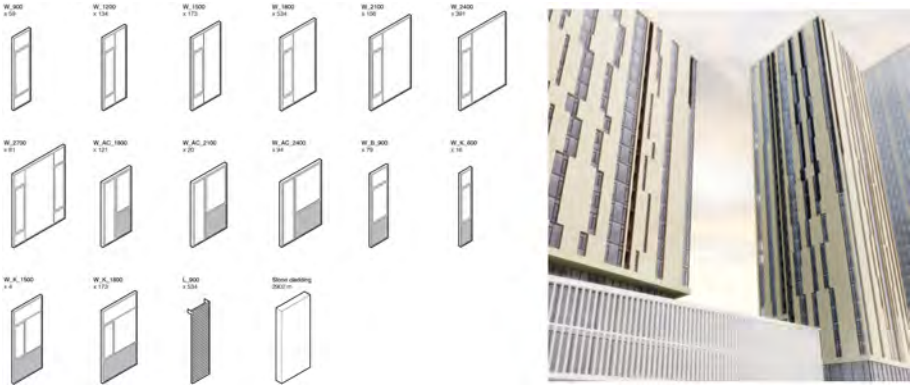


Figure 7. Generative modular façades based on the distribution of apartment types throughout the building.

5. Evaluation

Both projects presented here show how carefully calibrated generative design processes allow to control organisational complexity. When combined with a consistent architectural language based in regular spatial grids and modular construction elements, construction cost increase would be limited as there is increased logistics complexity but no need for custom fabricated elements or construction.

The design methodology employed here has deliberately been kept as a linear and relatively simple generative process, controlling certain key parameters in the design of the projects related to the social mixing and interaction of future inhabitants. There are many key assumptions in this process that are open to criticism, as decisions about the general principles of how inhabitation will work out in the real world are based on subjective judgement, experience and precedent analysis by the designers. It is difficult to verify in a rigorous and scientific manner which of the many possible design options would perform best, the next section of this paper will offer suggestions on how to improve this in the future. However, in the case of the projects presented here, the process of computational design was deemed successful as it generated project versions in an effective and time-efficient way, while the clients for the projects could make judgements on the architectural and urban qualities in the subjective manner that they are accustomed to.

The central ambition to the projects presented here was to combine the emerging practice of generative design of organisational complexity with a specific agenda for the social, political and economic effectiveness of residential developments in urban areas. Although the design operations shown here might have limited effect with respect to such wide-ranging issues, it can be argued that there is a significant importance in these first attempts to address social sustainability through computational design.

6. Conclusions and Future Development

The projects described here show how generative tools can help produce differentiation in residential projects at the scale of the urban block as well as at the building scale, to increase the range of life style choices for residents and to stimulate the mixing and collaboration between people of different age groups, social class or cultural background. The computational work flows enabled the projects to incorporate greater organisational complexity than standardised repetitive housing solutions, while keeping the complexity of the design workflow relatively low. Computational tools alleviated the increased work load in producing detailed design and construction documents that otherwise would have been cost prohibitive.

The type of computational process shown in these projects was a straightforward linear workflow, translating top-down strategic design decision into detailed geometrical output. While this type of process opens up a wide range of new possibilities for architects, it still relies on the human designer to embed the right assumptions about constructability, costs, client preferences etc. from the outset. There are more advanced computational processes that allow for a more open-ended exploration of the design solution space, through the use of multi-objective optimisation algorithms which are also referred to as ‘genetic algorithms’. These processes have been employed by the author in other projects such as urban master planning research (Van Ameijde and Song, 2018), but not in these cases as there were not enough resources available at the time. It is anticipated that in future projects, when similar residentials projects will reach a more detailed development stage, more advanced computational processes can be employed to test the complex reciprocities between the multiple and often contradictory aims related to residential buildings. A key potential in this future direction is the possible integration of construction characteristics and environmental analysis, as Rhino/Grasshopper is an open platform continuously expanding with improved plugins developed by third parties.

At the urban scale, there is a significant potential in the link between Building Information Modelling (BIM) and Geospatial Information Systems (GIS), the spatial databases at city level used by government agencies, planners and social scientists. Generative urban design processes for residential projects can be enhanced with data-driven or evidence-based design processes associated with the research field of urban analytics. An overlapping development is the introduction of new types data gathering methodologies at a large scale. Several ‘smart-city’ initiatives, a term popular with politicians, city managers and technology suppliers, are implementing urban management changes after the analysis of large data

sets, extracted through the increasing ubiquity of IT systems and sensors in the built environment. It can be speculated that if these sensing systems were to be integrated in a residential project, a feedback loop between usage patterns and building design can be established, offering the opportunity to establish continuously evolving living environments informed more directly by the complex and dynamic characteristics of everyday life.

Acknowledgements

The projects featured in this article were designed under direction of the author in collaboration with Brendon Carlin, Andrea Bugli, James Chung, Juan Jose Farres Prohens, Lei Guo, Wei Huo, Miguel Reyna and Kai Yang, as part of commissions received by Urban Systems Office for Generative Architecture in London.

References

Alexander, C., Anninou, A., Neis, H. and King, I.: 1986, *A new theory of urban design*, Oxford University Press, New York.

Van Ameijde, J. and Song, Y.: 2018, Data-Driven Urban Porosity, Incorporating Parameters of Public Space into a Generative Urban Design Process, *Learning, Adapting and Prototyping – Proceedings of the 23rd International Conference on Computer-Aided Architectural Design Research in Asia, vol. 1, edited by T. Fukuda, W. Huang, P. Janssen, K. Crolla, and S. Alhadidi*, Beijing, 173-82.

Forrest, R. and Wu, Y.: 2014, People like us? Social status, social inequality and perceptions of public rental housing, *Journal of Social Policy*, **43**, 135-151.

Gehl, J.: 2010, *Cities for people*, Island Press, Washington, DC.

La Grange, A.: 2011, Neighbourhood and Class: A Study of Three Neighbourhoods in Hong Kong, *Urban Studies*, **48(6)**, 1181-1200.

Hanson, J.: 1998, *Decoding homes and houses*, Cambridge University Press, Cambridge.

Hillier, B.: 1996, *Space is the machine: A configurational theory of architecture*, Cambridge University Press, Cambridge.

Jacobs, J.: 1961, *The Death and Life of Great American Cities*, Random House, New York.

Kós, J.R. and Lima, F.T.: 2014, Algorithmic thinking, parameterization and sustainable urbanism: an assessment of parameters for intelligent urban design strategies, *Conference of the Iberoamerican Society of Digital Graphics - SIGraDi: Design in Freedom*.

Lau, K.Y. and Murie, A.: 2017, Residualisation and resilience: public housing in Hong Kong, *Housing Studies*, **32:3**, 271-295.

Martin, L. and March, L.: 1972, *Urban space and structures (Cambridge urban & architectural studies, 1)*, Cambridge University Press, London.

Design Cognition

CATERPILLAR

A Gcode translator in Grasshopper

HAO ZHENG[1], BARRAK DARWEESH[2], HEEWON LEE[3] and LI YANG[4]
[1]*University of Pennsylvania, Philadelphia, USA*
[1]*zhhao@design.upenn.edu*
[2]*Massachusetts Institute of Technology, Boston, USA*
[2]*barrakd@mit.edu*
[3]*University of California, Berkeley, Berkeley, USA*
[3]*heewon_lee@berkeley.edu*
[4]*University of Sydney, Sydney, Australia*
[4]*lyan8357@uni.sydney.edu.au*

Abstract. Additive manufacturing has widely been spread in the digital fabrication and design fields, allowing designers to rapidly manufacture complex geometry. In the additive process of Fused Deposition Modelling (FDM), machine movements are provided in the form of Gcode - A language of spatial coordinates controlling the position of the 3D printing extruder. Slicing software use closed mesh models to create Gcode from planar contours of the imported mesh, which raises limitations in the geometry types accepted by slicing software as well as machine control freedom. This paper presents a framework that makes full use of three degrees of freedom of Computer Numerically Controlled (CNC) machines through the generation of Gcode in the Rhino and Grasshopper environment. Eliminating the need for slicing software, Gcode files are generated through user-defined toolpaths that allow for higher levels of control over the CNC machine and a wider range of possibilities for non-conventional 3D printing applications. Here, we present Caterpillar, a Grasshopper plug-in providing architects and designers with high degrees of customizability for additive manufacturing. Core codes are revealed, application examples of printing with user-defined toolpaths are shown.

Keywords. 3D Printing; Gcode; Grasshopper; Modelling; Simulation.

1. Introduction

1.1. PROJECT GOAL

3D printing, as the most common usage of additive manufacturing technology, also known as Fused Deposition Modelling (FDM), has been widely applied to design

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 253-262. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

and architectural manufacturing field, which leads a revolution of producing geometries. Often as an end application of techniques, architectural design regards 3D printing as a method to produce entities from digital models.

However, as the geometries become more and more complex, designers are no longer satisfied with the conventional printing technique, which prints the object from bottom to top, layer by layer, actually a 2.5D printing. A more flexible control method of 3D printers is required for making non-conventional 3D printings, which makes full use of 3 degrees of freedom (X, Y, and Z) of the printer.

Especially in recent researches, this trend of non-conventional 3D printing becomes clearer. (Wang, Sheng et al. 2018) (Sun, Xu et al. 2018) (Im, AlOthman et al. 2018) (Silva, Andersen et al. 2018) (Battaglia, Miller et al. 2018) applied a robotic arm with a printing extruder to print concrete with customized toolpaths. (Seibold, Hinz et al. 2018) (Carvalho, Figueiredo et al. 2018) (Bhooshan, Ladinig et al. 2018) also refined a robotic arm to print ceramic. (Mostafavi, Kemper et al. 2018) used similar robotic technique to print soft silicone on curved surfaces. (Zheng and Schleicher 2018) drew inspiration from the spinning behaviours of insects to program a 3D printer to print along given curves (Figure 1). (Yi-Chia and June-Hao 2018) focused on printing wire structures directly from the extruder, without breaking the continuity. (Molloy and Miller 2018) constructed a robotic system to print continuous filaments and lattice structures.



Figure 1. Bio-inspired 3D printings by (Zheng and Schleicher 2018).

So in order to spread the idea of the non-conventional 3D printing technique and achieve it in cheap desktop level 3D printers rather than expensive industrial robotic arms, we present Caterpillar, a Grasshopper plug-in helping designers transform geometries into Gcode, which runs the 3D printer according to customized toolpaths, with all 3 degrees of freedom.

1.2. WORK FLOW

Figure 2 shows the work flow of Caterpillar in Grasshopper. First, users should adjust the default settings to match the parameters of the printer they are going to use. Second, users can either input the printing and slicing geometries then use

the slicer to produce the toolpaths, or directly input the user-defined toolpaths as curves. Last, the generator will output the Gcode text in a panel. By saving the text as a Gcode file and load it to the printer, the customized printing will start working. Optionally, when a Gcode text is inputted into the decoder component, the toolpaths will be read and generated as geometries. Users can apply this optional function to rebuild the toolpaths from any Gcode files in modelling software.

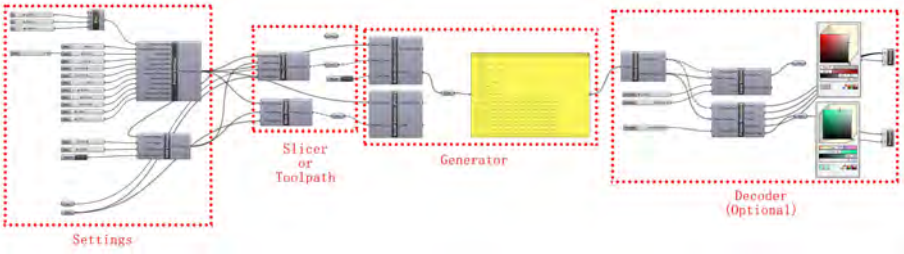


Figure 2. Work flow of Caterpillar in Grasshopper.

2. Settings

To make use of Caterpillar correctly, the first step is to tell it the settings of the printer and the printing object.

2.1. PRINTER SETTINGS

For the printer settings, there are totally 14 parameters. Printer bed size (MM) contains three numbers (x, y, z), indicating the maximum printing size of the printer. Heated bed temperature (°C), extruder temperature (°C), and filament diameter (MM) are based on the printing material, which normally will not be changed once settled. Layer height (MM) and subdivision distance (MM) control the precision of the printing, while printing speed (%), moving speed (%), retraction speed (%), and retraction distance (MM) control how fast the printer will act when printing, moving without printing, and retracting materials. Extruder width (%) and extruder multiplier (%) together decide the width of the printed toolpaths.

For conventional printing, the default settings are recommended. But changing some parameters may cause special effects, such as enlarging the extruder multiplier and lessening the printing speed to print very thick paths, or enlarging the extruder temperature to melt a base material along toolpaths. There is no limitation for the settings, so users can simply regard the printer as a moving machine with an extruder of any degrees of temperature.

2.2. INFILL SETTINGS

Another setting is for the infill, only needed when the users want to slice the model and apply infill inside. Infill degree defines the rotating degree of the web-like infill, while infill density represents the distance between each grid. More types

of infill patterns are being developed, but users can also model the customized infill with the printing object, to achieve more flexibility.

3. Slicer and Toolpath

Next, geometric manipulations will be executed to the printing objects to generate the toolpaths. As Figure 3 shows, there are three options for the users, planar slicer like most of the slicing software, curved slicer for printing on existing objects or curved toolpaths for special usages, and user-defined toolpath inputted from Rhino or Grasshopper curves.



Figure 3. Planar Slicer (left), Curved Slicer (middle), User-defined Toolpath (right).

3.1. PLANAR SLICER

For planar slicer, since the printing objects are always closed meshes, Grasshopper command 'Contour' here acts as the main role to generate the printing boundaries. Then infill settings will be applied, mapping infill pattern into the boundaries. Then all curves will be sorted to make sure the end point of the current printing path is close to the start point of the next printing path, avoiding time waste when moving the extruder.

3.2. CURVED SLICER

Different from other slicing software, Caterpillar provides users with an option to slice the printing objects with a curved plan. This function was originally designed to help generate toolpaths when users want to print on an existing object but don't know how to draw or generate toolpaths directly. Other than the slicing process, the infill producing and curves sorting processes are the same as the planar slicer. Users can transform a real-world object into a 3D model by 3D scanning or modelling it directly, generate the toolpaths, and then put the object in the right position on the printing bed. The printer will firstly move beyond the top of the object, and then start printing on it.

3.3. USER-DEFINED TOOLPATH

For advanced usages, it's recommended to directly input the toolpaths as user-defined curves, telling the printer to move and extrude exactly along the

defined paths. And the program will not sort the curves, but only move the extruder from curves to curves. The toolpaths can be any 3D curves, no need to be planar. This enables the full control of the printer.

4. Gcode Generator

Then, the toolpaths will be sent to the Gcode generator, the program will deconstruct the curves and generate Gcode text file based on the printer settings.

4.1. GENERATOR WORK FLOW

Figure 4 shows the work flow of the Gcode generator. First, since the Gcode only recognizes spatial points with the coordinate of (x, y, z), the inputted curves will be divided into points based on the setting of subdivision distance, which approximately represent the curves.



Figure 4. Work Flow of Gcode Generator.

Then, the toolpaths will be created based on the points. But different from other Gcode, here since it's acceptable if the users input 3D spatial curves, the printer should move up its extruder after finishing printing the current curve, then move to the position above the start point of the next curve, to avoid the collision with printed objects (Figure 5). The height that the extruder should be lifted can be figured out before printing by referring the current top point in the printed objects.

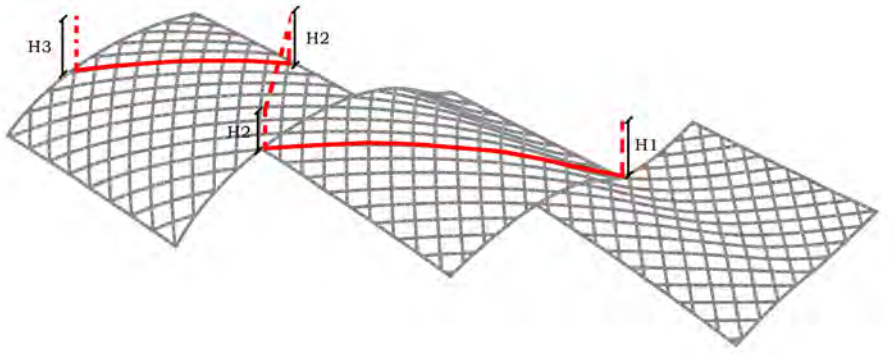


Figure 5. Toolpath to Avoid Collision.

Next, the extrusion amount, which is represented as a variable 'E', is calculated based on the printer settings of layer height, filament diameter, extrusion width, and extrusion multiplier. To be specific, for a given printing toolpath, which is a single line from the current position point to the next position point, its 'E' value is proportional to the settings of layer height, extrusion width, and extrusion

multiplier, while that is inversely proportional to the settings of filament diameter. So the formula can be expressed as following:

$$E = \frac{Height_{layer} \cdot Width_{extrusion} \cdot Lenght_{curve} \cdot M_{extrusion}}{sqr\left(\frac{D_{filament}}{2}\right) \cdot \pi} \quad (1)$$

What's more, to avoid the over extruding of extra filament, in the moment of finishing printing current curve, the extruding motor should spin back a little to suck back the filament, then after reaching the start point of the next curve, the motor should release the filament again to compensate this distance. This command should also be added into the printing toolpaths.

Finally, the data of (x, y, z) and 'E' with the variable 'F' in the printer settings, which represents the moving speed of the toolpaths, are formatted into text Gcode file (table 1). Together with the starting and ending codes, a completed Gcode is generated and ready to be inputted into the printers.

Table 1. Gcode Example.

G1 X65.7029 Y67.4932 Z44.1218 E0 F2160.0000
G1 X65.7029 Y68.4932 Z40.1287 E1.3947 F2160.0000
G1 X66.6977 Y67.4932 Z40.2310 E1.5861 F1440.0000

4.2. OPTIMIZATION

Mentioned before, the curves will be divided into points, and each line of the Gcode text represents a point that the extruder should reach. However, different from curved toolpath, there is no need to divide a linear toolpath into points (Figure 6). Experiments showed that, the file size will be greatly enlarged and exceed the file size limit for most of the printers, if dividing linear toolpaths, which widely appear in traditional planar printing. So before inputting the given curves to the dividing component, the program will detect and separate curved toolpaths and linear toolpaths, then divide the curved toolpaths as usual and extract the start and end points to represent the linear toolpaths.

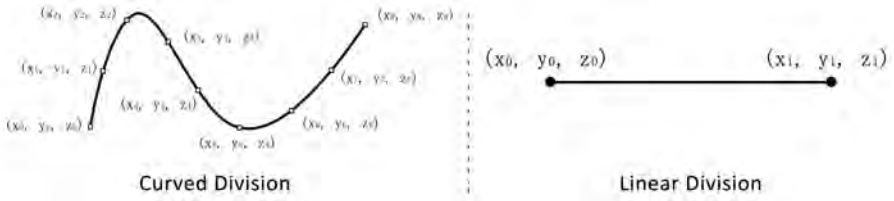


Figure 6. Different Division Rules for Curved Toolpaths and Linear Toolpaths.

5. Gcode Decoder

In addition to the Gcode generator, our team also developed a Gcode decoder to translate Gcode text file back to the toolpaths as Rhino or Grasshopper geometries,

helping designers preview, rebuild, and modify the printing model in modelling software.

5.1. KEYWORDS EXTRACTION

Although there are about 100 commands in Gcode format, most of them are designed to control other hardware, such as the fan speed or the extruder temperature, or the irrelevant parameters of the motors, such as the running speed or the working plane (Figure 7). The only two commonly used commands to control the position of the extruder (movement of the motors) are 'G1' (or 'G01') and 'G92'. 'G1' controls the position of the extruder by a following text, such as 'G1 X1 Y2 Z3 E4 F5', which tells the extruder to move to the spatial point of (1, 2, 3) with a speed of 5 unit, while extruding 4mm filament. 'G92' can set the current position as a new original state, mostly used by a following text of 'G92 E0' to set the position of the extrusion motor to 0, preventing the over increasing of the variable 'E'.

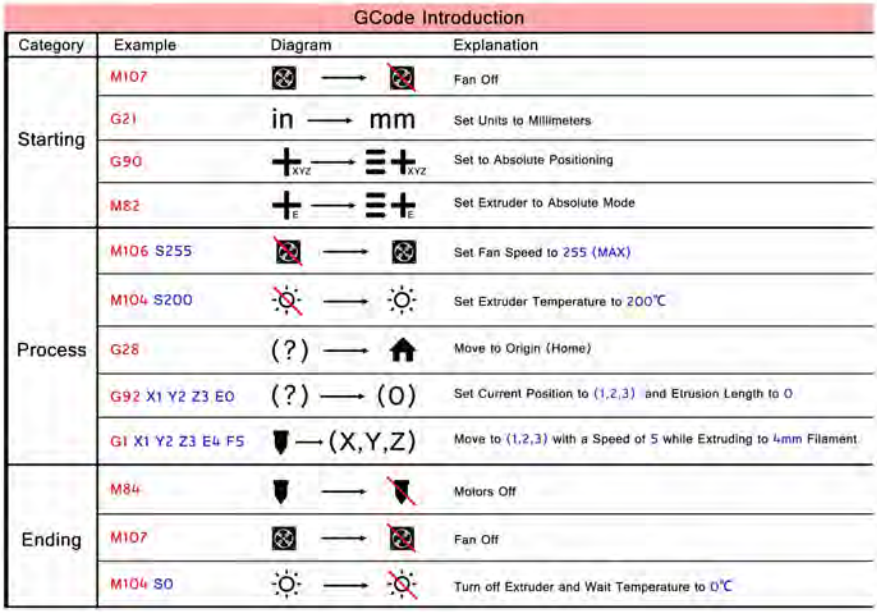


Figure 7. Commonly-Used Gcode.

So the rule to read and translate Gcode text is quite simple. Every time, when a line with a beginning code of 'G01' or 'G1' appears, the program will read the numbers after the characters of 'X', 'Y', 'Z', and 'E', then the numbers are the coordinate of one of the points in the toolpaths. Also, when 'G92' appears, the following numbers should be recorded as the reference point, which acts to transform the current coordinate to the world coordinate.

5.2. MODEL REBUILDING

After extracting all points from the Gcode text file, the program will check the recorded 'E' value to separate the toolpaths for printing and the toolpaths for moving. To be specific, if the 'E' value of the current point is the same or less than that of the previous point, the curve from the previous point to the current point is a moving path, which should not be rebuilt as the printing model. On the contrary, if the 'E' value keeps increasing, the points should be included in the printing paths.

Then, a printing simulator was developed, which takes in the printing paths, and outputs a dynamic model showing how the 3D printer will work to print the Gcode file (Figure 8). By adjusting a slider, the users can check the printed geometries and the position of the extruder in different printing percentage.

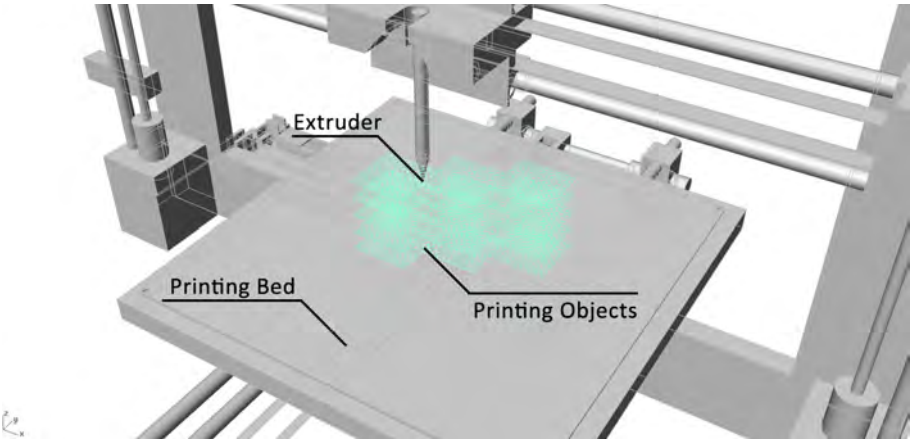


Figure 8. Printing Simulation.

Also, the users can bake the printing paths to Rhino as geometries for analysis or model rebuilding. This component not only enables the preview of printing objects in Rhino, but also provides a convenient method to adjust the Gcode by remodel the objects directly.

6. Customized Printing Examples

Last, several examples are shown to discuss the advanced usages.

The best way to make full use of the plug-in is to input user-defined toolpaths directly from users' design. Figure 9 shows the design 'Pimples', in which small circular disturbances will be applied to the printing paths in different positions, so that there will be buckles in the surface of the printing.



Figure 9. ‘Pimples’.

With the same technique, but larger layer height and extrusion multiplier, the printer will keep extruding thick filament and produce a cup-like art work as Figure 10 shows.



Figure 10. ‘Hair’.

Also, users can reform the printer with extra toolkits or replace parts of the components. Figure 11 shows a printer with a replaced sleeve motor, which supports a printing while rotating the printing platform. The Gcode can be generated based on the scaled toolpaths.



Figure 11. ‘Roof’.

By replacing the extruder with other tools such as a brush, the printer can become a writer to produce calligraphy, with customized toolpaths and Gcode generated by Caterpillar (Figure 12).



Figure 12. ‘Calligraphy’.

7. Conclusion

Caterpillar is a powerful plug-in for Grasshopper, which helps generate 3D printing Gcode from geometries, visualize toolpaths, and remodel printing objects from Gcode. It supports printing with the movement of all 3 axes, releasing all 3 degrees of freedom of the 3D printer. Customized printings can be achieved by modifying the hardware and generating Gcode by Caterpillar.

In the future, non-conventional customized 3D printing will be highly developed for both educational and industrial purposes. Low-cost 3-axis 3D printers with extra toolkits can handle a variety of tasks, providing an alternative for expensive robotic fabrication.

References

Battaglia, C.A., Miller, M.F. and Zivkovic, S.: 2018, Sub-Additive 3D Printing of Optimized Double Curved Concrete Lattice Structures, *Rob|Arch 2018*.

Bhooshan, S., Ladinig, J., Mele, T.V. and Block, P.: 2018, Function Representation for Robotic 3D Printed Concrete, *Rob|Arch 2018*.

Carvalho, J., Figueiredo, B. and Cruz, P.J.S.: 2018, 3D Printed Ceramic Vault Shading Systems, *IASS 2018*.

Hsu, Y. and Hou, J.: 2018, The Composite Material Wire Printing of Robotic Fabrication And Construction Process, *CAADRIA 2018*.

Im, H.C., AlOthman, S. and Castillo, J.L.G.D.: 2018, Responsive Spatial Print - Clay 3D printing of spatial lattices using real-time model recalibration, *ACADIA 2018*.

Molloy, I. and Miller, T.: 2018, Digital Dexterity - Freeform 3D printing through direct toolpath manipulation for crafted artifacts, *ACADIA 2018*.

Mostafavi, S., Kemper, B.N. and Fischer, D.L.: 2018, Multimode Robotic Materialization, *Rob|Arch 2018*.

Seibold, Z., Hinz, K., Castillo, J.L.G.D., Alonso, N.M., Mhatre, S. and Bechthold, M.: 2018, Ceramic Morphologies - Precision and control in paste-based additive manufacturing, *ACADIA 2018*.

Silva, W.R.L.D., Andersen, T.J., Kudsk, A. and Jørgensen, K.: 2018, 3D Concrete Printing of post-tensioned elements, *IASS 2018*.

Sun, S., Xu, W., Cheng, Y. and Gao, Y.: 2018, 3D Printing Concrete System Design and Fabrication Process Research Based On Robotic Arm, *CAADRIA 2018*.

Wang, S., Sheng, Y., Shih, J.Y., Georg, F.F. and Chang, T.: 2018, Transient Materialization, *CAADRIA 2018*.

Zheng, H. and Schleicher, S.: 2018, Bio-Inspired 3D Printing Experiments, *CAADRIA 2018*.

ADDITIVE MANUFACTURING WITH NATURAL COMPOSITES

From material intelligence to informed digital fabrication

STYLIANOS DRITSAS[1], YADUNUND VIJAY[2], RYAN TEO[3], SAMUEL HALIM[4], NARESH SANANDIYA[5] and JAVIER G. FERNANDEZ[6]
[1,2,3,4,5,6]*Singapore University of Technology and Design*
[1,2,3,4,5,6]*{stylianosdritsas|yadunund_vijay|ryan_teo|samuel_halim|naresh_sanandiya|javier.fernandez}@sutd.edu.sg*

Abstract. We present results on the development of a sustainable digital manufacturing technology, discuss the challenges associated with additive manufacturing with natural materials, how statistical modelling techniques enabled understanding the intricate relationship between material and fabrication and allowed to control material extrusion. We present a prototype created to assess the ability of the process to create large-scale artifacts. We believe steps towards advancing methods for environmentally-aware digital fabrication may pave the way in transforming the industry and society towards more sustainable production and consumption paradigms.

Keywords. Digital Fabrication; Bioinspired Materials.

1. Introduction

Additive manufacturing (AM) has been at the centre of research across disciplines for the past decades (Thompson et al, 2016). Potential of AM includes rapid design to production, innate ability for customization, functional integration and improved resource utilization (Tofail et al, 2018). Several shortcomings including materials, design software, sustainability, reliability and production speed, prevent its advancement (Royal Academy of Engineers, 2013). Research work presented here aims to address challenges in AM primarily from the perspective of its sustainability characteristics. The environmental impact of AM is a domain only recently has come to research attention (Ford and Despeisse, 2016). Indicative work includes comparative study between subtractive and additive manufacturing (Faludi et al 2015), life cycle analysis of AM products (Da Silva Barros, Zwolinski and Mansur, 2017), energy consumption studies (Hao et al, 2010; Baumers et al 2011; Kerbrat et al, 2016) and broader analysis of AM and sustainability (Huang et al, 2013; Gebler et al, 2014). Our work begins from the first principles of AM, namely its material domain.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 263-272. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

2. Bioinspired Materials

Biological materials and processes have been a source of design inspiration for architecture in the past (Hensel, Menges and Weistock, 2010; Mazzoleni, 2017). Nevertheless, difficulties in their synthesis and control in fabrication has prevented their wide adoption often resulting in morphological replication of their outcome or replication of their functional characteristics by synthetic polymers to suit manufacturing objectives.We developed Fungus-like adhesive materials (FLAM), a family of natural composites result of bioinspired design along a fabrication process to overcome some of those barriers (Author, 2018). They are composed of cellulose, a biopolymer common in plant matter, and chitin, a biomolecule often associated with the exoskeleton of arthropods and insects (Author, 2012). Study of the cell wall of oomycota, a fungus-like microorganism that combines those molecules, gave rise to FLAM. While arbitrary composition of the ingredients results to composites either too weak or uncontrollable, replication of the composition encountered on oomycota produced materials with strong and well-behaved properties. What makes them highly sustainable is their original components: cellulose is the most abundant bio-material on the surface of the earth (Reireter, 1999) and chitin may be the second most common natural material. Both originate from renewable sources and they are biodegradable outside special composting environments (Author, 2014). Moreover, both are obtained as by-products of industrial timber and food processing at low prices. We investigated various cellulosic sources including laboratory-grade cellulose, industrial wood flour fillers and waste saw dust from timber processing. The physical and mechanical properties of FLAM composites are in the range of high density synthetic foams and low-density timbers. Visually, when pure cellulose is used the material resembles paper while using wood flour, its appearance is closer to fibreboard products (Figure 1).

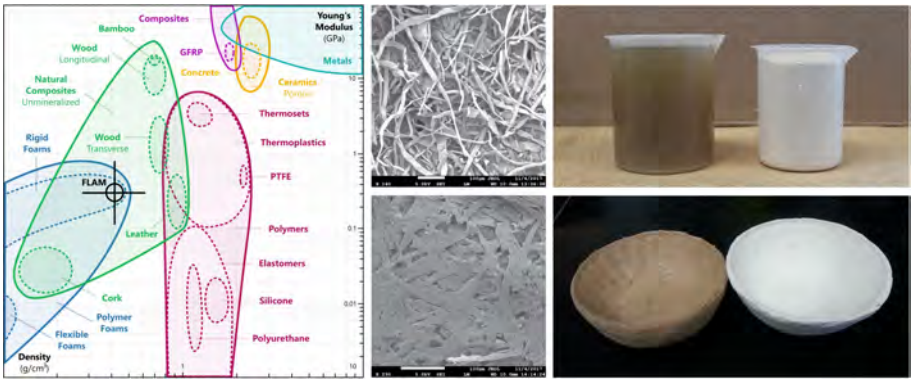


Figure 1. Left: Ashby plot of physical and mechanical material properties. Middle: Electron microscope photography. Right: Samples of FLAM with saw dust and pure cellulose.

3. Digital Fabrication

Robotic fabrication with natural materials has been a topic gaining acceptance in the past years in the architectural community with materials including clay (Friedman, Kim and Mesa, 2014; Dunn et al, 2016; Al Othman et al 2019), sand (Grammazio and Kohler, 2015) and wax (Gardinger and Janssen, 2014). Digital fabrication with FLAM composites is based on Material Extrusion (ME) principles (ISO/ASTM, 2015). The materials components are combined in an aqueous solution forming a viscous colloid deposited in linear filaments alike Fused Deposition Modelling (FDM) techniques familiar from rapid prototyping. As the material state is closer to liquid than solid, the process can be also considered as variation of the Direct Ink Writing (DIW) method. The process does not require temperature control during extrusion and the material dries overtime, as water evaporates, to form solid objects. The digital fabrication system developed for FLAM 3D fabrication is comprised of an industrial robotic arm, a high-pressure bulk material unloading pump, the associated volumetric dispenser attached to the robot's flange, various peripheral devices, such as an air drier and a die grinder, and integration components such as programmable logic controllers. To investigate how to improve the speed of production and product quality, the method combines three modes of operation including mainly additive (3d printing) but also net-zero (forming) and subtractive (machining) operations (Author, 2018).

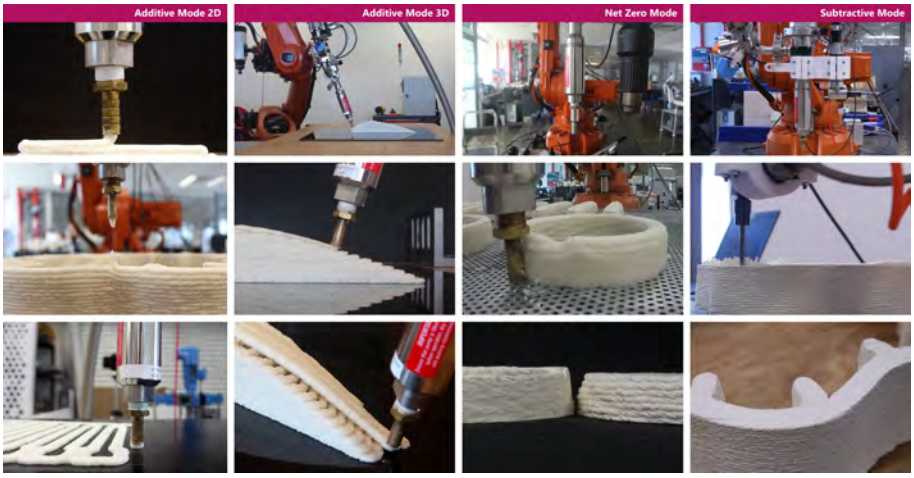


Figure 2. Left-to-Right: The digital fabrication process fuses 2D and 3D additive manufacturing with net-zero material change and subtractive principles.

4. Challenges

Using natural materials in additive manufacturing is challenging because of their innate variability. Insofar as no two pieces of wood are ever the same, FLAM composite fabrication needs to account for similar kind of variation. This is unlike standardized industrial products such as metal alloys and synthetic polymers,

developed exactly to avoid the unpredictability of raw natural material sources. We thus faced, and still do, significant difficulties before being able to 3D print with a certain level of confidence. Those include:



Figure 3. Various modes of failure due to difficulty of controlling natural materials.

1. Material viscosity is proportional to the pressure required for extrusion. If too low the material extrudes easily but it cannot support itself. High viscosities are prefered but require high-pressure systems. There is a limit of how much pressure can be applied on a material in suspension before its phases separate, the lower viscosity matrix pumps out first leaving behind a starved cellulose.
2. Particle size affects the pressure requirements due to interparticle friction. Waste saw dust requires higher pressures because of presence of a variety of other material components such as lignin and oils and contaminants.
3. While cellulose and chitin have low caloric value for most organisms, use of waste produced on occasions fungal growth. Using waste for sequestration is tolerated by the material but care is required to prevent such contamination.
4. The material cures at ambient temperature and humidity by water evaporation. If left to do so naturally, it takes several hours for parts to stabilize and several days before they fully harden. To accelerate curing, we tested oven baking and convective drying. Increasing the temperature rapidly yielded poor results as the exterior formed a crust trapping moisture or caused filament delamination.
5. The rate of moisture removal is related to wall thickness and surface area as parts dry outside-in. Thinner walls and larger surface areas exposed to air result to faster drying parts but too thin walls are also structurally weak.
6. Extrusion is dependent on motion speed and flow rate. If motion is too fast, filaments tend to break apart, detach from the base plate or one another. If flow rate is too fast, the shape of the filament becomes highly non-linear. Overall, the dimensions of the filament are highly sensitive to both velocity components.
7. Filament adhesion was approached by decoupling in vertical and in-plane directions. Vertically, it is insufficient to place beads on top of another as they do not adequately fuse. Instead, they are compressed to ensure a form of mixture. Care though is required because dynamic normal pressure applied affects shape, surface finish and overall stability.
8. In-plane fusion is also critical otherwise adjacent filaments delaminate while drying. Adjacent beads require approximately 40-50% overlap to bond. We printed several pairs at various overlap rates and mechanically sheared them.

When failure occurred outside the overlap we determined fusion was sufficient.

9. Wet FLAM is highly pliable and mechanically viscoelastic as is its stiffness is time dependent. It is difficult to model and simulate how an object will deflect overtime, as the behaviour is both dynamic and non-linear.
10. The most challenging aspect of 3D printing is in the transformation that takes place between wet and dry states. The material shrinks by as much as 5% along the direction of extrusion, 12% in the transverse and up to 32% vertically. Thus for achieving a specific geometry after curing, design geometry needs to be preset against anisotropic shrinkage.

5. Experimental Design

The process depends on numerous parameters, some identified and many still unknown. While their impact is observable their interactions are opaque. Attempting to model and drive the process analytically is as task of insurmountable complexity. It is possible however to perform experiments, observe results and instead of a mechanistic, develop an empirical model to systematize the problem and take steps forward. The method used, namely design of experiment (DOE), originates in statistical analysis and quality control (Montgomery, 1997). Its key idea is that a process can be approached as black box influenced by controllable and uncontrollable inputs. Varying controllable factors and measuring their effects, may explain statistically the source of variation and allows for control (Montgomery, 2009). We thus constructed a factorial DOE model. A unique aspect of the method is in varying multiple factors together, instead of one at a time. This reduces the number of tests performed while producing a picture across the process domain. Data collected were used to fit a polynomial model that accounts not only for the influence of the main factors but also their interactions.

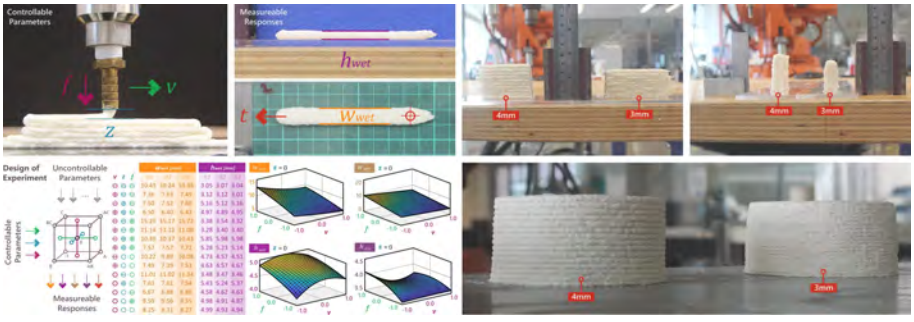


Figure 4. Left: Design of experiment main factors, effects and response surfaces. Right: Filament uniformity achieved using multi-response optimization for 3 and 4 mm heights.

Parameters used include the motion speed *(v)*, flow rate *(f)* and vertical nozzle offset *(z)*. We measured the filament width *(w)* and height *(h)* in wet and dry states and their tensile strength *(t)*. For each factor we established three test levels, low, medium and high, and constructed a face-centred central composite design (CCD) model to account for non-linearity (Author 2018). The model is expressed as a set

second order relationships between controllable parameters to expected outcomes. Analysis of variation, assisted in understanding which parameters and interactions affected results and those with low significance were purged. Graphically the model is represented by response surfaces where input parameters map to response outcomes. To confirm that the model was not merely statistically sound but it produced desirable results we printed several prototypes. The operating settings used, were result of multi-response optimization using composite desirability to mediate between responses (Derringer and Suich, 1980). Results were successful (Figure 4) as both 3 and 4 mm of layer heights produced consistent filament dimensions.

6. Prototyping

As a demonstration for being able to print large-scale objects we designed and built a pillar prototype. It measures 5 m vertically with diameter ranging between 0.6 and 1.0 m (Figure 5). The design was developed using implicit surfaces whereby a distance-field was loaded with seven pairs of parabolic arcs arrayed radially and level-set profiles were extracted by polygonization. This produced 14 tubular sections which fuse and detach from one another vertically, creating a geometrically and topologically a complex shape that cannot be fabricated easily by conventional processes. To 3D print the pillar efficiently, we segmented it into 50 vertical parts. Those were fused after partially drying with FLAM adhesive into larger blocks. Blocks were mechanically fastened for ease of transporting and assembling the pillar.

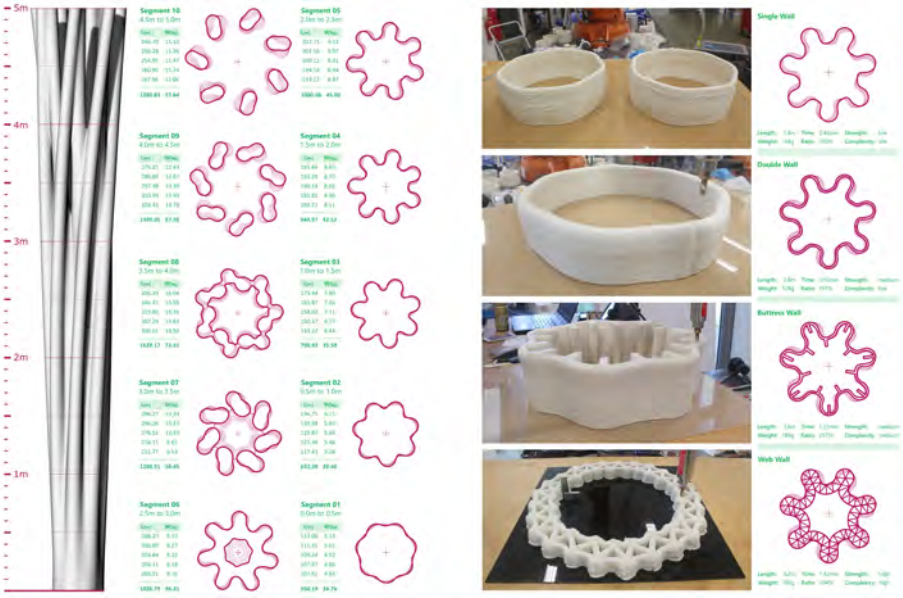


Figure 5. Left: Diagrams of the pillar at various levels. Right: Wall design properties.

Using single filament thick walls, circa 12 mm, was questionable because of structural considerations for supporting its total weight and because we expected dimensional errors due to shrinkage for which thin walled segments would leave little room for post-processing. An alternative wall profile design used an internal web, offset 40 mm inwards, to increase the sectional area (Figure 5). While the design was reasonable, it was abandoned because of increased material consumption as high as four times of a single wall case. Another alternative, incorporated 50 mm vertical fin stiffeners. The fins were radially arranged from the center of the pillar and beyond structural improvement, they aided registration and fixing between consecutive segments. This design also required triple the amount of material compared to single wall design and eventually the simpler double filament wall design, circa 20 mm, was used as it required only twice as much material per segment.

The pillar is comprised of 2,000 layers, 40 layers per segment, with each layer measuring 20 by 2.5 mm in cross-sectional width and height after curing. To measure material consumption, we use the travel distance of print for which we printed about 10.6 km of material total with 213 m per segment on average. With extrusion rate of approximately 0.045 kg/m, the total weight at wet state was circa 480 kg of which 370 kg was water. The pillar, without accounting for segment to segment adhesive and hardware, weights approximately 105 kg after drying. With motion speed of circa 50 mm/s the total print time was about 60 hours with the smallest segment requiring 30 min and the largest 2 hours. The cost in raw materials was approximately 275USD or about 2 USD/kg.



Figure 6. Left: Completed pillar. Right: Fabrication process.

Beyond a segment for which we printed without the correct surface to machine path offset and had to recycle the material and reprint; and another case of crashing the robot on a printed part due to registration error, the process was interrupted. It is encouraging that in terms of robustness the process seems already to perform very well and both incidents were due to human error. In terms of dimensional accuracy, even though the overall geometry was successfully reproduced, there is a lot more work to be done for improvement. We are not far from a few millimeters away though, something that is visually observable by the protrusions between consecutive segments. The cause of this is the anisotropic shrinkage between the bottom layers of a part which adhere to the printing base in conjunction with the top layers which are not compress fused and they dry faster as more surface is exposed to air compared to interim layers.

7. Conclusions

We presented part of the development for a digital fabrication technology aiming to approach additive manufacturing from a sustainable perspective. We highlighted the challenges of working natural materials and their highly complex behaviours. This explains why despite offering the most environmentally benign option for production, they have been largely rendered obsolete and displaced by standard industrial material products.

In architecture we rely on representations and mechanistic models aiming to prescriptively predict the future. It is impossible to perform comprehensive experimental design due to scale, time and cost. However, experimental methods are not absent as computer simulations cannot yet model intricate physical phenomena. Those include mechanical evaluation using tensile and bending tests, impact tests on cladding units and quality control procedures such as concrete slump tests. Statistical methods of experimental design are valuable for developing understanding of complex physical phenomena, extracting material intelligence, informing design thinking and eventually allowing for process control. As the barrier from design to production lowered by programmable design and production systems over the past few decades, it is now easier to perform physical experiments and also measure results. We believe the use of empirical predictive modelling techniques will progressively become an invaluable tool in the domain of digital design and fabrication. Computational experimental design techniques may exactly what eventually will allow us to understand natural materials and perhaps bring them back in manufacturing and construction.

The bulk of the research effort so far has been devoted in basic technology development including material and fabrication systems design. We have not investigated concrete applications for additive manufacturing with natural composites. We can only speculate of potential applications based on material and fabrication properties and initial interest expressed by the industry parties. Applications in product design include recyclable packaging, customized furniture, lightweight components for naval, automotive and aerospace, products that non-toxic materials properties are important, upcycling or sequestration of industrial waste. In construction, if unmodified by synthetic polymers which may deteriorate its sustainability aspects, the material is not yet structural in the

building sense nor weather resistant in the sense of plastics. As such we can foresee applications related to interior design such as fittings and partitions, reusable molds for cast building components, perhaps acoustic or insulating products, restorative applications for historical timber architecture. In any case a lot more additional work is required to assess its suitability for building applications.

In conclusion, we demonstrated positive steps towards creating large-scale artifacts with two of the most abundant natural material on earth. There is a lot more research work required to fully understand and control the process, but early results are encouraging. We believe that continued effort on integrating natural materials and digital fabrication will pave the way towards environmentally-aware paradigms of production and a more sustainable society.

References

Da Silva Barros, K., Zwolinski, P. and Ikhan Mansur, A.: 2017, Where do the environmental impacts of Additive Manufacturing come from? Case study of the use of 3d-printing to print orthotic insoles, *12ème Congrès International de Génie Industriel*, Compiegne.

Baumers, M., Tuck, C., Bourell, D.L., Sreenivasan, R. and Hague, R.: 2011, Sustainability of additive manufacturing: measuring the energy consumption of the laser sintering process, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2228-2239.

Derringer, G. and Suich, R.: 1980, Simultaneous Optimization of Several Response Variables, *Journal of Quality Technology*, **12**(4), 214-219.

Dunn, K., Wozniak O'Connor, D., Nemela, M. and Ulacco, G.: 2016, Free Form Clay Deposition in Custom Generated Molds, Producing Sustainable Fabrication Processes, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 317-325.

The Royal Academy of Engineering, R.A.E.: 2013, "Additive manufacturing: Opportunities and Constraints" . Available from The Royal Academy of Engineering<https://www.raeng.org.uk/publications/reports/additive-manufacturing> (accessed November 2018).

Faludi, J., Bayley, C., Bhogal, S. and Iribarne, M.: 2015, Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment, *Rapid Prototyping Journal*, **21**(1), 14-33.

Ford, S. and Despeisse, M.: 2016, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, *Journal of Cleaner Production*, **137**, 1573-1587.

Friedman, J., Kim, H. and Mesa, O.: 2014, Experiments in Additive Clay Depositions, Woven Clay, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 261-271.

Gardinger, B.J. and Janssen, R.S.: 2014, FreeFab, Development of a Construction-Scale Robotic Formwork 3D Printer, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 131-144.

Gebler, M., Anton, J.M., Uiterkamp, S. and Visser, C.: 2014, A global sustainability perspective on 3D printing technologies, *Energy Policy*, **74**, 158-167.

Gramazio, F. and Kohler, M.: 2011, "Prozedurale Landschaften 2" . Available from <http://gramazio-kohler.arch.ethz.ch/web/d/lehre/211.html> (accessed November 2018).

Hao, L., Raymond, D., Strano, G. and Dadbakhsh, S.: 2010, Enhancing the sustainability of additive manufacturing, *5th International Conference on Responsive Manufacturing - Green Manufacturing*, Ningbo, 390-395.

Hensel, M., Menges, A. and Weinstock, M.: 2010, *Emergent Technologies and Design: Towards a Biological Paradigm for Architecture*, Routledge.

Huang, S.H., Liu, P., Mokasdar, A. and Liang, H.: 2013, Additive manufacturing and its societal impact: a literature review, *The International Journal of Advanced Manufacturing Technology*, **67**, 5-8.

Lewis, A. J.: 2006, Direct Ink Writing of 3D Functional Materials, *Advanced Functional*

Materials, **16**, 2193-2204.
Mazzoleni, I.: 2017, *Architecture Follows Nature-Biomimetic Principles for Innovative Design*, CRC Press.
Montgomery, C.D.: 1997, *Design and Analysis of Experiments*, Wiley and Sons Inc..
Montgomery, C.D.: 2009, *Introduction to Statistical Quality Control*, Wiley.
Reiterer, A., Lichtenegger, H., Tschegg, S. and Fratzl, P.: 1999, Experimental evidence for a mechanical function of the cellulose microfibril angle in wood cell walls., *Philosophical Magazine A*, **79**, 2173–2184.
Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., Campbell, I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B. and Martina, F.: 2016, Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints, *CIRP Annals*, **65**(2), 737-760.
Tofail, S.A.M., Koumoulos, E., Bandyopadhyay, A., Bose, S., O'Donoghue, L. and Charitidis, C.: 2018, Additive manufacturing: scientific and technological challenges, market uptake and opportunities, *Materials Today*, **21**(1), 22-37.

PROGRAMMING INTELLIGENT ARCHITECTURE TO BE RESPONSIVE TO REAL-TIME DATA

HYUNJAE NAM
[1]*Architectural Association*
[1]*Hyun-jae.Nam@aaschool.ac.uk*

Abstract. This study examines the development of intelligent architecture capable of reading real-time data and controlling spatial configurations accordingly. In terms of responsiveness at an architectural scale, it is questionable whether an architectural system can adapt or adjust its spatial configurations to the time-based changes of social activities. The urban open data movement allows individuals to navigate or measure real-time occurrences in cities, and such data can be used to accommodate users' demands for social space. Exploiting urban open data, the design experiment focused on extracting data pertaining to real occurrences of social activities and weather conditions in a city, setting an algorithm mapping the sequence from the data to architectural behaviours, and simulating the architectural model in real time. By means of proposing a design strategy, this research contributes to cross-disciplinary approaches to developing smart buildings and cities.

Keywords. Real-time data; urban open data; weather API; architectural responsiveness.

1. Introduction

As a result of advancements in sensor and data-processing technologies, the improvement of systems in buildings and cities today focuses on real-time responsiveness (Picon, 2015). The recent realm of architectural practice has been extended to consider the changeable conditions of physical spaces (e.g. controllable façades and roofs, kinetic structures, and interactive media walls) (Fox, 2016). On the other hand, the 'smart city' slogan has directed the approach of city planning towards monitoring and managing technological systems in cities through ubiquitous information and communications technology (ICT) networks (e.g. transportation, energy, and online services) (Picon, 2015).

Regarding the potential applications of architectural adaptation and ICT networks, this design research integrates the kinetic adaptability of architectural skin with the techniques of real-time data streaming. The design experiment investigated an embedded system that can control spatial configuration and transformable structures that can adapt flexibly to different input data. The embedded system requires the ability to understand input data, to select and evaluate the data, and ultimately to decide on the best option for controlling spatial

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 273-282. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

quality. This programmable use of space is tested by digital simulations and algorithm designs in Grasshopper in Rhino 6.

For the simulation, Bryant Park in New York City (NYC) was selected as the site for the architectural model. Firstly, investigating one of NYC's open data, 'NYC-permitted-event information', a data visualisation technique was applied in order to observe social activities in open spaces in the city. Secondly, to provide the optimal conditions for the outdoor space, NYC weather data over the past 2 years were collected and analysed. Through an application programming interface (API), the two datasets were employed to trace real-time data. Based on the two datasets, the rule set was applied to activate the responsive skin system in real time.

This paper introduces the design experiment that utilises urban open data to design a computational model for real-time responsiveness. Mapping the sequence in an algorithm from the input of social and environmental factors to the output of spatial variations, the experiment developed an architectural skin system capable of being responsive to real-time data.

2. Background

2.1. INTELLIGENCE IN THE ARCHITECTURAL DISCIPLINE

In the 1960s, architects started to explore interactive and adaptive architecture. Cedric Price brought the concepts of not only cybernetics but also intelligence to the architectural discipline (Yiannoudes, 2016). Moreover, Nicholas Negroponte attempted to integrate architecture with artificial intelligence, computer science, and electronic engineering in order to extend the realm of architecture (Steenson, 2017). The Generator project (1976-1979) and the SEEK project (1970) demonstrated how architecture connected to central computer devices could improve physical spaces through the configuration of self-generated decisions. These projects first suggested the architectural possibility of artificial intelligence being applied in order to handle real-time occurrences in physical spaces (Yiannoudes, 2016; Steenson, 2017).

With the development of computational technologies, architectural practices have adopted the applications and enhanced the methods of generating or creating new types of architecture. Using sensor and actuator technologies, the projects of responsive architecture have attempted to realise programmable architectural elements that can interact with users (Yiannoudes, 2016). Furthermore, digital tools have become sufficiently powerful to model simulations of structures to generate spatial variations through computational algorithms capable of processing form-finding or form-searching. Eventually, the digital tools have aided in the design of structural complexity through machine intelligence (Carpo, 2017).

In fact, the term 'intelligence' remains an ambiguous concept in the architectural discipline. In general, intelligence can be described as the ability to perceive or understand information and to make adaptive decisions. In multidisciplinary fields, this term has been used to enhance the ability of human-made artefacts in order to connect them to the principles of cognitive processes. A gap exists between the emerging knowledge on intelligence and its

technical applications to architectural practice.

Meanwhile, the terms ‘intelligent’ and ‘smart’ have been aimed at technical realisation or achievement. There are ongoing projects, mainly developed by computer scientists and engineers, that involve installing intelligent systems in spaces such as intelligent environments (IEs) and ambient intelligence (AmI). IEs are intended to achieve the functional capacities of reacting to environmental conditions operated by sensory systems embedded in physical objects. The vision of AmI is that ubiquitous computing technology through wireless networks facilitates electronic environments to be sensitive and responsive to the presence of people in buildings (Yiannoudes, 2016). Through the Internet, increasingly connected and integrated systems are the technological goal, as initiated by Mark Weiser; the term ‘ubiquitous computing’ was to provide the vision for information technologies (Weiser, 1991).

2.2. SMART CITY

Since the advancement of ICT in the 1990s, near-ubiquitous access to the Internet has extended the means of communicating and sharing information, and an urban development strategy called ‘smart city’ has extensively utilised advanced technology. The smart city projects were encouraged to include the idea of utilising ICT through different approaches. For example, in Amsterdam, smart city projects developed saving energy; Southampton City Council expressed it as a means of emphasising the importance of e-services; and Malta Smart City aims at economic growth through the ICT of business organisations (Deakin and Waer, 2012, p.2). The term ‘smart city’ is not cohesively identified, but is, nonetheless, widely used as a slogan to promote city development (Hollands, 2008).

In order to develop smart cities, Paskaleva (2012) questioned how this new technology could impact upon social and cultural factors in cities. According to Hollands (2008, p.315), ‘smart cities must seriously start with people...rather than believing that IT itself can automatically transform and improve cities’. He pointed out that smart cities should consider cultural development; indeed, the term ‘smart cities’ is merely a label for intelligent, progressive, or entrepreneurial objectives of city development via high tech. Moreover, Paskaleva (2012) stressed that one of the city’s assets is people and citizen empowerment of their own wisdom. Recognising people as an asset and building social networks is the practical agenda for system change in cities.

Furthermore, the collection of spatial and temporal data in ICT enables urban information systems to improve various geolocation services. Visualisations of urban data have revealed many of the significant dimensions of a city, and the analysis of telecommunication data helps us to understand dynamic interactions in social networks (Ratti and Claudel, 2016). Batty (2013, p.274) argues that the increased collection of big data, which involves human activities, shifts the focus of city development ‘from longer-term strategic planning to short-term thinking about how cities function and can be managed’. ICT enables people to organise their own social events, and those activities are observable through the collection of data.

3. Analysis and visualisation of NYC open data

3.1. NYC-PERMITTED-EVENT DATA

The open data movement has allowed the public to access urban-related data resources such as population, income, and land use via the Internet. The NYC Open Data portal has provided a vast amount of data along with the categories of business, city government, education, environment, and health via the web address data.ny.gov or opendata.cityofnewyork.us. Given that some of the city data include geolocation (e.g. longitude and latitude, zip code, address), thematic mapping techniques facilitate the depiction of different conditions in the city. Digital technologies dealing with geolocation enable us to know 'the position of a multitude of stationary or moving objects, in real time' (Picon, 2015, p.13).

Using 'NYC-permitted-event' data, this research focused on the set of the algorithm in Grasshopper to visualise social events held in open spaces in Manhattan that took place at different times. An algorithm in Grasshopper was set to process the transmission of information from the input of data to the output of visualising locations of city events. The geographic data MapPLUTO-Manhattan (Shapefile) was used as the base map to superimpose the NYC event. The comma-separated values (CSV) format file was downloaded via the portal, and text-based data were inserted in Grasshopper for visualisation on the map.

Based on the collection of 1 year's data (from November 2017 to October 2018), the data visualisation attempted to depict the location, duration, and frequency of social events in Manhattan. As shown in the data visualisation (Figure 1), most of the locations of events were placed in open spaces, such as parks, small plazas, and streets. Because the events were organised in outdoor spaces, the frequency of events highly depended on the weather conditions. The overall frequency of events per month demonstrated that from December 2017 until April 2018 fewer social activities occurred in NYC open spaces than in other months.

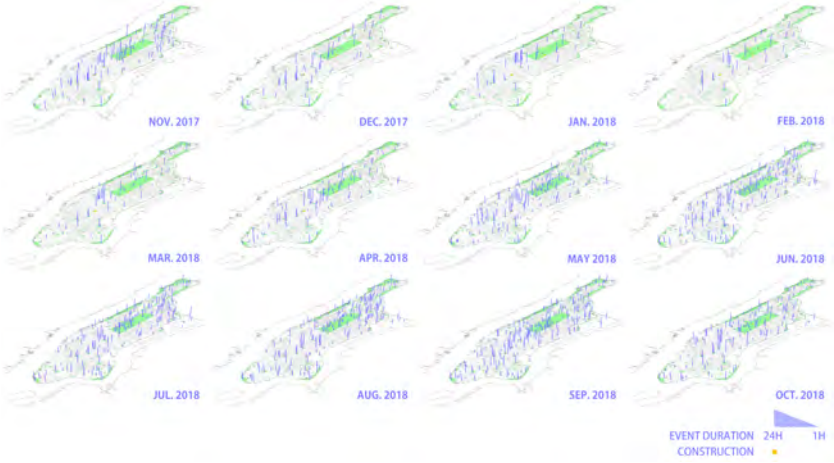


Figure 1. Location and duration of NYC permitted events in Manhattan.

The analysis of the number of events per month showed that the total number of events peaked in July and August (Figure 2). For 1 year, the highest number of events was 3,041 in August, whilst the lowest number was 733 in February. In the case of the special event, as shown in Figure 2, approximately twice as many events occurred in the months from May to October than in the months from November to April. The lowest number of special events occurred in January and February.

According to the analysis of event types, the events were mostly categorised into the type of special event that took place in parks and small plazas. The number of special events comprised 69.4% of the total number of events. The number of occurrences of construction captured 21.7%, which was the second-largest amount of frequency. The percentage of farmers' markets and sidewalk sales was 5.1%. The rest of miscellaneous events, such as street events, parades, and athletic races, which temporarily occupied streets, accounted for 3.8%.



Figure 2. Number of events per month in Manhattan.

Measuring the total number of events per location, based on the 1-year data, the most frequently used public open space for organising social activities was Bryant Park, located in Midtown Manhattan (Figure 3). Compared to other public spaces, many more events were arranged in Bryant Park: 850 in Bryant Park; 490 in Randall's Island Park; 450 in Inwood Hill Park; 400 in Madison Square Park; and 100 to 400 in multiple locations in Central Park (these numbers exempted the list of construction).

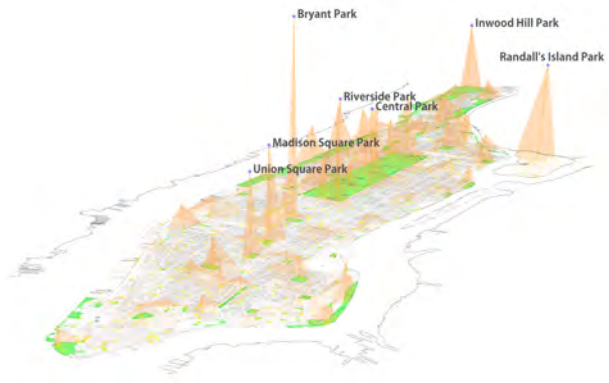


Figure 3. Frequency of NYC permitted events (from November 2017 to October 2018).

3.2. SOCIAL AND WEATHER DATA IN BRYANT PARK

With its successful restoration and redevelopment, Bryant Park has become one of the most popular public spaces in the city since the 1990s (Crabil, 2009). In 1979, the sociologist William H. Whyte suggested the strategies in order to improve the accessibility and amenity of the park (e.g. removing the fences, constructing the accesses of ramps, and restoring the fountain) (Francis, 2001). In the 1980s, the Bryant Park Restoration Corporation and the adjacent New York Public Library embarked on the renovation of the park based on Whyte's analysis (Crabil, 2009). In the 1990s, with the aim of making 'a multi-use and user-friendly urban open space', the landscape was redesigned by the landscape firm Hanna Olin (Francis, 2001, p.6). Nowadays, the Bryant Park Corporation, a non-profit organisation founded in 1980, has managed free public events and the information on social activities is easily accessible through its website (Bryantpark.org, 2018).

According to the analysis of the list of Bryant Park events, extracted from NYC-permitted-event data, most of the events reoccurred at selected locations in the park. Table 1 summarises the name and frequency of events within the locations. The most frequently repeated event was Juggling. The event called Winter Village, which had an ice-skating rink (replacing the lawn with the rink) and shops and bars, was the second most frequent event. In the Upper Terrace and Fountain Terrace areas, mostly recreational types of activities were arranged. In East 42nd Street Allee, the public could join workshops or book clubs. Through the data analysis, the information of location, event type, and schedule was obtained.

In addition, the weather data of Bryant Park, as specified by the zip code 10018 (Midtown Manhattan), were collected and analysed, since the frequency of outdoor activities was highly influenced by weather conditions, as shown in previous studies. By extracting the data through a weather application programming interface (API) via the website (https:www.worldweatheronline.com/developer), the 2-year weather data (2016 and 2017) were collected and sorted in order to observe the most repeated weather descriptions. Figure 4 displays the texts of weather descriptions over the 2 years, as well as the frequency.

Table 1. Social events in Bryant Park (from November 2017 to October 2018).

157 **Upper Terrace**	147 **East 42nd Street Allee**	146 **Fountain Terrace**	72 **Lawn**
115 Piano 17 Tuesday Yoga 12 Knitting 6 Sing-a-Long Thursdays 4 New York City Opera 1 National Week of Conversation 1 Conversation Day 1 Worldwide Knitting in Public Day	24 Celebration 20 Poetry 15 Author 12 BookClub 9 Reading Room Kids 8 Reel Talks 8 Word for Word Storytime 8 Reel Talks 8 Word for Word Storytime 8 Writers Workshop 8 Non-Fiction 7 HBSC Business and Finance 5 Beekeeping 3 Picnic 2 Crosswords Events 1 Poem in Your Pocket Day 1 Writers Workshop Teens	44 Tai Chi 39 Public Tours - Wednesdays 30 Boot Camp 16 Pilates 5 Dance Party 3 Scooper Bowl 3 Bingo 2 Chess Tournaments 1 World Tai Chi Day 1 Latin Festival 1 69th Annual Obon Dance Festival 1 Salsa Night	18 Thursday Yoga 18 Bryant Park Moves 10 Movie Nights 6 Contemporary Dance 6 Broadway in Bryant Park 5 Accordions Around the World 3 Kubb Tournaments 3 Picnic 1 Pedestrian Wanderlust Jam June 1 Accordion Festival 1 Square Dance
376 **Bryant Park**	26 **Heiskell Plaza**	22 **Stage Performance**	21 **Le Carrousel**
218 Juggling 155 Winter Village at Bryant Park 1 Celebration 1 Chick-fil-A First 100 1 Miscellaneous	14 Spring Birding Tours 12 Fall Birding Tours	15 Shakespeare 4 Carnegie Concerts 2 Emerging Music Festival 1 Carnegie Festival	9 Le Carrousel Magique 5 Puppet Shows 4 Le Carrousel Storytime 3 Party
24 **Library Plaza**	18 **Gravel Walk**	9 **Petanque Court**	
17 Fencing 7 Fly Fishing	18 Language Class	9 Petanque Tournaments	

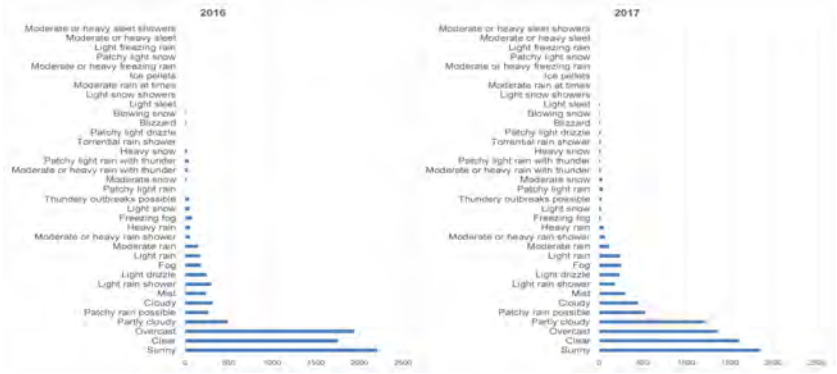


Figure 4. Weather description in Midtown Manhattan in 2016 and 2017.

4. Design experiment

4.1. PROGRAMMING CONTROL SYSTEM OF RESPONSIVE SKIN

Using such text-based data as described in Table 1 and Figure 4, the design experiment developed an algorithm mapping the sequence from the input of data to the output of the responsiveness of architectural skin (Figure 5). The two tabular datasets - event and weather data formatted in CSV files - were inserted in Grasshopper, and the texts were sorted by a set of rules in the algorithm. In the case of event data, the sorting process classified the texts by category of event name, schedule, and location. After sorting the data, the matching process extracted the texts for the specifically selected date and time. The two datasets were used as the input to command the performance of architectural behaviours: the event data activated folding the skin frames and the weather data controlled the angles of rotation of skin panels. The following describes the process of the algorithm:

1. Insert the two datasets (event and weather data).
2. Sort the event data by category and match with the selected date and time.
3. If matched, activate folding the skin frames. If not, do not process.
4. If activated, match with the weather data and find the right angle to rotate the skin panels.

This algorithm was tested with the datasets allocated in the location of East 42nd Street Allee in Bryant Park and with the date of August 1st, 2018 (Figure 6). Firstly, the algorithm was set in order to read the starting and ending times of the event in order to activate and deactivate folding the skin frames. Secondly, using weather data, the test examined the flow of the algorithm from the input of weather descriptions to the output of angles of rotation for the skin openings: the texts describing rainy conditions implemented closing the skin panels completely; for a sunny or clear sky, the openings of the panels were maximised; the roof and the wall panels were separately tilted depending on the different weather conditions. For this test, the weather data were based on the 1-year data (from January 1st, 2017 until January 1st, 2018) downloaded from the website https:openweathermap.org.

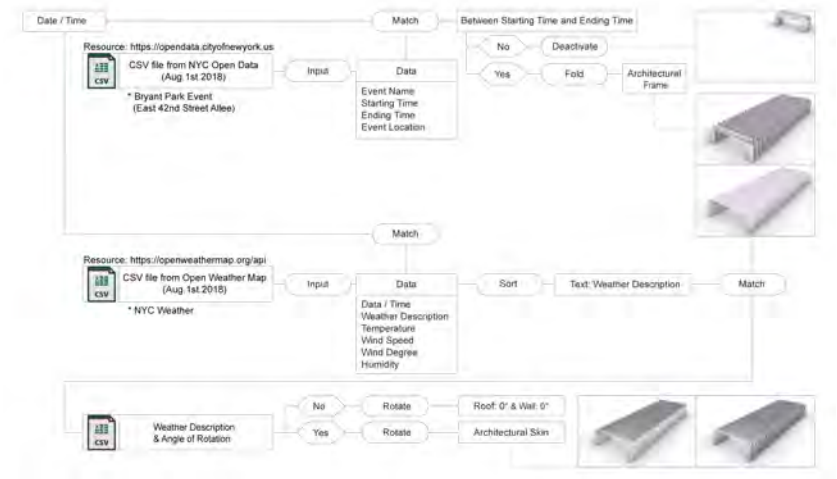


Figure 5. Algorithm of responsive skin.

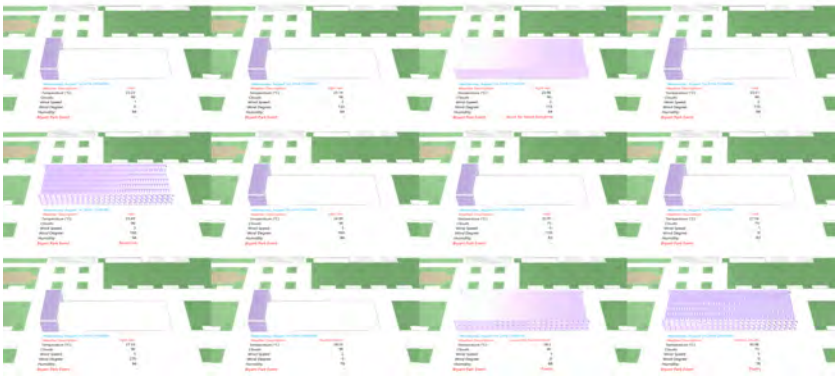


Figure 6. Simulation of responsive skin connected to social and weather data.

4.2. REAL-TIME SIMULATION

The test model verified that an algorithm could turn on and off the activation of the deployable skin frames as well as the opening of the skin panels in response to the two datasets using the CSV files. For real-time simulation, the algorithm was adjusted to connect APIs and to match the current time (Figure 7). That is to say, directly connecting to the online data and tracing the real time in the algorithm, the responsive skin could automate the performance of the behaviours for folding and opening in real time. The model, installing the skin system at four different locations on the map of Bryant Park, was simulated on September 26th, 2018 (Figure 8). The skin systems were activated by the different event schedules arranged in the four locations. In addition, because the real-time simulation was

tested in London, the time was converted to New York's time zone, i.e. Eastern Standard Time.

To extract the real-time data - the event and the weather data - two specified URLs (uniform resource locators) were typed to request Bryant Park's online data from the servers through APIs and the received data were sorted by the algorithm in Grasshopper. Through the web address on the World Wide Web, a script in the C # component in Grasshopper extracted the weather data in JSON format, and the set updating every 5 minutes traced the real-time data. Compared to the test model using the downloaded CSV files, which required inserting the files manually, extracting the online data through APIs facilitated the real-time simulation for the automation of the control system by means of a set of rules.

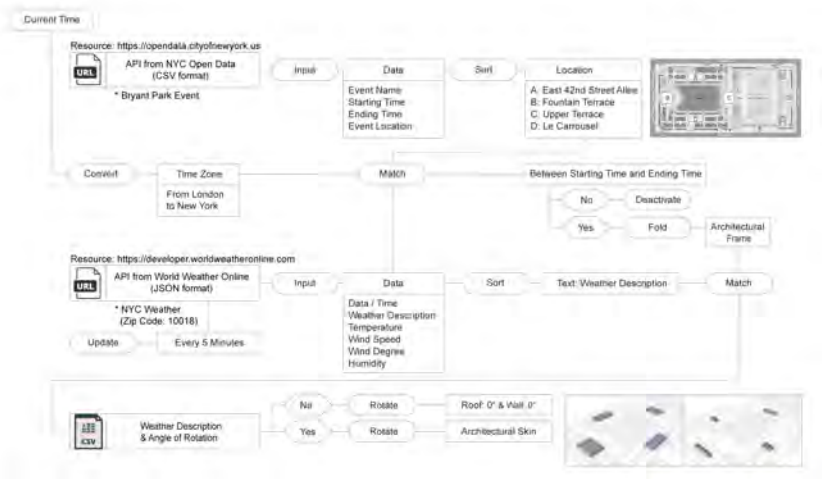


Figure 7. Algorithm for real-time simulation.

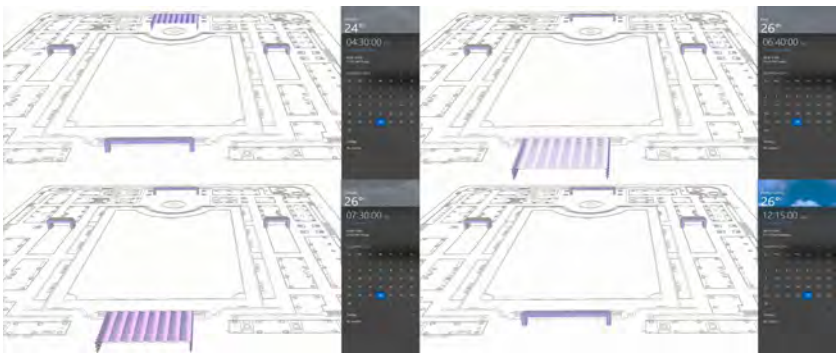


Figure 8. Real-time simulation.

5. Conclusion

Within this paper, exploring the keyword 'intelligence' in the field of architecture identified that the term has been used to describe technological applications capable of mediating people and their environments. In fact, the use of ICT - the utilisation of the Internet - to create 'smart' or 'intelligent' systems has tended to bridge the gap between digital and physical space (Deakin and Waer, 2012; Ratti and Claudel, 2016). Since it was crucial to consider what the advancement of ICT stands for, the focus in this research was on investigating sociocultural contexts in the city to suggest a place-making strategy for smart buildings and smart cities. The presented research utilised urban open data not only for the analysis of social events in the city but also for the practice of architectural responsiveness. By means of the set of algorithms, the analysis revealed the frequency and the repeated descriptions of social activities and weather conditions. The collection of data, indicated by a territorial condition, could be used as the input to activate real-time responsiveness of architectural skin. The real-time simulation examined whether the text-based data could promptly transform into the performances of architectural behaviours. This ongoing research further focuses on the investigation of contexts of social events and more detailed numerical values of weather conditions in order to develop a decision-making process within an algorithm.

References

"Bryant Park" : 2018. Available from <http://bryantpark.org> (accessed 20 November 2018).

Batty, M.: 2013, Big data, smart cities and city planning, *Dialogues in Human Geography*, **3(3)** , 274-279.

Carpo, M.: 2017, *The Second Digital Turn: Design Beyond Intelligence*, MIT Press, Cambridge.

Crabill, D.: 2009, Project for Public Spaces, *Agora Journal of Urban Planning and Design*, **1**, 43-47.

Deakin, M. and Waer, H.A. 2012, From Intelligent to Smart Cities, *in* M. Deakin and H.A. Waer (eds.), *From Intelligent to Smart Cities*, Routledge, London and New York , 1-20.

Fox, M.: 2016, *Interactive Architecture: Adaptive World*, Princeton Architectural Press, New York.

Francis, M.: 2001, A Case Study Method for Landscape Architecture, *Landscape Journal*, **20(1)**, 15-29.

Hollands, R.G.: 2008, Will the real smart city please stand up?, *City*, **12(3)**, 303-320.

Paskaleva, K.A. 2012, The smart city: A nexus for open innovation?, *in* M. Deakin and H.A. Waer (eds.), *From Intelligent to Smart Cities*, Routledge, London and New York, 21-39.

Picon, A.: 2015, *Smart Cities: A Spatialised Intelligence*, John Wiley & Sons Ltd.

Ratti, C. and Claudel, M.: 2016, *The City of Tomorrow: Sensors, Networks, Hackers, and the Future of Urban Life*, Yale University Press, New Haven and London.

Steenson, M.W.: 2017, *Architectural Intelligence: How Designers and Architects Created the Digital Landscape*, MIT Press.

Weiser, M.: 1991, The Computer for the 21st Century, *Scientific American*, **265(30)**, 94-104.

Yiannoudes, S.: 2016, *Architecture and Adaptation: From Cybernetics to Tangible Computing*, Routledge, London and New York.

OPTIMIZATION OF CLAY MOULD FOR CONCRETE CASTING USING DESIGN OF EXPERIMENTS

SIHAN WANG[1], ZACK XUEREB CONTI[2] and FELIX RASPALL[3]
[1,2,3]*Singapore University of Technology and Design*
[1,2]*{sihan_wang|xuereb_zack}@mymail.sutd.edu.sg*
[3]*felix_raspall@sutd.edu.sg*

Abstract. This paper presents a research work to optimize the Additive Manufactured (AM) clay moulds for concrete casting utilizing the Design of Experiments (DOE). The objective of this approach is to understand the impacts of clay moulds' fabrication parameters on the displacement of cast concrete artefacts. This will contribute to efficient and economical clay mould production without losing accuracy. We adopt a DOE approach to reveal insights into the influence of critical fabrication parameters on the displacement of the final concrete artefact and thus, suggest critical parameter settings to ensure that the lateral pressure exerted by concrete in the vertical build-up is sustained. We demonstrate experimental results for a case study: vertical columns of circular cross-sections.

Keywords. Clay Mould; Additive Manufacturing; Robotic Fabrication; Design of Experiments.

1. Introduction

In the past two decades, the use of cementitious materials in Additive Manufacturing (AM) technologies has grown substantially within the Architecture, Engineering, and Construction (AEC). These AM techniques, including Contour Crafting - concrete extrusion AM (Khoshnevis, 2004) and D-shape project - concrete binderjetting AM (Cesaretti, et al., 2014) present advanced options to concrete construction leading to high production rate, more geometry freedom and cost reduction (Perrot et al., 2016). In this paper we adopt a clay robotic approach for concrete casting (Figure 1), where the AM extrusion of a clay is used as a mould for concrete to be poured into (Wang et al., 2017). Once the concrete cures, the clay is demoulded and can be recycled for subsequent prints. Thus, this method takes the advantage of AM to enable the production of freeform geometries without depending on extensive one-off formworks. The use of clay as a mould, further sidesteps such problems of additive manufacturing as the printed material's performance is not equivalent to that of the final product.

However, there remain unsolved issues which need to be addressed in this fabrication method. The drying process, enhances its tensile strength and stiffness (Barnes, 2018; Tollenaar et al., 2017; Trabelsi et al., 2012), which in turn enables the clay mould to withstand material mass in large scale casting. However, as a

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 283-292. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

result of the drying process , the dry clay mould is likely to absorb water from the freshly cast concrete due to its lower water ratio, subsequently inducing the rapid dehydration of concrete resulting in cracks and even structural fractures (Yang, 2015; Figure 1, right). This primary problem comes along with low printing resolution - the 7mm layer heights and a noticeable shrinkage of the clay moulds through drying(Wang et al., 2017). As such, these provide us with the opportunities to improve the existing fabrication procedure by introducing concrete casting into wet clay moulds with smaller layer heights. We also hypothesize that the shrinkage cause by drying process might contribute to the self-demoulding, which means clay mould could shrink over time till cracking.



Figure 1. Clay Robotics, Left: 1.4 meters reinforced concrete column with its clay envelope half demoulded; Right: Structural fracture when concrete been cast into a dry clay mould.

When the clay mould is wet, it is likely to deform under lateral pressure induced by the concrete. In this context, our study is motivated by the challenge to identify the relationships between a set of fundamental parameters and the displacement of the final concrete artefact. We approach this challenge using design of experiments to help us reveal as much as information possible, with a minimum number of experimental runs. The remainder of the paper is organized as follows: Section 2 describes the experimental set up; the following section introduces DOE, followed by a case study of vertical columns with circular cross-sections.

2. Experimental set-up

2.1. PRINTING HARDWARE AND MATERIAL

We considered two main factors for the mass production of clay mould: the necessary torque for extruding rather viscous material and the precise material deposition rate. In this scenario, a ram pump mechanism was utilized to execute the constant clay extrusion (Figure 2, right). This was made up of a NEMA 34 stepper motor, a 1: 40-reduction gearbox with cylinder, piston with frames. We opted a KUKA KR 90 R3100 robot arm as our positioning apparatus that allows control of location and motion of deposition (Figure 2, left).

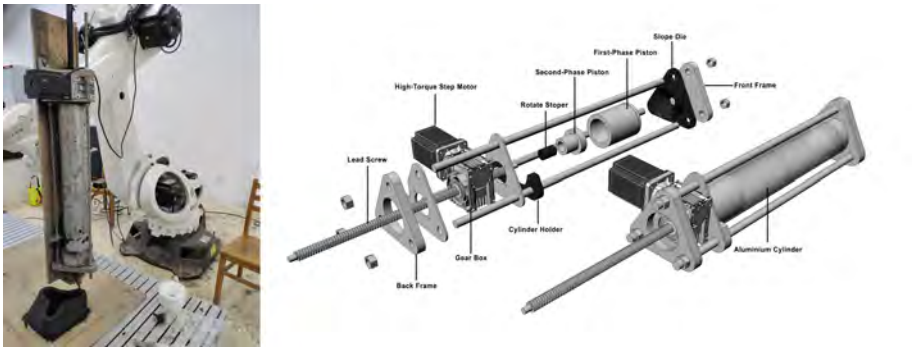


Figure 2. Left, Robotic Setup. Right, Design of the clay pump.

In this paper, we chose the terracotta clay which had a wide spread and accessibility among the world. The water ratio of clay was between 35-40% through extrusion. All the freshly printed clay moulds had been settled for 3 hours before casting. In terms of the casting material, we chose a type of cement mortar with the paste of sand, cement and water (3:2:1). The demoulding was executed 96 hours after the casting.

2.2. CLAY AM CONFIGURATION AND GEOMETRY

We first calibrated the clay AM system that matches the extrusion velocity with the nozzle movement speed to produce a constant filament. In the case of our pump, each round per minute (rpm) of the motor could extrude out 1/90 ml of clay. To match up a 100 mm/s nozzle movement speed, we set the rpm as: 36 for 4 mm extrusion nozzle diameter and 1 mm layer height; 72 for 8 mm nozzle diameter and 1 mm layer height. As for 3 mm layer height, we set the rpm times 3. In this scenario, the pump produced constant filament with 4 mm/8 mm width.

The geometries of clay moulds in this paper were designed as 200 mm tall rounded columns with 100 mm or 200 mm diameter. Each layer of the clay AM mould was a double-wall, multiple sided polygon. This means in each layer, after the printing drew a closed polygon, it would run an outer path offset from the polygon with the distance of filament width. In the circumstances, an 8 mm mould thickness was made of two 4 mm walls. Because of the motion of robotic arm in this experiment was set as linear motion, we transferred the circular sections of clay moulds into multiple sided polygon, 50 sides for a 200 mm diameter circle and 25 sides for 100 mm.

3. Design of Experiments

3.1. DOE

The time to set up and run one physical experiment for clay printing is demanding. For this reason, we adopt a design of experiments approach, in order to help us gain maximum information with the lowest number of experimental runs, possible.

DOE is a statistical technique, first introduced by (Fisher, 1935), which

involves selecting a combination of parameters, referred to as factors and for each, a discrete number of values, referred to as levels. These are represented in a design matrix as a sequence of experiments to be performed, whose rows and columns denote experiment runs and factor levels, respectively. These levels correspond to values that can be inputted into each each factor. The strategic sequence of levels will reveal useful information about the relationship between the parameters and observed physical behavior, when comparing and contrasting the results (Saltelli et al., 2000).

The following section (3.2) will describe factorial designs (FD), which are the most common type of experimental designs. For a more detailed review of this and other experimental designs and analyses of physical experiments , refer to (Robert, et al., 2003).

3.2. FACTORIAL DESIGNS

The most adopted type of FD is full FD, whose number of experiment runs m^k, which means the number of factors, k are investigated at m levels for each factor (Box, et al., 1978). For example, if there are 2 levels for 3 factors, the number of experiment run is equivalent to $2^3 = 8$. In General, the levels of a 2^k FD are denoted as '+' and '-' level (or 'high' and 'low' level).

Table 1. Sequence of '+' and '-' values represented in a design matrix for a #2^3# design.

Run	Levels			Result
	Factor A	Factor B	Factor C	y
1	-	-	-	y1
2	+	-	-	y2
3	-	+	-	y3
4	+	+	-	y4
5	-	-	+	y5
6	+	-	+	y6
7	-	+	+	y7
8	+	+	+	y8

Once the response values are measured and recorded, we can estimate the contribution of the parameters due to their independent and/or interacting effects. To do this, the response values y1,..., y8 are added as a new column to end of the design matrix in order to estimate the main and interaction effects. For example, from Table 1, the difference between the response y2 and y1, (experiment 2 and 1, respectively) is a consequence of the variation in the level of factor A only, since the other two factors are kept the same. This difference reveals a partial effect of A on the response Y when factors B and C are both set to -. Therefore, estimating the main effect of a factor can be defined as the average effect of that parameter overall scenarios when other factors were kept fixed. For example, the main effect of Factor A in Table 1 can be estimated by averaging the four possible scenarios:

$$\frac{(y_2 - y_1) + (y_4 - y_3) + (y_6 - y_5) + (y_8 - y_7)}{4} \quad (1)$$

Essentially, this is the difference between the average response for the + level

and the - level of A. The interaction effects between parameters are estimated in a similar way. For a more technical explanation of estimating both main and interaction effects, see Saltelli, et al., 2000.

4. Parametric Study

The scope of our study is to gain a better understanding of the relationship between fundamental parameters pertaining to the AM of clay moulds and the displacement of the concrete artefact, post-casting. In this section, we present a case study of vertical columns with circular cross-sections, which is a common topology in architectural components.

4.1. CHOICE OF PARAMETERS

Since we are considering only three parameters (DIA, H, W), we opted for a full factorial design which required a total of only $2^3 = 8$ runs. We ran each experiment twice, in order to account for various errors by then considering an average of the response values. Thus, we performed a total of 16 experiments. Two levels were assigned to each parameter as is typically recommended for such experimental designs. The extreme values of each parameters range were adopted as high and low levels, denoted by (+) and (-); these being: DIA [200mm (+), 100mm (-)], H [3mm (+), 1mm (-)], and W [16mm (+), 8mm (-)]. These levels were used to generate the design matrix as presented in Table 2. Each row in the table corresponds to a mould configuration. Each mould was printed via clay AM. Once the print was complete, we poured concrete directly into the freshly printed clay moulds. Once the cast concrete was dry, we measured the cross-section perimeter displacement of each cured concrete specimen at four different points of the mould: at the base, at the middle (50% height), at the top. We also recorded the maximum displacement including its position. The displacement was measured as the difference between the intended and post-casting geometry of the artefact.

Table 2. Design matrix for the full factorial design.

	Actual Levels			Levels		
Run	Factor DIA (mm)	Factor H (mm)	Factor W (mm)	Factor DIA	Factor H	Factor W
1	100	1	8	–	–	–
2	200	1	8	+	–	–
3	100	3	8	–	+	–
4	200	3	8	+	+	–
5	100	1	16	–	–	+
6	200	1	16	+	–	+
7	100	3	16	–	+	+
8	200	3	16	+	+	+

5. Results from factorial study

From each measurement, we recorded the resulting displacement. We observe how the displacement responds, when: (1) DIA, H and W, vary independently, and (2) when combinations of DIA and H, DIA and W, H and W are varied as

groups. Our scope is to identify the key parameter that contributes to the reduction of the displacements and whether there is an interaction between parameters. Subsequently, we demonstrate these characteristics in box plots and interaction plots utilizing python programming language. More specially, we visualize (1) as boxplots, one for each level, and (2) as three interaction plots, one for each combination.

Table 3. Displacement results of every experiment run.

Run	Max Displacement @ Height				Displacement at bottom				Displacement in the middle				Displacement on the top			
	First		Second		First		Second		First		Second		First		Second	
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
1	328, @64mm	4.41%	327, @64mm	4.09%	321	2.18%	322	2.50%	325	3.45%	325	3.45%	319	1.54%	321	2.18%
2	671, @62mm	6.79%	670,@66mm	6.63%	640	1.86%	638	1.54%	658	4.72%	655	4.25%	639	1.70%	638	1.54%
3	329, @62mm	4.72%	331, @65mm	5.04%	323	2.81%	326	3.77%	326	3.77%	328	4.41%	321	2.18%	325	3.49%
4	699, @70mm	11.25%	701, @69mm	11.57%	644	2.50%	645	2.65%	690	9.82%	697	10.93%	640	1.86%	645	2.65%
5	320, @64mm	1.86%	319, @66mm	1.54%	318	1.22%	316	0.59%	315	0.37%	315	0.27%	315	0.27%	315	0.27%
6	660, @67mm	5.04%	660, @67mm	5.04%	635	1.06%	634	0.90%	653	3.61%	653	3.93%	634	0.90%	634	0.90%
7	329, @68mm	4.72%	329, @61mm	4.72%	320	1.86%	322	2.50%	324	3.13%	324	3.13%	320	1.86%	321	2.18%
8	664, @64mm	5.68%	682, @65mm	5.04%	640	1.86%	643	2.34%	651	2.93%	654	4.09%	635	1.06%	634	0.90%

The boxplots present how the displacement values distribute around a level. The upper and bottom borders of each box represent the terminals of these values. Thus, we could estimate whether the impact of parameters is significant while changing from one level to the other. In terms of the interaction plots, the scope is to realize whether there is a correlation between the changing of two parameters. More specifically, the more tendency of intersection the lines have, the more interaction the parameters have. As such, these two plots should be looked together to get a general image of analyzing the effects.

For a more quantified understanding of the observed characteristics, we estimated the main effects [corresponding to (1)] and interaction effects [corresponding to (2)], using equation (1).

5.0.1. Maximum displacement and its position

At first glance, A, B and C (Figure 3) directly indicate that reducing DIA from 200mm to 100mm, causes a noticeable decrease in the displacement. While reducing H or increasing W will also contribute to a reduction of displacement. These results are highlighted by the deviations between the distribution ranges of A, B and C.

However, there are no significant (0.34%, -1.25%, -0.5%) effects on the maximum displacement regarding the interaction between parameters, comparing to A along (3.24%). When the DIA is small, increasing W doesn't have a significant contribution to reduce the maximum displacement. While when printing a mould with a large diameter, a larger W clearly helps to reduce the displacement (Table 4, 4th plot from the left).

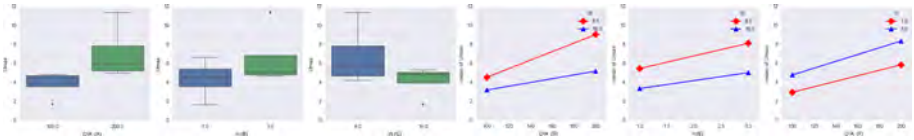


Figure 3. Bar chart plots of main effects (left), interaction plots (right).

Table 4. Estimated main and interaction effects of DIA, H and W, on maximum displacement.

Displacement	Main Effect DIA (A)	Main Effect H (B)	Main Effect W (C)	Interaction DIA & H (D)	Interaction DIA & W (E)	Interaction H & W (F)	Interaction DIA, H & F (G)
(Maximum)	3.24	2.17	-2.61	0.34	-1.25	-0.5	-1.69

5.0.2. Displacement at bottom

A indicates that the displacement ratio in percentage slightly decreases when increasing DIA, which has an opposite behavior compared with the maximum displacement. B and C present a decreasing displacement when changing H from 3mm to 1mm or increasing W from 8mm to 16mm, similar to the maximum displacement. On the other hand, D indicates that DIA has a larger impact on displacement when setting W as 16mm compare with 8mm. E and F show insignificant effects of intersection between parameters.

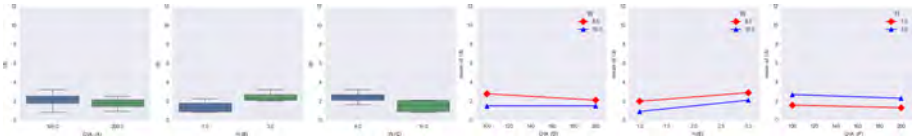


Figure 4. Bar chart plots of main effects (left), interaction plots (right).

Table 5. Estimated main and interaction effects of DIA, H and W, on bottom displacement.

Displacement	Main Effect DIA (A)	Main Effect H (B)	Main Effect W (C)	Interaction DIA & H (D)	Interaction DIA & W (E)	Interaction H & W (F)	Interaction DIA, H & F (G)
(Bottom)	-0.34	1.05	-0.94	-0.06	0.34	0.14	-0.02

5.0.3. Displacement in the middle

Figure 5, A and B show that increasing DIA from 100mm to 200mm and increasing H from 1mm to 3mm have a similar setback of the displacement in the middle of the mould, while raising W still contribute to a smaller deformation.

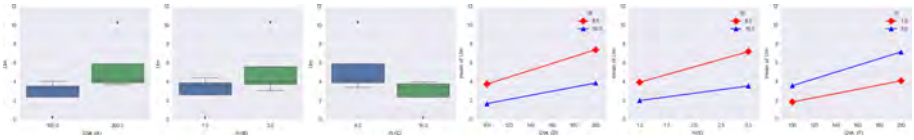


Figure 5. Bar chart plots of main effects (left), interaction plots (right).

Table 6. Estimated main and interaction effects of DIA, H and W, on middle displacement.

Displacement	Main Effect DIA (A)	Main Effect H (B)	Main Effect W (C)	Interaction DIA & H (D)	Interaction DIA & W (E)	Interaction H & W (F)	Interaction DIA, H & F (G)
(Middle)	2.92	2.41	-2.81	0.66	-0.74	-0.86	-1.97

5.0.4. Displacement on the top

The individual impact of each parameter on top displacement is very similar to the bottom condition (Figure 6, A, B and C). Due to D and E, no significant interaction occurs between DIA and W, H and W. However, there is a tendency of interaction shown in F, which indicates that when setting H as 3mm, the larger DIA is, the more contribution H has for decreasing the displacement.

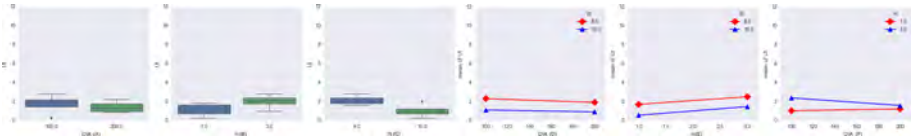


Figure 6. Bar chart plots of main effects (left), interaction plots (right).

Table 7. Estimated main and interaction effects of DIA, H and W, on top displacement.

Displacement	Main Effect DIA (A)	Main Effect H (B)	Main Effect W (C)	Interaction DIA & H (D)	Interaction DIA & W (E)	Interaction H & W (F)	Interaction DIA, H & F (G)
(Top)	-0.3	0.86	-1.09	-0.5	0.1	0.06	-0.34

5.0.5. Overall observation

Increasing the parameter W appeared to have the most contribution towards reducing the overall displacement for various heights of the mould. This is further justified by the result that in all cases, except the bottom displacement, there was almost no interaction between W and DIA, W and H. Such results indicate that W might be somewhat independent from DIA and H. The maximum displacements happen at the 30% - 35% positions of the overall height from bottom and approximate the middle displacements. The DIA has a more significant effect on these displacements compare with the other parameters. It shows the tendency that when increasing DIA, the mould has a larger deformation. One noticeable interesting aspect is the effects of the interaction between parameters are not as significant as their independent contribution.

The study suggests that keeping W at 16mm will improve the overall performance in terms of resisting the deformation, while DIA at 200mm, the maximum displacement is still noteworthy. The effect of parameter W accords with our expectation, while it appears that a lower printing layer height (parameter H) contributes to a smaller displacement. This might because of the layer adhesion conditions particularly in double-wall printing, that with the same width, smaller layer height has a denser bonding (Figure 7).



Figure 7. The cross sections of clay AM filaments in layers. From left: schematic of 3 mm layer height; schematic of 1 mm layer height; printed 3 mm tall filament; printed 1 mm tall filament.

5.0.6. Material observation

Before the displacement measurement we noticed that all the moulds cracked after fully air dried. This is because when casting concrete into wet clay mould, the dehydration time of concrete is shorter than the mould drying process in our lab environment (0.9 - 12.4 degree Celsius, 70 - 98 % Relative Humidity). After the dehydration, clay mould shrink against the solid concrete till crack. This helped us demoulding clay with no difficulties (Figure 8).



Figure 8. Clay mould self-demoulded due to the shrinkage caused by drying.

6. Conclusion

In this paper we took upon a systematic approach for studying the relationship between the configurations of AM fabricated clay mould and its displacement after casting concrete into utilizing a DOE technique. The results revealed that both increasing the width of extrusion filament (W) and decreasing layer height (H) contribute to a reduction of displacement in the overall concrete artefact. A reducing of layer height is also benefiting in a higher resolution in the cross-layer direction. However, these results in a longer fabrication time since extruding wider filaments means extra extrusion time and smaller layer height leads to less vertical build-up efficiency. As such, there exist a trade off between the efficiency, material consumption and the geometry accuracy.

Furthermore, when the diameter (DIA) of a round mould increase to 200mm, a noticeable displacement will always be detected with current set-up, which might suggest a larger printing width. In this scenario, we recommend such clay mould design as (1) to have a large filament width and small layer height, (2) to distribute more material from bottom to the middle to resist the lateral pressure exerted by concrete.

Acknowledgements

A part of the clay AM practice were done in the robotic lab of Zhe Jiang University.

References

Barnes, G. E.: 2017, Workability of clay mixtures, *Applied Clay Science*, **153**, 107–112.

Box, G.E., Hunter, W.G. and Hunter, J.S.: 1978, *Statistics for experimenters*, John Wiley & Sons.

Cesaretti, G., Dini, E., De Kestelier, X., Colla, V. and Pambaguian, L.: 2014, Building components for an outpost on the Lunar soil by means of a novel 3D printing technology, *Acta Astronautica*, **93**, 430-450.

Fisher, R.A.: 1935, *The Design of Experiments*, Macmillan.

Khoshnevis, B.: 2004, Automated construction by contour crafting - Related robotics and information technologies, *Automation in Construction*, **13**, 5-19.

Robert L, M., Richard F, G. and James L, H.: 2003, *Statistical Design and Analysis of Experiments: With Applications to Engineering and Science, Second Edition*, John Wiley & Sons, Hoboken.

Perrot, A., Rangeard, D. and Pierre, A.: 2016, Structural built-up of cement-based materials used for 3D-printing extrusion techniques, *Materials and Structures/Materiaux et Constructions*, **49**, 1213-1220.

Saltelli, A., Chan, K. and Scott, E.M.: 2000, *Sensitivity Analysis. Vol. 1.*, Wiley, New York.

Tollenaar, R.N., van Paassen, L.A. and Jommi, C.: 2017, Experimental evaluation of the effects of pull rate on the tensile behavior of a clay, *Applied Clay Science*, **144**, 131-140.

Trabelsi, H., Jamei, M., Zenzri, H. and Olivella, S.: 2012, Crack patterns in clayey soils: Experiments and modeling, *International Journal for Numerical and Analytical Methods in Geomechanics*, **36**, 1410-1433.

Wang, S., Philippe, M., Ho, K. and Stylianos, D.: 2016, Clay robotics : A hybrid 3D printing casting process, *Proceedings of the International Conference on Sustainable Smart Manufacturing (S2M)*, Lisbon, 83-88.

Yang, W.: 2015, *The Issues and Discussion of Modern Concrete Science*, Springer.

BLOCKCHAIN GRAMMARS - DESIGNING WITH DAOS

The blockchain as a design platform for shape grammarists' decentralised collaboration

THEODOROS DOUNAS[1] and DAVIDE LOMBARDI[2]
[1]*Robert Gordon University*
[1]*t.dounas@rgu.ac.uk*
[2]*Xi'an Jiaotong Liverpool University*
[2]*davide.lombardi@xjtlu.edu.cn*

Abstract. This paper presents an application of Decentralised Autonomous Organisation (DAO) in the field of design and AEC industry. The model is applied in the realm of shape grammar proposing the possibility of allowing multiple grammarists to collaborate in the definition of a new grammar within a Blockchain environment that acts as a distributed ledger. DAOs systems and Blockchain are introduced as well as shape grammar and its fundamental rules. The collaborative nature of a DAO with the inner logic of shape grammar, which bases its principle and rules in multiple variations and combinations of simple initial shapes, brings to the problem of recording and validating changes and improvements in the design chain. For this reason, a voting system to govern the process is introduced, based on both quantitative values, i.e. number of votes, and qualitative power, i.e. the reputation of who votes, applying a factor that scales the vote according to the expertise of the voter. An example is provided showing a possible scenario in a design environment along with validation criteria, and predicting future stages applied in an always more BIM-oriented practice.

Keywords. Decentralised Autonomous Organisation; Shape Grammar; Intelligent organisms; Distributed Ledger; Blockchain; .

1. Introduction

1.1. MOTIVATION.

The AEC industry remains a conservative, change-resistant, and risk-averse industry compared to other industrialised industries that have incorporated a plethora of digital tools in their operation. In particular Architects see themselves as authors of artistic works, or at least that myth is perpetuated through marketing, social media activities but also within schools of Architecture. Modern and contemporary practices are based on the effort of collectives of experts working together, even from different continents, from the early design stages till the construction of the design proposal. CAD and BIM files are shared and updated

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 293-302. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

constantly with the introduction of solutions addressing all the possible issues that a building can face. This new working style that killed the previous concept of the architect as the sole genius who supervises the entire process brought the problem of dealing with the authorship and the responsibility of who takes decisions and makes changes in the project. In team collaboration the model that has been identified as dominant in the past two decades is the BIM, a centralised Building Information Model shared by all where each discipline shares and inputs their own information. However, the manner in which this takes place has not been investigated extensively. Is the model orchestrated by a single authority? Are the disciplines and their experts deciding according to their own interests or for the interests of their clients? What kind of mechanisms are there to ensure the Building Information model and the architectural study are developed in a competent, transparent, complete and collaborative manner?

A such the present paper presents a radical approach to collaboration and collective authorship by proposing a decentralised model of decision making, by running a shape grammar on a smart contract and digital ledger mechanism. Due to the constraints of the length of paper at present we present the working model, leaving testing and validation in a further paper. Still, the present paper describes in detail the experimental and implementation set up and describes validation criteria.

2. Context and frameworks: Blockchain(s) in the built environment

A Blockchain is a digital Distributed Ledger Technology (DLT) that records transactions, encrypting the difference between each transaction in a block of information and embedding the cryptographic (#) hash into the next block, forming a chain of blocks with encrypted hashes, hence the term Blockchain. Common applications for Blockchains are cryptocurrencies such as Bitcoin and Ethereum. Li et al [Li 2018] describe an extensive technical, political and social framework for the application of Blockchain technologies in the construction sector. Belle [Belle 2018] also describes organisational models of Blockchain in the built environment and the impact they will have in whole countries such as China. Earlier work by the authors have already described a technical implementation framework of connecting Computer Aided Design applications with the Blockchain [Dounas, Lombardi 2018]. Within the same publication, we describe the four levels of integration that are possible between a Blockchain and a CAD system.

3. Background

Distributed ledger technologies and specifically Blockchain are distributed databases. They have a unique way of establishing consensus on which operation & transaction on a network is true and which one is not when comparing distributed sets of data. Compared with querying a central database directly, a Blockchain is distributed in various computer nodes over the network. Due to the distributed nature of the database, computational mechanisms had to be developed that would synchronise all nodes of the database with a single version of the truth. The main

mechanisms with which nodes establish the truth between them are proof of work and proof of stake. Both of the mechanisms create a new block on the Blockchain, validating one operation.

In mechanisms where proof of work is employed, nodes on the network compete between them to solve a complex mathematical equation that proves the creation of a new block, thus validating an operation. As such to have any kind of monetary reward for validating a block, a node not only needs to be fast but also first with the correct result of the computation. In proof of stake the nodes and the transaction/operation use other parameters that are designed to build trust. These are the duration of how long a node has participated in the network and the amount of transactions that one has verified. As such one would trust their validation of a new block since a trustworthy node would hold a vast number of validated blocks within their record. Ethereum and Bitcoin currently use proof of work, thus having a geometrically increasing computational problem to solve, while Ethereum has designed a system to transition to proof of stake mechanism, once the proof of work mechanism becomes energy and computationally expensive.

Ethereum and its network have introduced the concept of the smart contract as a use for Blockchains beyond currencies. Within this, a transaction does not have to only be monetary but simply the execution of a computer code when certain conditions are met. In the Ethereum network one can then build smart agencies by using smart contracts, i.e. organisations that are governed and their behaviour determined by smart contracts. Smart agencies, given enough of participants and complexities can be determined to be thus Decentralised Autonomous Organisations. In a DAO there is no board of directors or governors and all decisions are taken and operated on the infrastructure of networks similar to a decentralised and distributed one.

4. Methodology

We have used a combination of qualitative research and experimentation, with the explicit goal of building a working prototype. Within the constraints of the paper we describe the algebraic theoretical model for the DAO grammars, and the process for creating the Blockchain infrastructure on the Ethereum network.

5. Implementation

5.1. DECENTRALISED AUTONOMOUS ORGANISATIONS D.A.O

All infrastructure projects in the area of DAOs (daostack.io, buckfeed.cc) describe in their whitepapers the imbalance of growth and attention that takes place in a growing organisation. Within this framework the internet is essentially an infrastructure that allows peer-to-peer exchange of information. In parallel, a Blockchain network can be conceptualised as a peer-to peer infrastructure for value, as Blockchain solves the trust problem and the ownership of digital assets in online transactions. Essentially, as a facsimile a DAO resembles more an organism rather than an artificial organisation.

5.2. DAOSTACK.IO

The DAO as presented by DAO Stack is a new organisation that operates by smart contracts on a Blockchain, i.e. decisions are taken and activated by the operation of smart contracts. DAOstack at the time is using the Ethereum infrastructure, even though there is a discussion on expanding the platform to other Blockchains as well, as an ultra-organisation that operates across various distributed ledgers.

5.3. GOVERNANCE MECHANISM

For each decision taken in an organisation one can set up smart contracts that execute code once an event takes place, but also, they can use smart contracts to govern the organisation's decision in a democratic manner. Instead of assigning one vote to each agent, the DAO uses 'Gen tockens 'and each agent's reputation in the organisation. Each agent in the DAO has a set number of GEN tokens that they can vote with but also a set amount of reputation/influence that they can stake in a vote. As such when a vote takes place, Gen tokens act as votes but reputation/influence of the voting agents come into play.

5.4. TOPOLOGY OF AGENTS

There two manners in which agents within a DAO can be topologically distributed, either in Assembly mode, which equates more or less with a central organisation model or in a Fractal Federal governance where each agent has their own sub-assembly mode, potentially in a recurring scale, with each subassembly having N subassemblies.

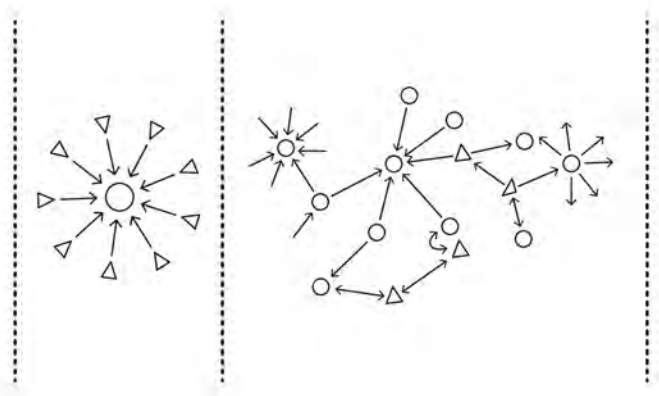


Figure 1. Assembly (left) vs Fractal mode of organisation (right).

Within a decentralised autonomous organisation, one can of course, as in any organisation have competition between the agents that participate. If structured with current economic models, then the non-cooperative Nash equilibrium applies

in their competition, i.e. some of the agents will behave in a competitive manner to strike a local win for them, but not one for the whole organisation. This forms the key question on how a DAO will steer towards good decision making, bottom-up avoiding both the pitfall of a non-cooperative Nash equilibrium, and also be resilient, i.e. allow sharing of voting power, instead of concentrating voting power to the agents with the most tokens. The first structural idea for DAOs is then the incentivising and reward of open shareable resources [DAOstack whitepaper] that lead to more growth and more openness, replacing essentially organisation that operate within non-cooperative Nash equilibriums.

Returning to the voting power with GEN tokens and reputation: within DAOstack one can transfer GEN tokens, but one cannot transfer reputation. The DAO white paper mentions: "Reputation is used here interchangeably with influence power, and can form the basis for a meritocratic governance system, where those who are most appreciated - due to their past contributions - have the most influence." One way to award reputation is through proposals. For example, within a shape grammar making organisation there could be a proposal to award 100 SG tokens to Shape Grammarist George Stiny for his contribution to the field. Reputation can also be algorithmically computed by considering research publications on shape grammars, citations and other research impact indexes. The difference here is that a shape grammarist would translate their research impact and influence H-Index and/or C-Index into decision making power within a larger organisation, say one consisting of all shape grammarists in the world.

Essentially by using the GEN tokens and the reputation system, DAOstack builds a system where voting of an elect minority aligns with the interests of the grander majority, and ensures that the system is transparent, resilient -since even the transfer of all gen tokens to one agent will not dissuade reputation voting power but also reputation guarantees that certain propositions will always receive the attention of the community, and scalable, since through the Ethereum Blockchain anyone can participate in it. The situation where a minority makes an 'edge' decision', as long as it is in line with the consensus, is called by DAOstack : 'Holographic Consensus' as a reference to holograms where each sliver of the three dimensional image reflects and contains the information for the whole picture.

5.5. SHAPE GRAMMARS AND SHAPE GRAMMARISTS

A shape grammar consists of a set of initial shapes S1, and a set of rules R1 that when chosen and applied to the set S1 they produce other shapes on the right-hand side of the rule. It also includes a shape rule K that is the final shape rule, that once activated, will halt computation. In essence it is a productive system, a generative system for design.

```
A U22 Shape Grammar in algebraic format
S1= a1, b2, c3, …. ,xn  / where the shapes are of i=2 dimensions
R1=r1, r2, r3, …., rn  / where the rules are of j=2 dimensions
```

In most of the shape grammar literature authorship remains with the all-seeing shape grammarist that retains authority and decision making in all aspects of the grammar. In certain cases, the grammarist attempts to emulate a known style, and

within that one finds computational innovation, where the grammar produces more, previously not existing examples of the styles, but still within the same language [Duarte 2005]. Problems that are relevant to architectural design and authorship are the selection of the rules, the ad-hoc changing of the rules in the middle of the application of the grammar, shape recognition and emergence, and much more importantly shape ambiguity, that runs counter to the initial idea of a specific set of shapes S1 that the grammarists begins designing with. Figure 2 briefly describes the example grammar.

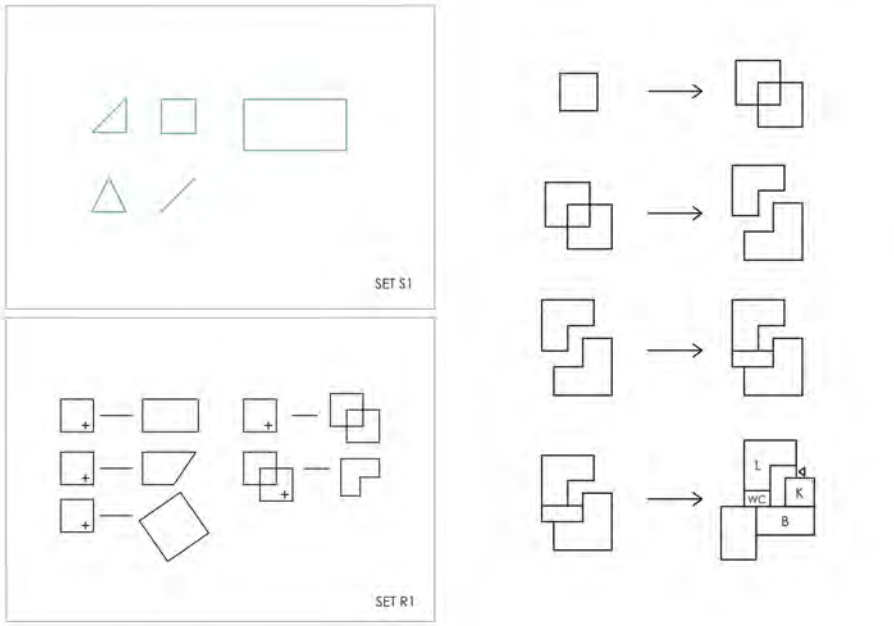


Figure 2. Shape grammar application and termination.

Within this application of the grammar there are N possibilities for changing the rules, in the in between steps. We can define a set Gx of Shape Grammarists that participate in a DAO with the common goal to create an apartment grammar that creates the most variations with the most compact apartment layouts possible, by using a proportion of the global integration number (where integration is defined as the distance from a space of origin to all other spaces in the system, run for each space in the system, hence its globalism) to the floor area. The lowest fraction indicates a more compact apartment. To ensure liveable spaces, minimum sizes for the shapes in set S1 can be used, to ensure that the apartment plans produced are both mathematically compact but also provide a minimum of architectural quality. What are the possibilities that these shape grammarists have for collaboration over the internet with a record of all steps taken? How does one negotiate which of the rules is selected for application? Algebraically we have still the S1, R1 sets with the set of Gx of shape grammarists added, plus the validation

criteria for the apartment:

```
S1, R1, Gx, and V= Global Integration /
Floor Area, with S1 constraint with minimum dimensions
```

Lets suppose that within the set Gx there are 5 experienced shape grammarists, Duarte, Stiny, Knight, Economou, Stuffs and 883 junior shape grammarists with the intention of collaboratively creating the apartment grammar that creates the most variations with the most compact apartment possible? While one needs the experienced shape grammarists F,E,D, K, S to guide the Set Gx one also needs innovative ideas from all of the constituents of the set. How does one address the whole group without creating the need to create a lot of traffic, i.e 888 emails for each step?

```
Gx: F,E,D,K,S…,., G883
```

5.6. COMBINING BLOCKCHAIN WITH SHAPE GRAMMARS: OPERATING MODEL

Thus we propose the creation of a Blockchain grammar, the first shape grammar engine run on the DAO. We define the Blockchain grammar as the human-machine cooperation on the DAO stack, i.e. the collaboration between shape grammarists using the smart contracts that constitute the computation engine of the Blockchain grammar. The Blockchain grammar has these functionalities: Tokens distribution, where tokens get distributed to each of the 888 shape grammarists, Reputation Assignment, which assigns reputation according to research experience and impact, collective data curation, which is the creation and application of the shape grammar, and governance upgrade, where the mechanisms with which the Blockchain Grammar operates change and get upgraded to the next version. Within the reputation assignment contingent, there is a halftime calculator parameter of which can be decided by the Blockchain grammar itself. Indicatively we mention that the reputation a person has will dissipate over time if the academic does not publish, or their work does not get a citation or other reference over a specified amount of time. We propose that the initial set of shape grammarists all have the same amount of tokens, however their reputation score should be determined by the number of papers they have authored within the shape grammar paradigm, and their H-Index as calculated for their papers in the shape grammar paradigm. The formulae for initial token and reputation distribution are given below [Stallings], 1 Shape grammarist: T tokens plus N (number of papers) + H-Index (as calculated for their papers in the shape grammar paradigm) + C-Index (as calculated for their papers in the shape grammar paradigm). We thus can define the voting power of each member as

```
Vt=T+N+Hi+Ci
```

5.7. RUNNING A GRAMMAR AS A DAPP

The set Gx of 888 shape grammarists belong to the Blockchain Grammar, which runs the creation of the prototype shape grammar as a dAPP on ‘Alchemy’,

DAOstack's layer for DAOs that runs in sequence on the Ethereum network. Table 1

Table 1. DAOstack layers: ARC and Alchemy.

Implementation	道 DAO Grammars
Operating system	DAOstack.io
Infrastructure	Ethereum Network & Blockchain

6. The DAO Grammars operations Model

At each step, each shape grammarist, whether experienced or not, reads the state of the grammar, and has the right to propose the next rule(s) to be applied. Suppose that 30 proposals are submitted to the DAO. Then each of the grammarists has the potential to vote which of these rule set will be applied next, and then votes using GEN and reputation. The expectation is that the 5 senior grammarists will have their vote carry more reputation, due to their experience. At the same time though one can see that innovative solutions that have results might get voted through, as any of the 888 members will be able to propose efficient solutions. An interesting scenario of course is the voting of a proposal by a minority, say the grammarists K, S. Mathematically if all GEN tokens are the same for each of the 888 grammarists a proposal with the backing of only two members should not pass. However if the reputation of K & S weights above the other 886 members of the DAO the proposal shall pass, and given their potential high reputation and track record, it will have a good impact on the application of the grammar.

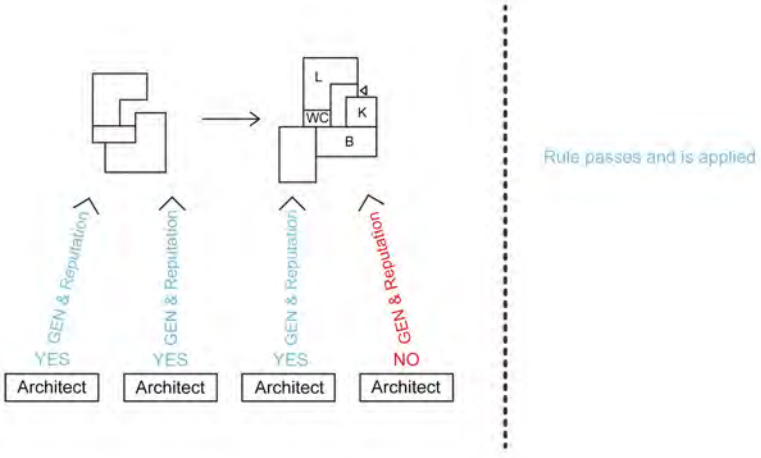


Figure 3. Voting Process inside the Blockchain Grammar.

6.1. TURING COMPLETE: SHAPE GRAMMARS AND SMART CONTRACTS

Within the Blockchain Grammar running on DAOstack a smart contract calculates how compact an apartment is and awards GEN and reputation to the shape grammarists that proposed the rule that produced it, but also proportionally to the shape grammarists that voted for the rule. As such internally the DAO grammar can work algebraically: each shape grammar rule is encapsulated into the algorithm of a smart contract and as such when the rule is about to be applied the smart contract get applied. This, of course, raises the question of shape recognition within the shape grammar. Since we do not yet have a reliable shape recognition engine, the DAO delegates this task to the human part of the organization, a shape grammarist who will encode the new shape into a new parameter in a smart contract.

7. Discussion

We have presented a model for massively scaled collaboration on shape grammars, presenting a mechanism that harnesses DAOs, Decentralised Autonomous Organisations on the Ethereum Blockchain. We believe that the mechanism we describe is viable as a wider collaboration feature of the AEC industry. Our mechanism has a collaborative content curation mechanism, distributes rights and decision-making power according to expertise, and due to the immutable nature of the blockchain accounts for responsibility of decisions on the organisation level. In particular the reputation allocation mechanism can lead into increasing the competitiveness of smaller, efficient AEC firms in a supply chain that might lack the capital to complete but they can compensate by biding via reputation in a public procurement process. It can lead for examples in more transparent and efficient collaboration in situations where the yet-undefined BIM level 3 is employed, or in situations where architects would like to harness the wisdom of non-experts in participatory design projects, but do not have the resources to collect every stakeholder's opinion.

Both Shape Grammars and Solidity, the Ethereum language are Turing complete, which means that they can simulate any other Turing machine. In our case we have outlined the development of a shape grammar, with the addition of collective decision making as a model of organisation and content curation, within a smart agency, the DAOstack, which runs on smart contracts on the Ethereum Blockchain. The governing smart contract of the DAO runs essentially on ARC & Alchemy, the two libraries that make DAOstack possible. The possibility of running a collaborative shape grammar process on a 'Universal computer' such as the Ethereum blockchain claims to be, creates in certain aspects a contrast in the possible blockchain applications in the built environment. On one hand the Blockchain grammar will allow for the lifting of restrictions that shape grammars might have faced in the past in terms of Turing-completeness, where a human was able to compute with them in a much more thoughtful manner compared to a machine. At the same time for Blockchain grammar presents as a cybernetic intelligent organism, where there is a reciprocal reliance of humans and computing machines to execute the design. In contrast thought, the lack of absolute

predictability of Turing-complete systems might wreck havoc in other aspects of the AEC industry with a particular reliance in reliability and predictability, for example supply chains. Still that would be an aspect to consider in our future work.

8. Further work

The mechanism we have developed will need to be tested with a vast amount of shape grammarists so that we can validate its responsiveness, transparency and computational efficiency as an operating model. Please contact us via email or fill in this form [https:goo.gl/forms/6eEbzcO5tzASEuVL2] to participate in the Blockchain grammar project.

References

"Backfeed Technical summary" : 2018. Available from <http://backfeed.cc/assets/docs/TechnicalSummary.pdf> (accessed 1st December 2018).

"DAOstack whitepaper" : 2018. Available from <https://daostack.io/wp/DAOstack-White-Paper-en.pdf> (accessed 1st December 2018).

Belle, I.: 2017, Blockchain framework The architecture, engineering and construction industry and Blockchain technology, *Conference: DADA 2017 International Conference on Digital Architecture*, Nanjing, China.

Chase, S. and Ahmad, S.: 2005, Grammar Transformations□: Using Composite Grammars to Understand Hybridity in Design, *CAAD Futures 2005*, Vienna, Austria, 89-98.

Dhillon, V., Metcalf, D. and Hooper, M.: 2017, *Blockchain enabled applications*, Apress, Orlando, Florida, USA.

Dounas, T.: 2013, Some notes on the incompleteness theorem and shape grammars, *Communications in Computer and Information Science*, **369**, 368-375.

Dounas, T. and Lombardi, D.: 2018, A CAD-Blockchain Integration Strategy for Distributed Validated Digital Design - Connecting the Blockchain, *eCAADe2018*, Lodz, Polland.

Duarte, J.: 2005, Towards the Mass Customization of Housing: The Grammar of Siza's Houses at Malagueira, *Environment and Planning B:Planning and Design*, **32**, 347-80.

Economou, A.: 2001, Four Algebraic Structures in Design, *ACADIA 2001*, 192-201.

Grasl, T.: 2012, Transformational Palladians, *Environment and Planning B:Planning and Design*, **39**, 83-95.

Knight, T.: 2003, Computing with emergence, *Environment and Planning B:Planning and Design*, **30**, 125-155.

Knight, T.: 2003a, Computing with Ambiguity, *Environment and Planning B:Planning and Design*, **30**, 165-180.

Li, J., Greenwood, D. and Kassem, M.: 2018, Blockchain in the Construction Sector: A Socio-technical Systems Framework for the Construction Industry, *Advances in Informatics and Computing in Civil and Construction Engineering*, **Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management**, 51-57.

Stallings, J. e.t. a.l.: 2013, Determining scientific impact using a collaboration index, *Proceedings of the National academy of Science of the United States of America*, **110**(24), 9680-9685.

Stiny, G. and March, L.: 1981, Design Machines, *Environment and Planning B:Planning and Design*, **8**, 245-55.

Wortmann, T. and Stuffs, R.: 2018, Algorithmic complexity of shape grammar implementation, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **32, special issue 2**, 138-146.

REFLECTION IN ACTION

An educational indie video game with design schema

ALICE SANDSTROM[1] and HYOUNG-JUNE PARK[2]
[1,2] *University of Hawaii at Manoa*
[1,2] *{alice3|hjpark}@hawaii.edu*

Abstract. This paper outlines the development of an educational indie video game in which a set of design rules are generated as a schema from player actions with the spatial components of architectural precedents in a given library. Each player's outcome is scored with its comparison to the functional sequences of the original precedent and its formal arrangement. The implementation of the proposed game within UNITY is introduced.

Keywords. Shape Grammar; Indie Game; Schema; Design Rules; Scoring.

1. Introduction

Shape grammar is a means of calculating with shapes in order to generate new and unique designs by applying a set of shape rules, generated based on the spatial relationships formed and transformations undergone between a set of shapes, to an initial object (Stiny 1980a, Stiny 2006). This approach to design can also be used retroactively to analyze precedent architectural styles to understand their spatial compositions and to create new architectural designs that fall within that style through the development of specific shape grammars (Duarte 2005, Koning and Eizenberg 1981, Stiny and Mitchell 1978, Tepavčević and Stojaković 2012). Shape grammar has also been one of the approaches to design education which tacit knowledge in architecture is capable of being taught. This form of tacit knowledge relies on learning in action, which occurs in design through the act of designing without an awareness of learning contents themselves (Schön 1983). However, most applications that employ the use of shape grammar require a user to first create a rule prior to its application within the design. This order is opposite to how people naturally want to develop and use shape grammar where user does the designing *making* playing first and develops the design rules and their schema based on the analysis of their design actions (Piazzalunga and Fitzhorn 1998, Tapia 1999, Park and Vakaló 2001, Trescak et al 2010, Grasl and Economou 2013). The design rule based shape grammar's usage within the design process has also made it difficult to develop such a program for use in design practice. A fair amount of understanding morphological transformation functions is required before dealing with the generation of and experimentation with shape

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 303-312. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

grammars in design process (Tepavčević and Stojaković 2012). These issues of shape grammar's inaccessibility for beginners limits the number of people who can learn about and experiment/play with shape grammars. This further limits its use in the field of both design and design education (Fischer and Herr 2001).

2. Methodology

To solve the problems outlined above we are developing a simple Unity-based game whose purpose goes beyond entertainment and includes education. Unity is a game engine by Unity Technology which supports 2D and 3D games across multiple gaming platforms, including mobile, web, pc, and console, and was chosen due to its flexibility as a game engine and the online resources available to us during the development process. We develop a video game as a potential solution to these problems as they are highly interactive, allowing the user/player to manipulate virtual 3D objects within the game while having the game analyze and provide feedback to the player throughout the whole process, in real time. This real-time analysis allows for the generation of design rules based on a player's design activity and their resulting schema to occur while the player is actively playing with their design rather than requiring them to define the rules and schema prior to the making of their design. This real-time feedback to players present in games allows the player to review a score for their design solution, guiding the player as they play through meaningful feedback (Deterding et al. 2011).

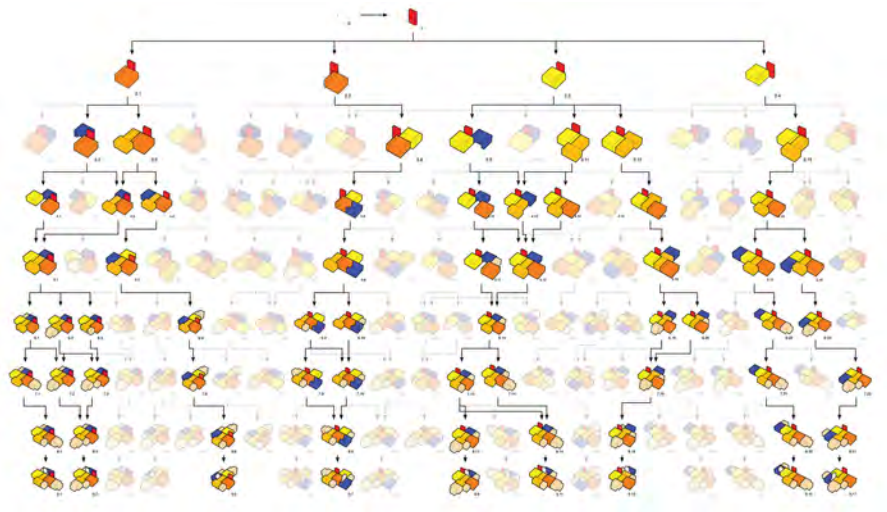


Figure 1. Various Ground Floor Schemas of Martin House within Game.

The proposed game is, at its core, a 3D puzzle game where the player is guided through a series of levels (also referred to as *scenes*) each based on a specific architectural precedent. In each of these levels, the player is provided a set of puzzle pieces (*labeled placeholders*), which function as abstractions of a precedent's different rooms and/or formal/functional delineations. The players

progress through each level by arranging the puzzle pieces provided to them, creating their design variations. While the player is going through the process of arranging these puzzle pieces, the game tracks their process of doing so as a list of design rules. These lists of design rule are then compiled into an overall design schema list of that considers where and when a player changes their course of action by undoing previous decisions they had made, see Figure 1 for a visual representation of this idea.

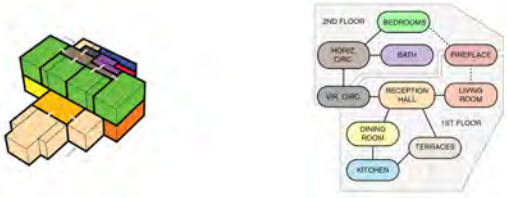


Figure 2. Original Arrangement & Functional Diagram for Martin House.

Our proposed game contains a library of architectural precedents ranging in building typology, style, time period, etc. which the player will be able to tacitly learn about as they progress through the game. These precedents serve as the basis for a puzzle given to the player in each game level. They determine the set of puzzle pieces and labels (space functions) the player is provided with at the start of the level, as well as serve as the basis for scoring the player after they solve the levels' puzzle, providing them meaningful feedback on the actions and choices they make. One of the initial puzzle levels currently being developed for testing is inspired by a paper written by Koning and Eizenberg titled "The Language of the Prairie: Frank Lloyd Wright's Prairie Houses" where they detail a parametric shape grammar which can be used to generate a design within the style of Frank Lloyd Wright's Prairie Homes.

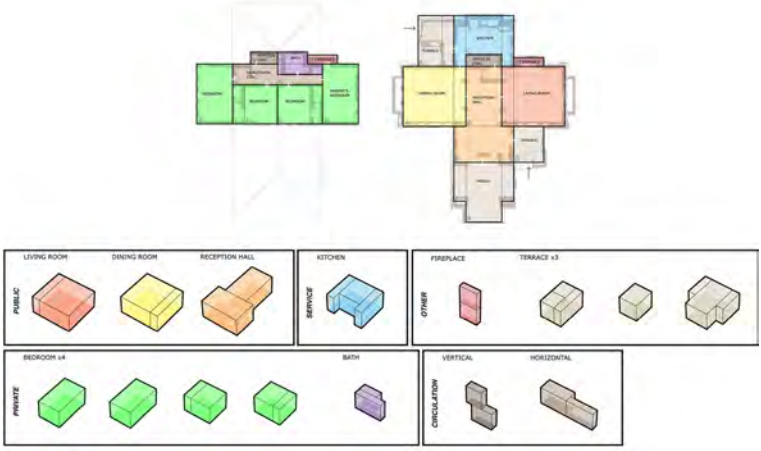


Figure 3. Abstracted layout of Martin House and its 3D placeholders .

Puzzle pieces are derived from the abstraction of a precedent's spatial and functional layout, and act as placeholders for architectural elements. There are four main categories of puzzle piece shapes used in our game: basic, which are simple cuboids; compound, which are comprised of a series of basic geometric forms which act as the components; unique, which consist of non-cuboid forms; and unique compound, which are identical to compound shapes but are comprised of both basic geometric forms and unique forms. These four types where the result of a series iterative abstractions for precedents selected for the games initial prototyping. The following shows the placeholders from an abstract layout of a selected precedent.

Alongside the abstraction of the formal aspects of a precedent design, the connections between the different functions assigned to each abstracted shape are articulated. These functional sequences are compared against the original precedent's functional connects which serve as the basis for the functional scoring criteria. The scoring criteria provide the player a guideline for designing with meaningful syntax while providing the player with the level of design freedom when assembling a solution to each puzzle given to them.

3. Gameplay

Our game serves two purposes: one at the player level and one at the researcher/developer level, both looking at different key motivational factors. At the player level, the game serves as an educational tool for the player to study and learn about architectural precedent styles and their vocabulary and design rules in order to obtain tacit knowledge of their design. A player's motivation within the game would vary from one player to another, much like in all games. This variation in player motivation affects how different players would approach the puzzles we give to them. For example, while one player might care more about obtaining a high score at the end of each level, seeking to create solutions which perfectly match the original precedent another player might care more about the freedom in form making. At the researcher/developer level, the game serves as a tool for larger scale data collection on the player's step-by-step process and their subsequent design schema developed as they move through the various precedent levels (Park and Vakaló 2001).

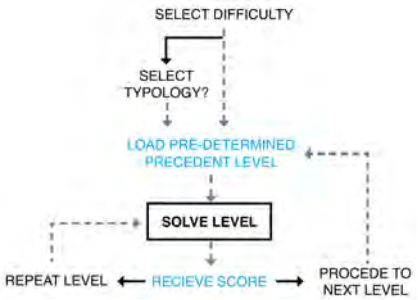


Figure 4. Game Overview Flowchart.

At the start of each level, the player is provided with a set of labeled puzzle pieces (game objects assigned a room function). The player then goes through an iterative process of object *instantiation* and *manipulation*, and *connection* using said puzzle pieces. *Implementation* refers to the initial placement of a game object in the active scene. *Manipulation* refers to the basic transformation of a game object within the scene (translation, rotation). *Connection* refers to the designation of two adjacent game objects as being 'connected', i.e. that a person could move between the two rooms. These three action types, in addition to other types of actions involved in the exploration of design schema and the recreation of a player's prior puzzle solutions, form the *action-cycle* of our game. At the end of each cycle, the actions taken by the player are compared against the original precedent's solution to score the player's most recent actions in addition to saving said actions as a *design rule*, which are then added to a list of design rules that form a *design schema*.

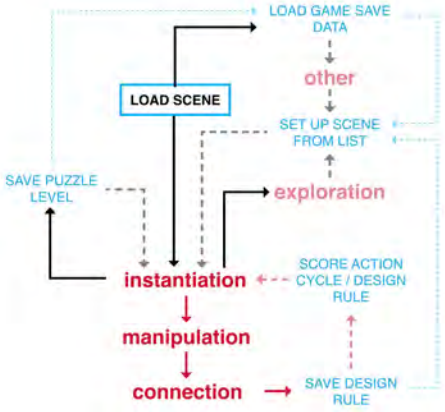


Figure 5. Action Cycle Overview.

Currently, we are looking at scoring in terms of the player's outcome's accuracy in terms of two different aspects of design: 1) overall design - how closely does their outcome match up with the original precedent's formal arrangement? and, 2) functional relationships - how closely does the player's connections between different room functions match to the originals? Not every player is going to prioritize obtaining a perfect score, caring more about the freedom of form-making. The ability for players to create design variations becomes an important part of setting up each scene. The elements of a precedent's abstraction will affect how easily a player will be able to create a variation which makes sense using the set of objects provided to them. The process of generating design alternatives by the player is saved as a design schema which is a morphological sequence in the process.

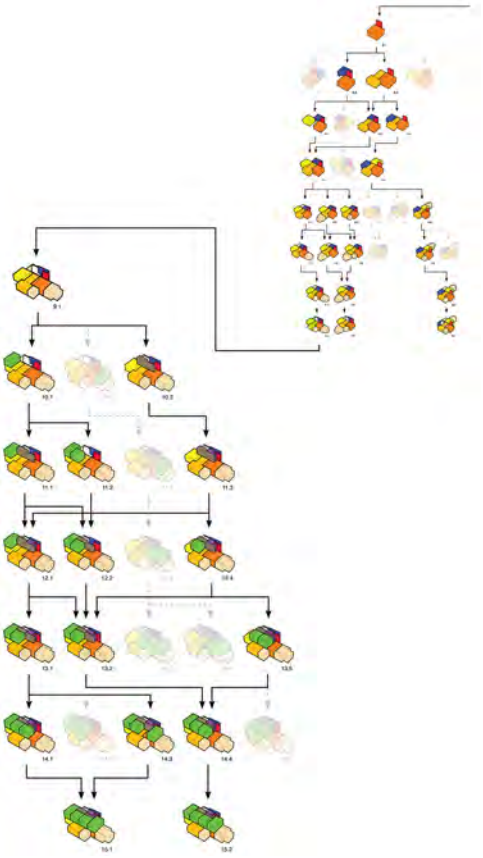


Figure 6. Generation of Design Alternatives.

One of the key issues that came up early in the development process was the question of what information is the player provided with at the start of each level? There are three types of information that are currently being explored in their potential for implementation in future development: 1) information embedded within the objects themselves, providing the player with not just the room geometry, but its respective function name; 2) images and information about the precedent given to the player just prior to the start of the level, but not accessible within the level itself (isometric drawings, building pictures, etc.); 3) information contained within the scene which could help guide players if they get lost or do not know where to start. The last type of information will convey the overall flow through the precedent spaces and provide basic functional organization between public, private, and service spaces.

The player controls are most directly tied to a player's ability to instantiate game objects within the scene, and manipulate properties and values assigned to each game object. Instantiation is done through the instantiate method native to *Unity*. Manipulation of the game object includes the translation and rotation

of the said object. Currently, translation and rotation are done through the adjustment of said object's transform component which is responsible for defining the position, rotation, and scale of the game object within the active scene (the current level) based upon a set of constraints (i.e. corner-to-corner object snapping). Corner-to-corner snapping is exactly what it sounds like. The player can adjust a selected object's position by aligning one of its corners with the corner of another object within the scene. Connection is done through the detection of touching surfaces and player input on which game objects whose surfaces touch, should the game consider "connected".

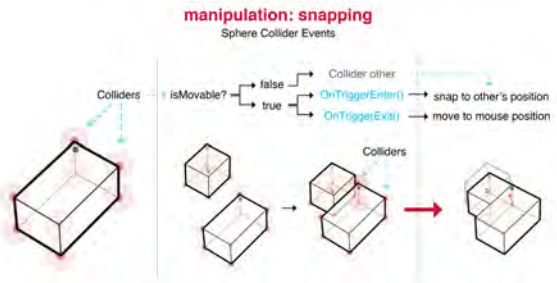


Figure 7. Manipulation: Snapping.

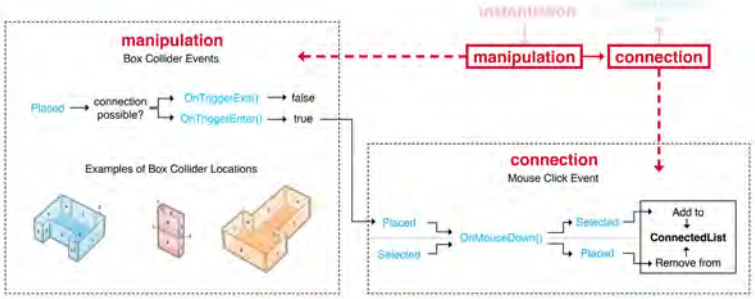


Figure 8. Connection.

There are several outcomes on the player's side of our proposed game. The most immediate two relate directly to two of the core player motivations looked at earlier in this paper: scoring and design variations. Another potential outcome relates to the idea of form as a placeholder. The game objects that constitute the puzzle are generated, on the game development side, through an abstraction process whereby architectural details were removed. These game objects could go through the opposite process on the player's end: applying architectural details to the puzzle pieces after the player has arranged them in a way they see fit. In this way more and more of the meaning behind the puzzle pieces and their arrangements could be unveiled to the player. Similar to the exploration of gameplay difficulty options, the potential for the later application of architectural

elements to a player's puzzle solution has not been implemented within our game but is being explored for its potential implementation in future development.

4. Implementation

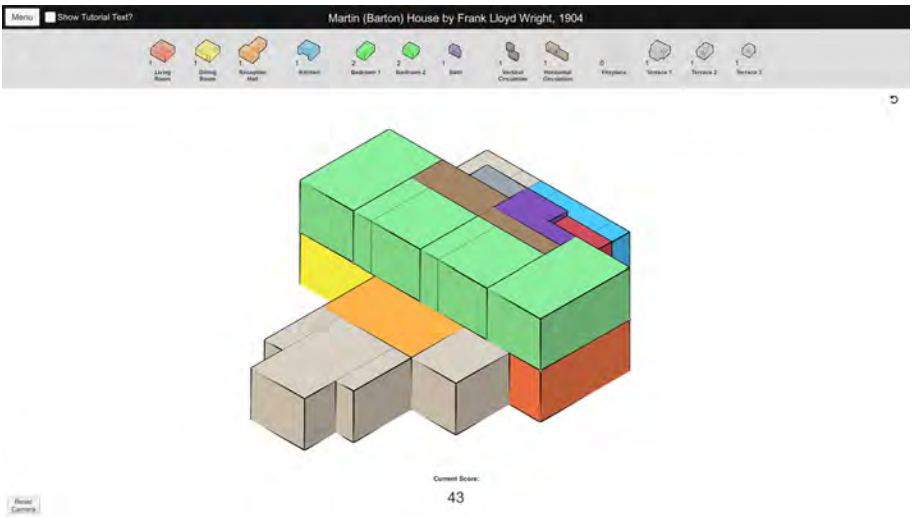


Figure 9. Screenshot of User Interface .

Instantiation is done using the *Intantiate* method native to the *Unity* game engine. When the *Intantiate* method is called, an instance of a prefab game object located within the game files is instantiated at a designated position (*Vector3*) and rotation (*Quaternion*) within the currently active scene.

Manipulation is done in *Unity* by changing the transform component of the game object using the dot operator (*transform.position* and *transform.rotation*). The specific constraints placed on each game object's potential positions are done through a series of trigger colliders attached to specific corners of each game object, resulting in the desired corner-to-corner snapping.

Connection is done using various trigger colliders that are attached to the surfaces of each game object that tell the game when two game objects come into contact. The game then conveys this information to the player in the *connection* stage, at which point a player clicks on the game objects they wish to connect to the piece they just placed (manipulated). Lists of which game objects the player as designated as "connected."

Design rules are saved every time a player completes an *action-cycle*. The game does this by saving a series of variables into a list. These variables are assigned based off of the puzzle piece instantiated in the most recent *action-cycle* (referred to as the current puzzle piece): information specific to both the prefab puzzle piece game object as well as its specific instance within the scene (like its function, shape, and id number specific to each individual game object); the

position and rotation of the current puzzle piece within the game world space; and a list of puzzle piece game objects that where connected to the current puzzle piece (the one instantiated this *action cycle*).

Design Schema refers to the list of player's generated *design rules* that are structured in such a way that they show the path the player took to arrive at their solution. The *design schema* shows not only the choices the player chooses to keep but also the ones they discard, i.e. where they backtracked. This list is continuously updated during gameplay which each new *design rule*.

Scoring looks at the variables saved to the *design rules* and it compares them to predefined lists based on the formal and functional properties of the precedent the current game level's puzzle is based on.

Library refers to the set of scenes which contain each precedent puzzle. These scenes of an instantiation UI specific to the set of labeled puzzle pieces for the precedent, the list used for scoring, and any hints specific to the precedent. The geometric models are imported into *Unity* by the developer, defined by them during each scene's construction. Accordingly, the labels and scoring criteria are defined per each scene in the library.

5. Discussion

Shape grammar is a rule-based design system in which shape rules are created and applied based on the spatial relationships formed and transformation undergone by and between a set of placeholders within a given style. The basic structure of shape calculation lends itself to computer applications within the field of design, however, at present this requires making and applying design rule first in the design process rather than engaging the practice of design. Furthermore, a fairly high level of understanding morphological transformations necessary for applying design rules has been problematic for the usage of shape grammar in the process. These limit shape grammar's use as both a design tool as well as an educational tool when it comes to understanding the spatial relationships found within a given precedent style.

Our proposed game seeks to address the problems and provide an educational tool for learning about formal and spatial relationships found in a variety of architectural precedents with translating design actions into design rules and accumulating those rules as a design schema. The game provides a rigorous way of producing design variations in the guideline of the meaningful syntax with maintaining the level of design freedom to assemble given placeholders/objects, scoring the players' outcome, providing them feedback based upon the precedent they are working with, also allow the player to backtrack on a recorded design schema. The proposed game's ability to provide immediate player feedback based on their actions along with their playful nature allows us to a sense of reflection in action in the design process.

We are currently in the pre-production phase of development, with the goal of creating an alpha build (an early prototype). This level will be based on the Martin (Barton) House by Frank Lloyd Wright. This alpha level build will be used to perform preliminary, small scale player testing in order to determine any further

tweaks to the overall gameplay mechanics prior to the further implementation of additional precedent levels.

References

Bojan, T. and Stojaković, V.: 2012, Shape grammar in contemporary architectural theory and design, *Facta Universitatis-series: Architecture and Civil Engineering*, **10**, 69-178.

Deterding, S., Dixon, D., Khaled, R. and Nacke, L.: 2011, From game design elements to gamefulness: defining "gamification", *Proceedings of the 15th International Academic MindTrek Conference*.

Duarte, J.P.: 2005, Towards the Mass Customization of Housing: The Grammar of Siza's Houses at Malagueira, *Environment and Planning B: Planning and Design*, **32**, 347-380.

Fischer, T. and Herr, C.: 2001, Teaching Generative Design, *The Proceedings of the Fourth International Conference on Generative Art 2001*.

Grasl, T. and Economou, A.: 2013, From Topologies to Shapes: Parametric Shape Grammars Implemented by Graphs, *Environment and Planning B: Planning and Design*, **40**, 905-922.

Koning, H. and Eizenberg, J.: 1981, The Language of the Prairie: Frank Lloyd Wright's Prairie Houses, *Environment and Planning B: Planning and Design*, **8**, 295-323.

Park, H.-J. and Vakaló, E.-G.: 2001, A Form-making Algorithm. Shape Grammar Reversed, *Proceedings of the Ninth International Conference on Computer Aided Architectural Design Futures*, 453-466.

Piazzalunga, U. and Fitzhorn, P.: 1998, Note on a Three-Dimensional Shape Grammar Interpreter, *Environment and Planning B: Planning and Design*, **25**, 11-30.

Schön, D.A.: 1983, *The Reflective Practitioner : How Professionals Think in Action*, New York : Basic Books.

Stiny, G.: 1978, The Palladian Grammar, *Environment and Planning B: Planning and Design*, **5**, 5-18.

Stiny, G.: 1980a, Introduction to shape and shape grammars, *Environment and Planning B: Planning and Design*, **7**, 343-351.

Stiny, G.: 1980b, Kindergarten grammars: designing with Froebel, *Environment and Planning B: Planning and Design*, **7**, 409-462.

Stiny, G.: 2012, *Shape : talking about seeing and doing*, MIT Press.

Stiny, G. and Mitchell, W.J.: 1978, The Palladian Grammar, *Environment and Planning B: Planning and Design*, **5**, 5-18.

Tapia, M.: 1999, A visual implementation of a shape grammar system, *Environment and Planning B: Planning and Design*, **26**, 59-73.

Trescak, T., Esteva, M. and Rodriguez, I.: 2010, Shape grammar interpreter for rectilinear forms, *Proceedings of. 4th Int. Conf. Design Computing and Cognition*, Stuttgart.

COMPUTATIONAL MEASUREMENT OF PROSPECT-REFUGE PERCEPTION IN TWO-DIMENSIONAL BUILT SPACE

WENZHI HUANGFU[1] and WANG LEUNG THOMAS CHUNG[2]
[1,2]*The Chinese University of Hong Kong*
[1]*wzhf198812@163.com* [2]*tchung@cuhk.edu.hk*

Abstract. Prospect-refuge theory, as a noted environment preference pattern, holds that the environment providing conditions to unimpededly see others without being seen can evoke a psychobiological pleasure for people. Although being an effective approach to understand successful and enduring emotional experience, less special attention has been paid to uncover the concrete degree of "prospect" and "refuge" properties of locations. With this background, this paper develops a computational model, Prospect-Refuge Analysis(PRA), for quantitatively measuring the diverse prospect-refuge perceptions in two-dimensional built space. Then the paper verifies the measuring effectiveness of the PRA via comparatively examining the data-perception consistency in Frank Lloyd Wright's domestic projects.

Keywords. Simulation and Analysis; Environmental and Behavior Psychology; Prospect and Refuge Theory; Spatio-Visual Analysis Model.

1. INTRODUCTION

As a well-known environment preference pattern, the prospect-refuge theory was firstly proposed by geographer Jay Appleton in *The Experience of Landscape*(1975). The theory holds that taste in art is "an acquired preference for particular methods of satisfying inborn desires(Appleton,1975). These desires include the simultaneous possession for opportunity and safety, which is genetically derived from survival needs in the primal environment. In order to survive, any species needs environment benefitting to track its prey to realize successful hunting and simultaneously enable itself to easily hide from its predator's attack. The spatio-visual environment property supporting the former unimpeded gaze is defined as "prospect" by Appleton, while that supporting the latter convenient hiding is defined as "refuge". Appleton(1975) argued that, in a suitable combination, these two properties define an environment that is conducive to survival. During the long evolutionary process, such pragmatic superiority is gradually transformed from a biological need into an environmentally derived pleasure in a psychological and aesthetic sense.

Since its proposition, the theory has been widely supported by plentiful parallel researches and experiments, such as Stephen and Rachel Kaplan's(1989) information-processing mechanism, Fisher and Nasar's(1992) crime prevention

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 313-322. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

study as well as Komar and Melamid's(1993) paintings preference experiment. However, although tracing these two bidirectional spatio-visual properties, prospect and refuge, constitutes one of effective approaches to psychobiologically understand successful and enduring emotional experience, less special attention has been paid to measure the degree of them of locations in two-dimensional built space. The application of such theory is largely limited to the symbolic definition regarding prospect and refuge places(Appleton,1975) rather than the quantitative state description of them. This deficiency leaves a potential gap in both accurately understanding diverse prospect-refuge perceptions in two-dimensional built space and controlling such a perceptual state in relevant design practice.

With this background, this paper seeks to explore a special Prospect-Refuge Analysis(PRA) model for quantitatively measuring these double properties of locations in two-dimensional built space. The first part explores the two-dimensional space mechanism for influencing the degree of prospect-refuge perception; Based on it, the paper then constructs the rule of PRA model; The third part aims at using Grant Hildebrand's(1991) perception recording about Frank Lloyd Wright's domestic projects to verify the measuring accuracy of PRA; Finally, the paper concludes with a discussion about the main research limitations.

2. TWO-DIMENSIONAL SPACE MECHANISM FOR INFLUENCING DEGREE OF PROSPECT AND REFUGE

To measure the above degree of prospect and refuge perceptions, it is necessary to transform the static and symbolic concept of prospect-refuge into a gradient and measurable spatio-visual state. A careful analysis suggests that "prospect" referring to favorable conditions to see others, to track act of prey in the primitive sense, can be described by relatively easy conditions in which the considered viewpoint actively recognizes the behavior of a target, generally another person in the context of built space. Similarly, "refuge" referring to favorable conditions to hide, to escape from predator's visual locking in the primitive sense, can be described by the relatively difficult condition in which the considered viewpoint's behavior is passively recognized by that target person. Therefore, the measurement for prospect-refuge degree of locations in two-dimensional built space can be equivalently transformed into the measurement about how the accuracy of visual recognition of target person's behavior in a scene is influenced by the architectural plan. In this agenda, the "prospect" degree of considered viewpoint is equivalent to the recognition accuracy in which he or she actively see others' behavior, while that of "refuge" is equivalent to the recognition accuracy in which his or her behavior is passively seen by others.

From common sense, the understanding of a person's behavior in architectural plan relates to two spatial factors: One is the integral degree of visible surrounding environment where the person behave, which can be abbreviated to visual integrity; The other is the enduring time in which target person appears in the scene, in other words, the shortest distance the person can choose when escaping from another person's gaze, which can be abbreviated to visual continuity. It can be empirically found the more complete these two factors are, the more accurately the viewer can understand the scene narrative.(Fig.1a) Theoretically,

such intuition can be validated by several visual-cognition theories. One is the Gestalt theory(Hochberg,1968,etc.), which holds that the human brain has an initiative information processing capacity to construct visible content as a meaningful whole. As the loss degree of visible content increases, the relevant completion structure becomes increasingly difficult to be identified, thus making the scene cognition increasingly rely on complement reorganization from the perceiver's brain. In this process, the cognitive deviation between actual and processed content about such scene is increasingly enlarged. Similarly, another theory, Empiricism Perception(Gregory,1974,etc.) also holds that the scene with information loss will be inferentially reconstructed. However, such process relies on the perceiver's experience and knowledge accumulation rather than the physiological brain as asserted in Gestalt. As the loss degree of visible signal increases, the signified units in a scene will reduce, thus increasing the deviation in such reconstruction. The third is Ecological Optics(Gibson,1979,etc.). It holds that direct visual perception realizes by receiving a series of informative optical arrays reflected from the scene objects. During movements, the array patterns of change are lawful. For adapting intricate environment, human have evolved the ability to extract such invariant array patterns in changing scenes for understanding scene narratives. Therefore, any information loss of a scene will disturb the invariants cognition by synchronically mutilating the completeness of optical array pattern or diachronically interrupting the regularity of its movement sequence. Both of them will reduce cognition accuracy.

On above basis, it can be found that built components like wall and column in an architectural plan can make the visual integrity and visual continuity in both active and passive visual interaction of considered viewpoint to be different via visual occlusion. This occlusion shapes the asymmetrical behavior recognition accuracy in such bidirectional gaze, thus defining the differentiated degree of "prospect" and "refuge" properties of the considered location.(Fig.1b)

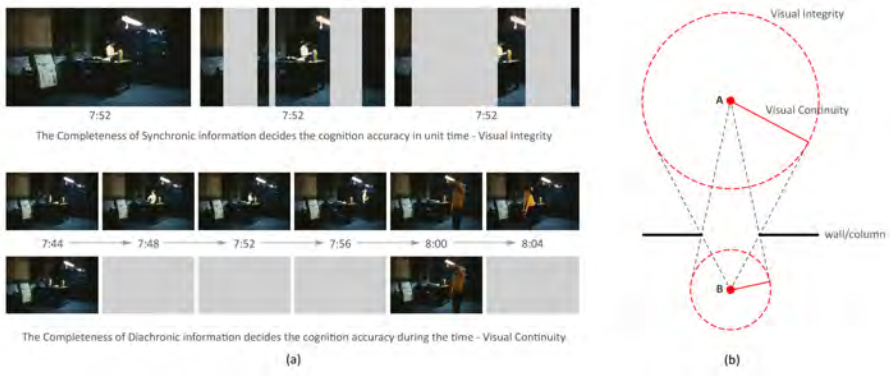


Figure 1. (a)Spatial factors for influencing accuracy of behavior recognition. (b)Two-dimensional built component(wall, column, etc.) shaping asymmetry in active(A sees B) and passive(B sees A) visual interaction of considered point(A).

3. CONSTRUCTING A PROSPECT-REFUGE ANALYSIS(PRA) MODEL

3.1. ABSTRACTION OF ARCHITECTURAL PLAN AS INPUT DATA

Building on the above findings, the actual measurement of PRA can be conducted via programming.

In the modelling, the built case can be sectioned at 1.7 m, the height of the human eye, from the standard floor height of major plan zone. If necessary, the plan zone with a slight height difference, usually less than 1m, with the major zones can also be involved considering less impact such difference evokes. The zones that do not satisfy the above conditions will be eliminated from consideration.

The plan area after the above sectioning can be represented by two point matrix systems with same density. One is the main point matrix including all bodily inhabitable positions in plan. Another is the secondary matrix including all visible contextual positions. Under this rule, the secondary matrix should always cover and sometimes exceed the area of the main matrix. Generally, the interval of around 1 m between two adjacent tested main points can be set to simulate the walking stride of person. Any position which can neither be bodily arrived nor be visually seen in plan will be excluded from both matrices.

Within these established nodes, all built components in plan will be abstracted into two types of polyline. The first type refers to the sight-blocking line such as walls higher than eye height and thick columns. The second type refers to all path-blocking line which not only covers all sight-blocking lines but also includes lines such as a fence above 0.5 m which is hard to step over, or a glass wall which blocks physical passage but maintains visual interaction.

3.2. PROSPECT-REFUGE DEGREE MEASUREMENT TO ANOTHER SINGLE VIEWPOINT

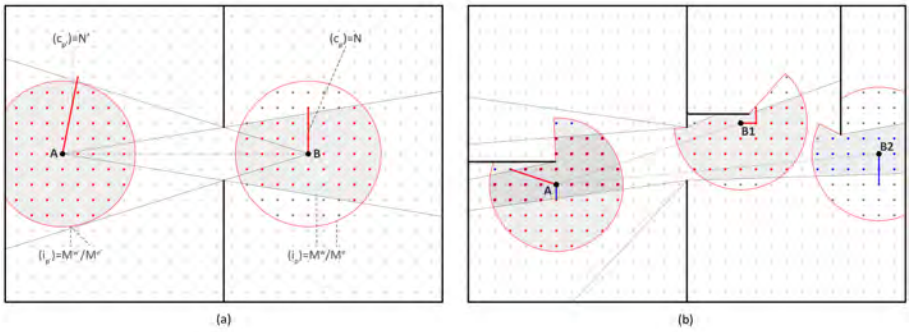


Figure 2. (a)Prospect-refuge degree measurement to another single viewpoint(B).
(b)Prospect-refuge degree measurement to overall viewshed(B1,B2 as two sampling points).

Based on the previous cognition theories, the recognition accuracy to a person's behavior(s_p) is positively correlating to both the visual integrity(i_p) and visual continuity(c_p). Quantitatively, we can use the product of (i_p) and (c_p) to measure

such accuracy, which means the accumulated amount of visible scene information defined by visible information of unit time and the shortest enduring time of such information:

$$s_p = i_p c_p \tag{1}$$

Procedurally, visual integrity(i_p) can be calculated with the following steps: 1.Setting a circle around the viewed point B to represent the contextual area of target person behavior. The radius of the circle can be adjusted for maximizing the differentiated condition of each location. 2.Connecting the viewed point B to all secondary sample points within the circle. The number of connection without intersecting with any sight-blocking wall line can describe the whole effective contextual area of target person(M^e). 3.Connecting the viewer point A to all effective points in step 2. The number of connection without intersecting with any sight-blocking wall line can describe the watchable contextual area of target person from viewer in point A(M^w). 4.The ratio of step 3 to step 2 could quantitatively describe the visual integrity in which point B exposes to point A(i_p):(Fig.2a)

$$i_p = M^w / M^e \tag{2}$$

Similarly, visual continuity(c_p) can be calculated by several steps: 1.Connecting the viewer point A to all the secondary sample points in the plan. The points of which connection line intersects with any sight-blocking wall line can describe the blind positions of point A. 2.Connecting the target point B to all blind points in step 1. If the connection line intersects with any path-blocking wall line, defining the shortest polyline which goes through any other secondary point as the effective connection line. 3.Selecting the shortest one of all effective connection lines in step 2 to describe the shortest sight-escaping distance a person could choose(N), in other words, the visual continuity of which point B exposed to point A(c_p):

$$c_p = N \tag{3}$$

Within the above measuring logic, the considered viewpoint will be given double values, (X) and (Y). The (X) is produced in direction this viewpoint actively views target person as the degree of "prospect" property, while (Y) is produced in direction this viewpoint is passively viewed by target person as the degree of "refuge" property. In such manner, the "prospect-refuge" degree of the considered viewpoint to another single viewpoint can be described as below:(Fig.2a)

$$(X, Y) = \left(s_p, s_{p^I}\right) = \left(i_p c_p, i_{p^I} c_{p^I}\right) \tag{4}$$

3.3. PROSPECT-REFUGE DEGREE MEASUREMENT TO OVERALL VIEWSHED

In actual space analysis, the target person may appear in every points of viewshed of viewer. In this sense, the behavior recognition accuracy to a whole viewshed(s_n) can be measured as the summation of synthetic information completeness of every inhabitable location of target person:

$$s_n = \sum(s_{p1} + s_{p2} + s_{p3} \ldots\ldots + s_{pn}) \tag{5}$$

Being similar with logic of two interactive viewpoints, the considered viewpoint

will also be given double values, (X) and (Y). The (X) is produced in direction the viewer views all potential locations of target person in his viewshed represented by the main point matrix. The (Y) is produced in direction this viewer is viewed by all above potential locations of target person. In such manner, the "prospect-refuge" degree of a considered viewpoint to its whole viewshed can be described as the continuous addition formulation:(Fig.2b)

$$(X, Y) = (s_n, s_{n^I}) \tag{6}$$

3.4. POSSIBLE SUB-MEASUREMENT OPERATION

Like other spatio-visual models, the PRA can be flexibly operated based on diverse purposes. For example, we can take all visible points into calculation to describe the absolute "prospect-refuge" degree of a location, while we can only take visible points outside convex space of considered point into calculation to describe the relative one of a location considering all points in same convex space have other interactive behaviors which can restrain the visual interaction effect.

3.5. OUTPUT DATA REPRESENTATION AND ITS PERCEPTION MEANING

In above measurements, the double values, (X) and (Y), of every location can be visualized as two concentric circles with respective areas to reveal several basic spatio-visual conditions associated with relevant perception implications: First, if (X) is larger than (Y), relevant location is a type of prospect-refuge area evoking more security and promising feeling; if smaller, such location evokes more insecurity and unpromising feeling. Second, the greater difference between (X) and (Y) means the location accommodates intensified feeling in either security and promising aspects or insecurity and unpromising aspects. Third, when the ratio is constant, the higher total value, (X) plus (Y), implicates the location is more strongly influenced by prospect-refuge related perception.

4. VERIFICATION OF PRA: A CASE STUDY OF WRIGHT'S DOMESTIC SPACE

After constructing the PRA model, the following part aims at using Hildebrand's (1991) prospect-refuge perception recording about Wright's domestic space to verify its measuring accuracy.

4.1. PERCEPTUAL PATTERN

Wright's domestic designs after 1901 have been widely praised for their capacity to stimulate positive phenomenological attraction(Laseau and Tice,1991; Lind,1994; Hienz,2006). One of convincing perspectives that explains the experience of Wright's houses is from its elaborately-designed spatio-visual property(Blake,1964; Twombly,1979; Salter,1999). By applying and extending Jay Appleton's prospect-refuge theory, such spatio-visual property is embodied by Hildebrand(1991) into a prospect-refuge related perception system described as "Wright Pattern". Based on that, Wright's post-1901 domestic projects share the two types of prospect-refuge perception quality that conjunctively shape the

psychobiological pleasure of their inhabitants(Hildebrand,1991):

More Similar Processional Incredibility: The first aspect lies in the more similar processional incredibility of prospect-refuge property along the path from entrance to heart of living room in most post-1901 houses. The concrete similarity includes: 1.Dominant refuge perception in the entrance foyer. 2.Remarkable increasing of prospect perception in the end of entry foyer near the living room. 3.Increasing refuge perception from the end of entry foyer to the seating space near fireplace(Prairie) or alcove(Usonian). 4.Decreasing refuge perception from the seating space near fireplace(Prairie) or alcove(Usonian) to the center of living room. 5.Increasing prospect perception from the seating space near fireplace(Prairie) or alcove(Usonian) to the center of living room. By providing such continuously changing dominant spatio-visual quality between prospect and refuge in dynamic path, Wright enables the visitor to first set foot on the room with a curious mind and lower expectation; Then surprisingly discover and continuously experience either a more exposed or a more covert location after entering. Such "processional incredibility"(Johnson,1958) can evoke positive emotional responses by allowing a person to move to a more prospect-dominant position when searching for resources or information and to a more refuge-dominant one if danger appears(Hildebrand,1991).

Increasing Global Heterogeneity: The second aspect lies in the increasing global heterogeneity of prospect-refuge property in most post-1901 houses. It means that the combinational relation of prospect and refuge properties of every location in public living zone of post-1901 houses presents higher diversity than that in prevailing Victorian style houses. By shaping such richer array of prospect-refuge condition, Wright provides diverse individuals with varying moods generated from not only gender and individual personality but also time of day, time of year, and time of life a suitable position to inhabit(Hildebrand,1999).

4.2. MEASUREMENT METHOD

Eight houses are chosen in each of three typical periods of Wright's domestic designs, the Victorian before 1901, the Prairie and the Usonian after 1901. The measuring results of both groups are compared with the recorded perception via specific statistical methods. By observing if the output data of post-1901 cases with "Wright pattern" has a higher consistency with prospect-refuge perceptual recording of them(Hildebrand,1991) than that of pre-1901 cases with those day's prevailing style, we can comparatively verify the PRA measurement.

The measurement will be implemented within the inhabitable area in built function zones of house while the surrounding areas will not be sampled. Since such surrounding area is dark for half of the day and is obscured by environment for much of the year, the visual interaction between built inhabitable area and it is partially symbolic just as "overlooking postage-stamp lawns"(Twombly,1979,245). Instead, since artificially connected, the visual interaction between different built function zones is arguably more possible to shape the actual prospect-refuge perception because it guarantees clear information acquisition all the time and allows for possible body-gathering right after visual interaction(Ostwald,2018). Using the above point matrix, a "relative"

PRA measurement is applied to each case considering the visual interaction within single convex space is generally restrained by other interactive acts.

4.3. MEASUREMENT RESULT



Figure 3. Three examples of PRA map of Victorian, Prairie and Usonian houses(left), sampling of processional regional similarity(middle) and sampling of global heterogeneity(right).

More Similar Processional Incredibility: After PRA testing, we make a data chart revealing the result of tested positions from entrance to living heart for each case. In the chart, the perception of dynamic walking positions is represented as the data of a series of successive tested points along the path based on Hildebrand's text and diagram, while that of static positions, like the seating space near fireplace(mainly in the Prairie), the alcove(mainly in the Usonian) and the center of living room, is represented as the average data of several tested points within relevant areas to insure the most veracious regional correspondence with the place evoking relevant perception in Hildebrand's(1991) recording. The results of all plans are compared with the expected standard result abstracted from Hildebrand's perception recording. We set 20 percent weight for each of the five regional similarities of prospect-refuge perception. The higher percentage means the higher regional similarity. The calculation result suggests the average similarity degree of post-1901 houses is higher than that of pre-1901 houses for around 15 percentage points although some individual samples like Adams have lower similarity than the average degree of pre-1901 houses. This result generally corresponds to Hildebrand's description about the higher processional regional similarity of prospect-refuge perception in Wright's Prairie and Usonian house.(Figs.3,4)

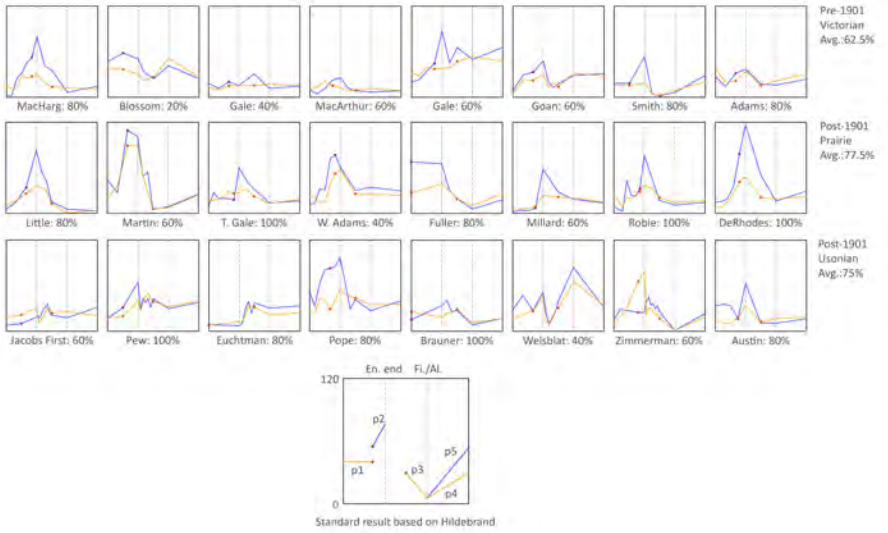


Figure 4. The comparative analysis for data-perception consistency of processional regional similarity between pre-1901 and post-1901 houses of Wright.

Increasing Global Heterogeneity: For global trend, we make a scatter plot containing the data result of all "public livable" zones for each case. According to the implied area condition in Hildebrand's(1991) recording, the increasing global heterogeneity of prospect-refuge is perceived in zones where all members of house owners and guests can stay comparatively long for enjoying domestic life. Therefore, the kitchen-pantry zones for servants in Victorian and Prairie houses, the bedroom zones for limited family members in all styles, and some extremely functional zones in all styles, such as heating room or storage room where people cannot stay long, are excluded from the data sampling. Based on the range of output data, a 20x20 grid is set for each plot to divide the whole value domain into 36 regional units. Statistically, each square unit in the grid can be approximated to reflect a type of obviously perceivable prospect-refuge state, since the data locating in the same unit of grid are comparatively close. Therefore, the more square units the data of a case occupy, the more diverse types of prospect-refuge perception the case can provide. The calculation result suggests the average amount of occupied "type" units of post-1901 houses is around five more than that of pre-1901 houses although some individual samples like Millard with less "type" units than average amount of pre-1901 houses exist. This result exactly reflects to Hildebrand's description about the increasing global heterogeneity of prospect-refuge perception in Wright's Prairie and Usonian houses.(Fig.5)

5. CONCLUSION AND DISCUSSION

In this paper we have presented and comparatively verified a spatio-visual analysis model for measuring the prospect-refuge related perceptions in two-dimensional built space.

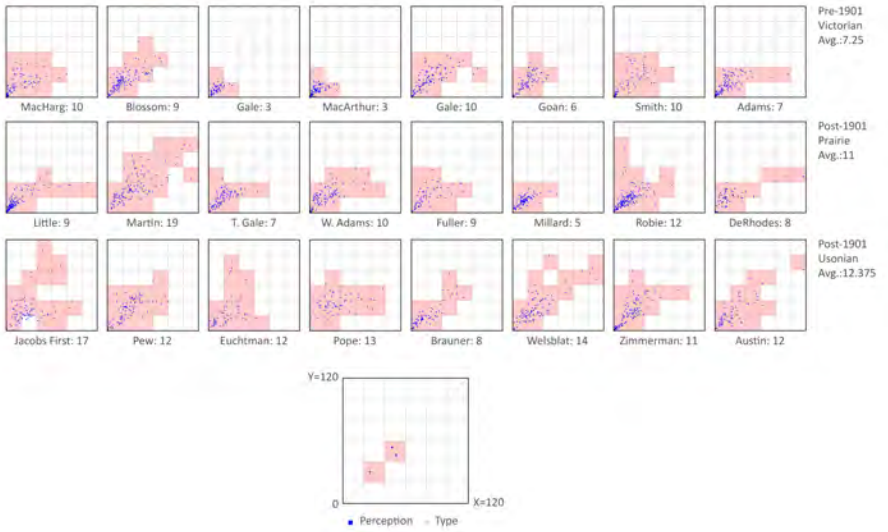


Figure 5. The comparative analysis for data-perception consistency of global heterogeneity between pre-1901 and post-1901 houses of Wright.

Admittedly, the present research has several technical and theoretical limitations. First, the current model mainly considers the enduring influence evoked by fixed space composition. If necessary, further work is needed by involving the lighting factor which will bring instantaneous influence on the recognition of person's behavior, the prospect-refuge degree. Second, the model mainly considers the architectural plan. More research is needed for extending it into three-dimensional space. Third, the congruity of verification is found in the present sample size. The result involving more cases is left for further examination.

References

Appleton, J.: 1975, *The Experience of Landscape*, John Wiley and Sons.

Archea, J.: 1984, *Visual Access and Exposure: An Architectural Basis for Interpersonal Behavior*, Ph.D. Thesis, Pennsylvania State University.

Batty, M.: 2001, Exploring isovist fields: Space and shape in architectural and urban morphology, *Environment and Planning B: Planning and Design*, **28**, 123-150.

Gibson, J.: 1979, *The ecological approach to visual perception*, Houghton Mifflin.

Gregory, R. 1974, Perceptions as hypotheses, *in* S. Brown (ed.), *Philosophy of Psychology*, Macmillan.

Hildebrand, G.: 1991, *The Wright Space: Patterns and Meaning in Frank Lloyd Wright's Houses*, University of Washington Press.

Hildebrand, G.: 1999, *Origins of Architectural Pleasure*, University of California Press.

Hillier, B. and Hanson, J.: 1984, *The Social Logic of Space*, Cambridge University Press.

Hochberg, J. 1968, In the mind's eye, *in* R. Habet (ed.), *Contemporary research in visual perception*, Holt, Reinhart and Winston.

Laseau, P. and Tice, J.: 1991, *Frank Lloyd Wright: Between Principle and Form*, Wiley.

Ostwald, M. and Dawes, M.: 2018, *The Mathematics of the Modernist Villa: Architectural Analysis Using Space Syntax and Isovists*, Springer.

Twombly, R.: 1979, *Frank Lloyd Wright: His Life and His Architecture*, John Wiley and Sons.

STEREOLITHOGRAPHY WITH RANDOMIZED AGGREGATES

ELIZABETH TEO[1], YUN JIE PANG[2], YU XIE[3],
PHEERAPHAT RATCHAKITPRAKARN[4], REBEKAH LOW[5] and
STYLIANOS DRITSAS[6]
[1,2,3,4,5,6]*Singapore University of Technology and Design*
[1,4,5]*{elizabeth_teo|pheeraphat|rebekah_low}@mymail.sutd.edu.sg*
[2,3]*{yunjie_pang|yu_xie}@alumni.sutd.edu.sg*
[6]*stylianosdritsas@sutd.edu.sg*

Abstract. The paper documents the design and development of an additive manufacturing process based on stone aggregates. Unlike conventional 3D printing technologies which target miniaturization of the material grain and deposition layers to achieve as high resolution as possible, our process deploys sizeable and randomized grains of stone. The objective of this is to leverage between physical scale of the particulate and time it takes to produce large enough artefacts, fast enough to potentially evoke spatial qualities. Perhaps unavoidably, due to its materiality, the process revisits one of the most archaic methods of building technology, namely masonry, and suggests for a unique digital perspective for structures and landscapes made from stone.

Keywords. Digital Fabrication; Additive Manufacturing; Aggregate Assemblies.

1. Introduction

The progress of cultural development is often associated with the materials that dominate technological applications of an era. Stone is the most archaic material used through history, while today we may associate our age with silicon. The study investigates digital fabrication with one of the oldest materials for design and construction of architecture. The method used is additive manufacturing which has been a topic of active research in the past decades (Tofail et al, 2018). The objective of the work is to explore contemporary modes of approaching masonry, create a process that can produce larger objects than those capable by common rapid prototyping 3D printers and produce a range of suggestive design objects.

Perhaps the most striking characteristic of additive manufacturing is in its geometric freedom and resource efficiency afforded by precise localized spatial arrangement of materials. Its enabling concept is in the assembly of coherent objects from microscopic grains of material which once fused together we can no longer discern them apart. Miniaturization of material grain is directly associated with the resolution of 3D printing and its ability to assign complex geometric features within a quantized space indexed by the underlying mechanical positioning system. However, resolution is inversely proportional to time required

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 323-332. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

for producing 3D objects from fine layers or filaments; thus, a compromise is required if we aim to move towards architectural applications. Here we take the approach of increasing the size of material particle to enable faster production of larger objects and exploit the randomness of natural materials to achieve end product coherence. We use stone aggregates because of their abundance in almost every part of the world, their low cost, embodied energy, high compression strength and association with architecture and landscape design (Figure 1).



Figure 1. Randomised stone aggregate prototypes .

2. Background

The project was inspired by traditional East Asian dry landscapes, also known as rock gardens, and gravel sculptures such as the Kogetsudai located within the garden of Ginkaku-ji in Kyoto, Japan (1482). The Dominus Winery by Herzog and de Meuron in Napa Valley California, USA (1995-1998), where use of coarse stone aggregates encased within steel cages suggested for a unique perspective to drywall masonry. Additive manufacturing already spans over 30 years of research and development (Huang et al, 2015) with early applications targeting rapid prototyping using thermoplastic and thermoset polymers, with fused deposition modelling (FDM) and stereolithography (SLA) being respective examples thereof. One of the earliest relevant methods, commercially available by Z-Corp, used a plaster-like material which was fused by inkjet printing of a binder. Applications of 3D printing in architecture and construction generally pivot about material extrusion of concrete (Khoshnevis, 1998; 2004; Lim et al 2012; Bos et al 2016) while some of the earliest applications of robotics targeted additive assembly of masonry structures (Andres, Bock and Gebhart, 1994; Gambao, Balaguer and Gebhart, 2000; Gramazio and Kohler 2008). Experimental methods of additive manufacturing progressively incorporated a wide range of materials including clay (Friedman, Heamin and Mesa, 2014), silicone (Snooks, and Gwyllim, 2016), wax

(Gardiner and Janssen, 2014) and wood composites (Tan et al, 2017). Stone, a material which is generally considered difficult to use because of its high density and hardness, has been part of digital fabrication methods including subtractive processes (Ariza et al, 2016; Block et al, 2016; Burry, 2016). Relevant research here includes 3d printing of stone-like materials (Morgante, 2011; Lowke et al 2018), additive manufacturing with sand particles (Gramazio and Kohler, 2011; Dillenburger and Hansmeyer, 2014), additive assembly with large spherical particles (Kurilla and Svoboda), friction-based randomized aggregations (Dierichs and Menges, 2010; Dierichs, Schwinn and Menges, 2012) as well as cord reinforced aggregate assemblies (Aejmelaeus-Lindström, 2016; 2018).

3. Digital Fabrication

The operating principle of our method is classified as binder jetting (Figure 2). Powdered material is deposited layer by layer within a fixed-size printing volume and it is locally fused together by dispensing a liquid binder. The container supports progressive accumulation of material vertically and retains loose particles until the adhesive hardens. This simplifies machinery programming as there is no requirement for provision of 3D printing scaffold structures. However, printed parts are extracted from the build volume by a characteristically laborious excavation type of process. Nevertheless, material that has not been fused in the solid body or contaminated by the binder can be reused.

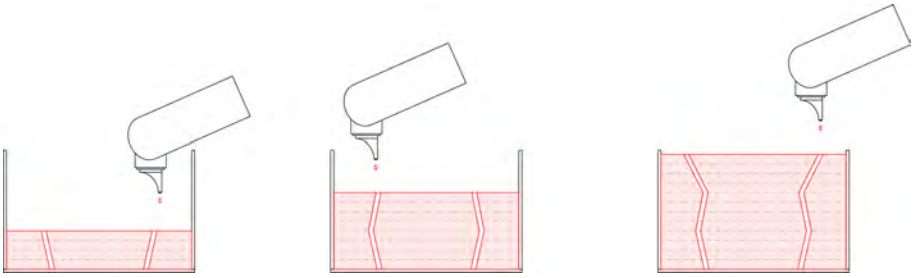


Figure 2. Binder jetting additive manufacturing process as per ISO/ASTM 52900:2015.

3.1. SYSTEM OVERVIEW

Implementation of binder jetting here is based on an industrial articulated 6-axis robotic arm with 5 kg payload and 0.9 m horizontal reach used as a positioner. The robot is employed as a flexible programmable space indexer as its full breath of motion on 6-axes is not required; a three-axis or even two-axis cartesian robot would have sufficed. The binding material is transported from a stationary container next to the robot via hose using a pump and directly dispensed from a 3D printed coupler mount on the robot's flange. The pump operation is synchronized with the robot's motion using a programmable logic controller (PLC). Its firmware binds the robot's controller digital outputs to an analog pulse width modulated (PWM) signal controlling the DC motor-based pump's speed via voltage changes.



Figure 3. Industrial robotics setup for 3d printing with pebbles.

3.2. MATERIAL PROPERTIES

The aggregate material is a coarse stone with diameter circa 3-5 mm and weight 2-3 g/cm^3. It is commonly used for gardening, landscaping and construction. It is available in multiple colours and costs approximately 0.4 USD/kg. Unlike rough surface aggregates used for concrete fabrication, its texture is smooth, and shape rounded. It is pleasant to touch and in appearance it resembles sea or river pebbles. The binder used is a commercial off the shelf two-part epoxy adhesive with 20 min open time. Typical viscosity of thermoset polymer adhesives, such as epoxies is circa 10,000 cP, even though low viscosity 200 cP and ultra-high 1,500,000 cP formulations exist. Compared to familiar liquids such as water's 1 cP and other common adhesives such as low and medium cyanoacrylates ranging about 5-100 cP, the rheological properties of epoxies are challenging for binder jetting processes being too viscous.

While it is not impossible to dispense high-viscosity liquids, it often requires high-pressure mechanical units such as those used for clay or concrete extrusion. High viscosity is also associated low flow rate, by Hagen-Poiseuille law, and consequently dispensing needs to slow down substantially such that motion speed can track material flow. In addition, strong universal material adhesives such as epoxies are very difficult to handle because their open time window is often limited and once it closes the system requires laborious purging and disposal of consumable components. Finally, while the cost of aggregates is low, the cost of epoxies is rather high, particularly in small quantities, while in large batches one needs to consider its limited shelf-life.

To overcome dispensing challenges and accelerate printing we diluted the epoxy binder with an acetone-based product and lowered its viscosity such that it could flow through a 2 mm internal diameter hose. Diluting epoxy with thinners is generally not advised by manufacturers because it compromises its

adhesive strength and overall mechanical properties. Ratios of acetone to resin experimentally tested were 1:2, 1:4, 1:8 and 1:12 by weight, with 1:8 determined as sufficient for transport and layer penetration. A collateral effect of acetone to resin mixture was in widening the curing time window from its advertised 20 to 40 min. Binding material transport could then be performed using a low power and cost peristaltic pump driven by a 6 V DC motor. To prevent clogging and disposal of consumables we used silicone hosing and utensils.

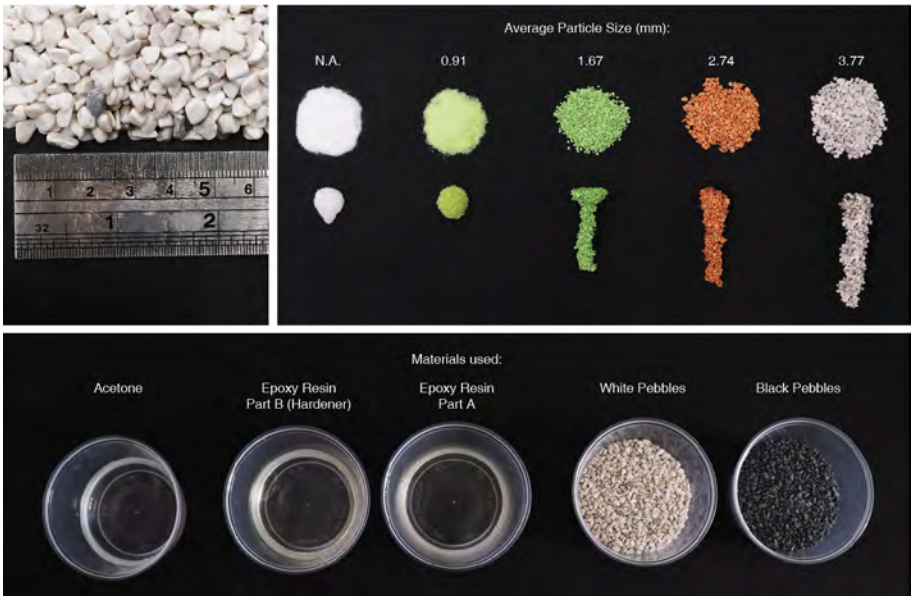


Figure 4. Material samples and preliminary experiments.

3.3. PRINTING PROCESS

The process requires a bounding envelope where coarse aggregates are placed in 10-15 mm high layers. We built a cabinet with 0.4 by 0.4 by 1 m featuring detachable walls to reduce part extraction time. Currently aggregate layer layout is performed manually unlike commercial 3D printers which often use two mechanically actuated containers transferring material from one another using an additional mechanically actuated wiper. While manual material layering is far from ideal, for experimental purposes it allowed testing different materials and thickness per layer. In addition, as the aggregates used are large in diameter it takes only 50 layers to print a 0.5 m high artefact. After each layer of aggregates is placed, the contours extracted from a 3D shape are traced by the epoxy dispenser. Thinned epoxy resin is dispensed from 700 mm above the pebble layer and on impact infiltrates the porous pebble layers and binds them horizontally and vertically. Contour extraction, translation to machine paths, compilation to robot programing language and communication with the controllers were performed

through a digital fabrication library within Rhinoceros and Grasshopper.

3.4. PROCESS PARAMETERS

Achieving consistent results with binder infiltration is not an easy task: Insufficient adhesion due to resin starvation resulted to numerous parts being fractured during extraction. Excessive use of epoxy produced undesired effects such as over penetration and pooling at the bottom of the container. In addition, use of a peristaltic pump for dispensing was not ideal as its reciprocating action overlayed a harmonic on binder flow which resulted in uneven penetration along linear motions. This can be observed by the formation of undesired, but otherwise beautiful, stalactites suspended from the surface of the 3d prints. To approach this problem methodically we performed a series of experiments and measured the results of single linear stone beads (Figure 5).

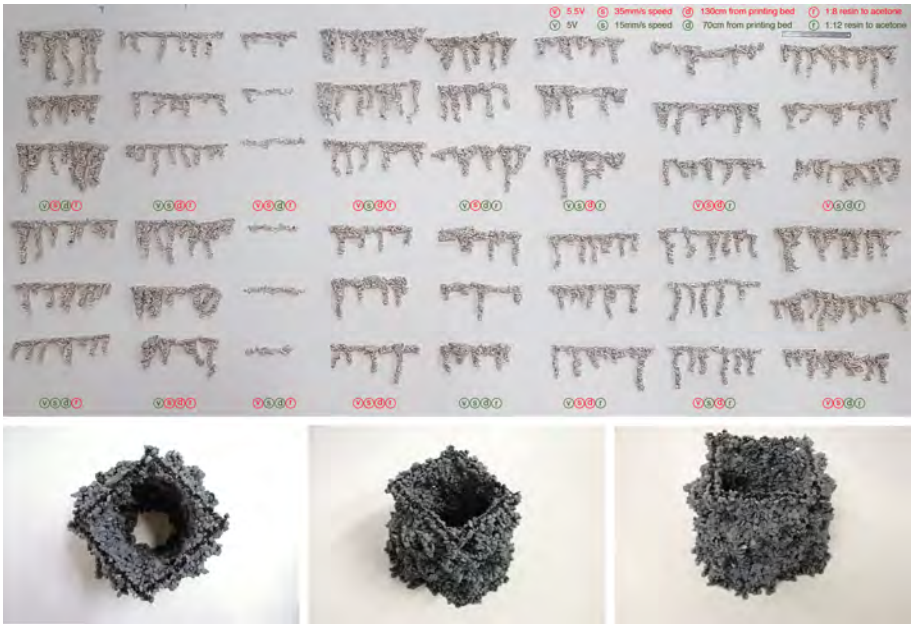


Figure 5. Experimental design tests aiming to control binder flow and penetration.

The objective of this study was to achieve approximately 15 mm depth of penetration consistently, to ensure subsequent layer adhesion, while reducing the amount epoxy used to prevent it from appearing on the exterior surface of parts or worse causing the formation of stalactites. Controllable parameters include: the material flow rate *(f)* for which we measure via the voltage applied on the pump, the motion speed of the robot *(v)* measured in mm/sec, the acetone to resin ratio *(r)* and distance of dispensing *(d)* in mm. We performed a two-level combinatorial set of experiments using 5 and 5.5 V flow rate, 15 and 35 $mm/$sec motion speed, 1:8 and 1:12 ratio; and 70 and 130 cm dispensing distance. We measured the average penetration depth at three points along each bead and number of stalactites

generated. While attempt to fit a regression model to allow for prediction of an optimal operating point was not statistically fruitful, perhaps because of innate non-linearity of material dosing, we did identify useful parameter configurations. Prototypes created using those parameters resulted to coherent exterior surface without gaps seen in earlier prints.

4. Prototyping

During project development we produced a large number of prototypes. Early experiments focused on variations of materials including adhesives and grain sizes such as soil, sand, gravel and pebbles. Once the use of pebble aggregates was determined as most effective, experiments focused on investigating visual, morphological, material and structural capabilities of the produced artefacts. Visually a unique characteristic of aggregate assemblies is in their ability to read simultaneously randomized and noisy but coherent from distance, while their granularity can be appreciated from closer proximity. The ability to locally inject the binder, produced stone-like artifacts with counterintuitively thin walls and low overall mass. The unexpected property of harmonic pump pulsation and early inability to control it sufficiently was reflected on some of the parts as a rhythmic introduction of surface perforations, localized erosion or stone lattice-like structures. Experiments with material variations include mixture of colored pebbles, at progressive interpolating ratios between thereof, producing a material gradient vertically.



Figure 6. Prototypes developed exploring the material and geometry interactions.

Working near the starvation bound of resin-to-pebble ratio was effective as the adhesive remains hidden internally within 3D printed surface walls. This results in a sense of ambiguity for the creation process behind the artefacts. They appear to be formed by natural forces, such as conglomerate sedimentary rocks, as it is unclear how pebbles are fused together. The dichotomy between the source of origin of the artefacts was exaggerated, or perhaps resolved, by structurally

counterintuitive geometric features such as tapering walls, cantilevering edges and low spanning arches achieved. The rather broad range of unique aesthetic attributes enabled by the pebble binding method, some of them discovered by accident and/or lack of process control, demonstrates that often there are interesting tangential design opportunities beyond achieving initially planned conventional targets.

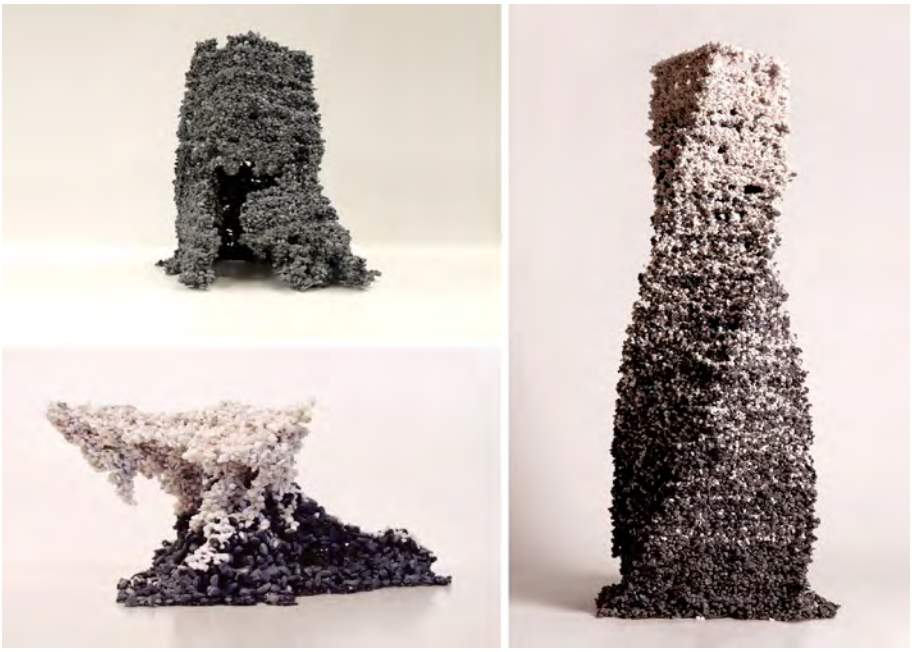


Figure 7. Randomized pebble aggregate prototypes with various color combinations.

5. Conclusions

We presented the development of an additive manufacturing process using coarse randomized assemblies of pebble aggregates. The motivation that guided the development of the project was driven by the desire to produce large artefacts by accelerating additive manufacturing. Using large grained, ubiquitous and low cost materials directed us towards the use of stone. Use of not particularly environmentally-benign nor cost-affordable adhesives, directed development efforts towards minimizing its use. Prototypes created demonstrate some unique characteristics of a process that can produce artefacts that fuse natural, machine and man-made aspects. This could have not been possible without integration of materials and fabrication: if the pebbles were not coarse while smooth and convex enough to allow binder flow through their interstitial spaces and cavities; or if objects were structurally not primarily working in compression this method would not have worked. In terms of scaling this process to create larger objects closer to architectural scale, our perspective is that we do not need to scale the machine to

the size of the building. Instead we believe that reducing the time and effort for producing transportable components is more meaningful. An interesting aspect of randomized aggregate assemblies is that tectonics are baked-in the material and fabrication logic. Placing components next or on top of one another is often sufficient to blend them together due to randomization which at broader view homogenizes the visual and mechanical properties of the whole. We envision that the process developed and presented, can be used for both architectural as well as dry landscape design applications.



Figure 8. Rock garden feature prototype.

Acknowledgements

This research was supported by the Singapore University of Technology and Design Office of Education and the SUTD-MIT International Design Centre.

References

Aejmelaeus-Lindström, P., Rusenova, G., Mirjan, A., Gramazio, F. and Kohler, M.: 2018, Direct Deposition of Jammed Architectural Structures, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 270-281.

Aejmelaeus-Lindström, P., Willmann, J., Tibbits, S., Gramazio, F. and Kohler, M.: 2016, Jammed Architectural Structures: Towards Large-Scale Reversible Construction. Granular Matter, *Granular Matter*, 2-12.

Andres, J., Bock, T. and Gebhart, F.: 1994, First results of the development of the masonry robot system ROCCO: A Fault Tolerant Assembly Tool, *11th International Symposium on Automation and Robotics in Construction (ISARC)*, 87-93.

Ariza, I., Sutherland, T.S., Durham, J.B., Mueller, C., McGee, W. and Clifford, B.: 2016, Robotic Fabrication of Stone Assembly Details, *Proceedings of FABRICATE*, 106-113.

Block, P., Rippmann, M., Van Mele, T. and Escobedo, D.: 2016, The Armadillo Vault: Balancing Computation and Traditional Craft, *Proceedings of FABRICATE*, 286-293.

Bos, F., Wolfs, R., Ahmed, Z. and Salet, T.: 2016, Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, *Virtual and Physical Prototyping*, **11**(3), 209-225.

Burry, M.: 2016, Robots at the Sagrada Família Basilica: A Brief History of Robotised Stone-Cutting, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 3-16.

Dierichs, K. and Menges, A.: 2010, Material Computation in Architectural Aggregate Systems Formation, *Proceedings of the Association for Computer Aided Design In Architecture*, New York, USA, 372-378.

Dierichs, K., Schwinn, T. and Menges, A.: 2012, Robotic Pouring of Aggregate Structures, Responsive motion planning strategies for online robot control of granular pouring processes with synthetic macro-scale particles, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 196-205.

Dillenburger, B. and Hansmeyer, M.: 2014, Printing Architecture: Castles made of sand, *Proceedings of FABRICATE*, 92-97.

Friedman, J., Heamin, K. and Mesa, O.: 2014, Experiments in Additive Clay Depositions Woven Clay, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 261-274.

Gambao, E., Balaguer, C. and Gebhart, F.: 2000, Robot assembly system for computer-integrated construction, *Automation in Construction*, **9**, 479-487.

Gardiner, J.B. and Janssen, S.R.: 2014, FreeFab, Development of a Construction-Scale Robotic Formwork 3D Printer, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 131-146.

Gramazio, F. and Kohler, M.: 2008, *Digital Materiality in Architecture*, Lars Muller Publishers.

Gramazio, F. and Kohler, M.: 2011, "Prozedurale Landschaften 2" . Available from <http://www.dfab.arch.ethz.ch/web/d/lehre/211.html> (accessed November 2018).

Gramazio, F. and Kohler, M.: 2011, "Prozedurale Landschaften 1" . Available from <http://www.dfab.arch.ethz.ch/web/d/lehre/208.html> (accessed November 2018).

Huang, Y., Leu, M.C., Mazumder, J. and Donmez, A.: 2015, Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations, *Journal of Manufacturing Science and Engineering*, **137**(1), 1231-1241.

Khoshnevis, B.: 1998, Innovative rapid prototyping process making large sized, smooth surface complex shapes in a wide variety of materials, *Materials Technology*, **13**, 52-63.

Khoshnevis, B.: 2004, Automated construction by contour crafting, related robotics and information technologies, *Automation in Construction*, **13**, 5-19.

Kurilla, L. and Svoboda, L.: 2012, Geometry Optimization, Realization of a fluid-form structure composed of spherical components, fabricated by means of computer software and robotic arms, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 184-195.

Lim, S., Bushwell, R.A., Le, T.T., Austin, S.A., Gibb, A.G.F. and Thorpe, T.: 2012, Developments in construction-scale additive manufacturing processes, *Automation in Construction*, **21**, 262-268.

Lowke, D., Dini, E. P.e.r.r.o.t., Weger, D., Gehlen, C. and Dillenburger, B.: 2018, Particle-bed 3D printing in concrete construction - Possibilities and challenges, Cement and Concrete Research, *Volume 112, 50-65*.

Morgante, A.: 2011, Radiolaria Pavilion, *Proceedings of FABRICATE*, 232-235.

Snooks, R. and Gwyllim, J.: 2016, Closeness: On the Relationship of Multi-agent Algorithms and Robotic Fabrication, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 219-230.

Steinhagen, G., Braumann, J., Brüninghaus, J., Neuhaus, M., Brell-Cokcan, S. and Kuhlenkötter, B.: 2016, Path Planning for Robotic Artistic Stone Surface Production, *Proceedings of Robotic Fabrication in Architecture, Art and Design*, 123-136.

Tofail, S.A.M.: 2018, Additive manufacturing: scienti fi c and technological challenges, market uptake and opportunities, *Materials Today*, **21**(1), 22-37.

ROBOTIC FREE-ORIENTED ADDITIVE MANUFACTURING TECHNIQUE FOR THERMOPLASTIC LATTICE AND CELLULAR STRUCTURES

MANUEL LADRON DE GUEVARA[1], LUIS BORUNDA[2], JEREMY FICCA[3], DARAGH BYRNE[4] and RAMESH KRISHNAMURTI[5]
[1,3,4,5]*Carnegie Mellon University*
[1,4,5]*{manuelr|daraghb|ramesh}@andrew.cmu.edu* [3]*jficca@cmu.edu*
[2]*Universidad Politecnica de Madrid*
[2]*lborunda.eco@etsav.cat*

Abstract. This paper presents a novel Additive Manufacturing application of situated Robotic Fused Deposition Modeling (RFDM) for thermoplastic cellular and lattice structures, called Free-Oriented Additive Manufacturing (FOAM), to accommodate variations in spatial conditions, deposition direction, and geometry in order to adapt to complex infrastructure settings, thus, breaking the conventional layer-by-layer stacking principle and the constant constraint of locking the tip of the nozzle to the negative Z direction when fabricating at an architectural scale.

Keywords. Robotic 3D Printing; Situated Fused Deposition; Thermoplastic Lattice Structures.

1. Introduction

Fused Deposition Modelling (FDM) is the most common method of Additive Manufacturing (AM) or 3D printing to alter manufacturing processes, because it affords freedom of design, waste minimization, complex modelling and fast prototyping (Ngo et al. 2018). Both in practice and academia, AM techniques contribute to discovering new design methodologies coordinated to fit with emerging robotic fabrication techniques (Oxman R. 2008, Willmann et al. 2013).

Fabrication of architectural elements by robotic systems has been broadly reviewed (Warszawski 1984, Haas et al. 1995) foreseeing robotic ubiquity, advances in automation construction, deconstruction and re-customization, providing tools for reconsidering existing construction practices (Bock 2015). Large-scale AM requires data, which can be efficiently introduced into the informed design for improved functionality (Ackoff 1974), reproduced with uncanny precision by automated systems (Hack et al. 2014) and improve the economics of production even for highly complex geometries (de Soto et al. 2018).

Conventional FDM techniques follow a stacked, layer upon layer, continuous thermoplastic polymer deposition of material, which pose problems for large scale

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 333-342. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

prototyping and construction field application. Recent studies have explored adjustments to 3D printers and robotic arms, as well as developing highly specialized end effector tools for specific applications (Felbrich et al. 2018, Kwon et al. 2019), that considers thicker material, optimized tool-paths to avoid material waste, costs, and time-consuming processes.

Spatial FDM is a method by which molten polymer sections are configured in a space frame pattern, which has demonstrated capability of fabricating functional products with optimized performance (Liu et al. 2018), and reduce fabrication time for prototype prints by differentiating the local value of a printed specimen along the extrusion process (Mueller et al. 2014).

Robotic arms augment the scale of fabrication. Their benefits and application within design processes have been explored (Tam & Mueller 2017, Yuan et al. 2016). In particular, Branch Technology implements a RFDM technique slightly tilting the nozzle when required, and without changing the orientation of the base. Recent advances in robotic AM (Huang et al. 2018) explore near impossibility of in-situ printing unless the piece is anchored to the ground, and the need to generalize to novel design methodologies.

This paper describes an AM technique, which breaks the constraint of printing along a negative Z axis (Figure 1), and utilizes the compacity of the end effector tool, for maximum reach and robotic motion in order to print complex infrastructures. This technique requires the study of the physical tool, material, and specifically contextualized computational design and tool-path workflows.

This research also provides insight into possible applications of extending AM techniques using commercially available equipment. In particular, we implement a flexible printing orientation method, suitable for novel spatial FDM applications, where minimum equipment dimensions for maximizing geometric production capabilities is required.



Figure 1. Free-Oriented Additive Manufacturing printing in the +Z direction.

2. FOAM Technique

We describe a technique, Free-Oriented Additive Manufacturing (FOAM), for robotic printing on an existing infrastructure, which bypasses assembly of parts, and decreases both cost of and time for construction. FOAM is able to cooperate with gravity and print in a counter-intuitive fashion. We explore variability by being able to change orientation of the tool while printing, by not constraining the tip of the nozzle to pointing down. We consider application to non-planar, curved infrastructures, and contrast this approach with conventional techniques.

2.1. EXTRUSION SYSTEM

2.1.1. End of the Arm Tool (EOAT)

To achieve maximal freedom of orientation and maneuverability, a compact unit is designed with all needed components for printing, integrated at the EOAT. The extrusion system is housed in a small box as illustrated in Figure 2, containing the motherboard and electronic components, a material spool as a feeder source, and a commercial extruder. The distance between the default Tool Center Point (TCP) and the tip of the nozzle is 450mm, perpendicular to the normal vector of the ATI plate. Collision cushioning is achieved by elongating the distance between the nozzle and the electronic box with a non-rigid 50x300x3mm aluminum plate, making it flexible enough to bend under collision, protecting the nozzle from breaking. For simplicity, no scanning tools or proximity sensors were employed.

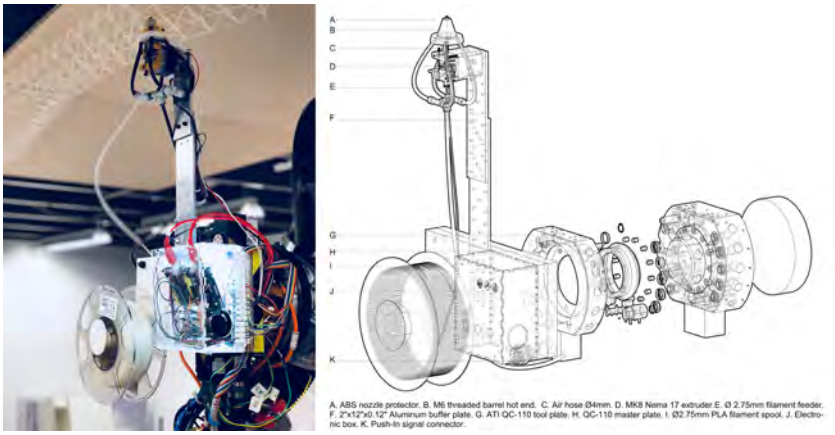


Figure 2. FOAM tool components: (Left) The working tool mounted on the robot arm. (Right) An annotated view of the components .

2.1.2. Thermoplastic Polymer Extrusion System

To make a cost-effective tool, we harvested components from commercial 3D printers. A regular 1.75mm diameter MK8 extruder is adapted for an M6 threaded barrel to feed a 3mm diameter thermoplastic filament through its interior. The barrel is wrapped with a 22 gauge nichrome wire, 1.04m length, yielding a

resistance of 3.5 ohms to provide 12VDC 60W. This is sufficient to keep the nozzle at a melting temperature, up to 300C, within the range of the types of thermoplastics tested (PLA, PLA+, ABS, PETG). A 0.33mm stainless-steel wire was also tested, using 1.5m length of wire to obtain the same resistance. An NTC 3950 100K Thermistor as temperature sensor is attached to the tip of the barrel. To protect the hot-end from the ambient temperature, ceramic-fiber insulation and an ABS printed cover are needed. This custom piece also holds four air-hoses connected to the 6640 ABB air supply unit, solidifying the material upon extrusion. Best results are obtained by keeping a distance of 25 - 40mm between the air hose and the tip of the nozzle, maintaining an operating air pressure of 15 PSI. An electronic box contains Arduino boards to control temperature and feed flowrate. The logic voltage of the A4988 motor driver varies from 3 to 5.5v, having a max current per phase of 2A if pressurized cooling air is provided, or 1A otherwise.

2.1.3. Printing Materials

FOAM uses commercial 3mm diameter filament rolls which can result in 4mm thick printed material, depending on time, feed-rate and velocity parameters. For instance, if velocity of the robot is set to 3mm/s, and feed rate is set to 1/8 steps/s , it would generate ˜3.5mm extrusion. Maintaining the same feed-rate and incrementing the speed of the robotic arm to 8mm/s, reduces thickness to 20%.

Tested thermoplastic filament rolls include PLA, PLA-PRO, ABS and PETG. ABS and PETG offer higher capabilities than PLA such as lightweight properties (1.04, 1.23 and 1.24g/cm3 respectively), major elongation at break (22%, 228% and 8%), and major distortion temperature. Although not vitrifying as quickly as ABS or higher temperature thermoplastics, PLA presents the best results as it maintains a successful melting point at a wider temperature range, 190 - 210 (see Table 1.).

Table 1. Thermoplastic properties, eSUN Industrial CO.LTD.

FILAMENT	Print Temp(°C)	Density (g/cm3)	Distortion Temp (°C, 0.45MPa)	Melt Flow Index (g/10min)	Tensile Strength (MPa)	Elongation at Break (%)	Bending Strength (Mpa)
PLA	190 – 210	1.24	56	5(190°C/2.16kg)	65	8	97
PLA+	205 – 225	1.24	52	2(190°C/2.16kg)	60	29	87
ABS	220 – 270	1.04	78	12(220°C/10kg)	43	22	66
ABS+	220 – 270	1.06	73	15(220°C/10kg)	40	30	68
PETG	230 – 250	1.23	64	20(250°C/2.16kg)	49	228	68

2.1.4. Robotic Reach

To print freely in the space, it is possible to mount a pellet feeding system on the robotic arm, locking the nozzle position in its -Z direction (Soler et al. 2017). Alternatively, configurations can be liberated from the axis constraint by developing a highly engineered system to achieve a steady supply of plastic pellets, compromising cost-effectiveness (Oxman N et al. 2013). To expand the reach of the robotic arm and reduce system cost, we work closely with a commercial 3D printer configuration, housing its components and feeding system directly at the

EOAT, thus, being able to print over non-horizontal and non-planar infrastructures at reduced cost (see Figure 3.).

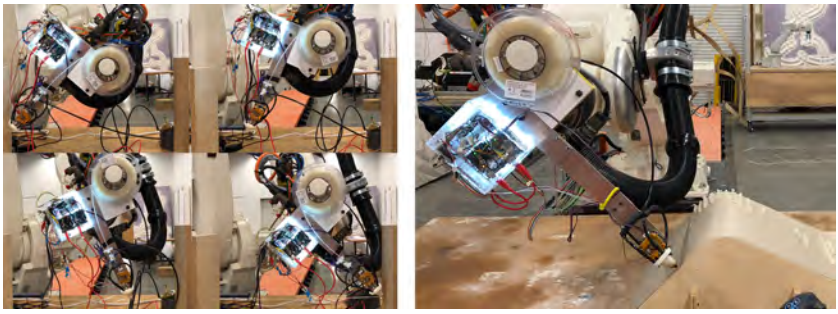


Figure 3. (Left) Tool operating within a 80cm space between vertical walls. (Right) FOAM applied over a non-planar surface.

2.2. FREE ORIENTED ADDITIVE MANUFACTURING METHOD

2.2.1. PID, Cooling System, and Stepper Synchronization

A critical factor for consistent filament extrusion is the control of temperature. For this, we use a proportional integral-derivative (PID) algorithm, a standard for industrial control systems.

2.2.2. Physical Constraints

The process starts by heating up the nozzle at a melting temperature. The robotic arm moves the hot end following a given toolpath. Normally rectilinear segments are chosen over a curvilinear typology, as the latter would require alternative techniques to solidify the material in such shape. Each point of discontinuity has a different wait time, to ensure proper solidification of the molten plastic and accurate bonding with already printed material. The algorithm is capable of computing a print at any orientation and direction without altering the quality of the print, challenging the force of gravity in the process. The direction and taper of angles are directly constrained by the angle of the nozzle (Figure 4a).

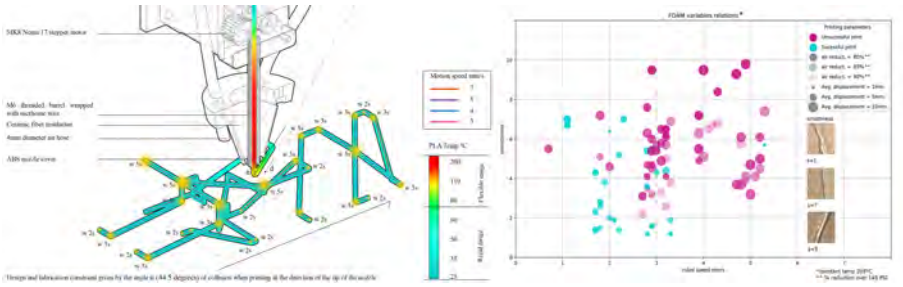


Figure 4. a. (Left) Spatial printing analysis. b (Right) Printed tests varying FOAM parameters.

3. Computational Methods

3.1. DESIGN

Two distinct algorithms were tested to design the workpieces of each case study.

The first is a similar to an oct-tree algorithm, for cellular structures, which determines whether a voxel lies inside or outside the volume. We assign a set of polylines to each voxel, which respond to a design criteria. The algorithm computes an overall set of individual geometries, responding to parameters such as opacity, structural behavior and material budget. The principal part of the algorithm ensures that every unit is printable and that none collide with the already printed neighbor. A backtracking algorithm finds a printable in-budget solution, making the design process informed by its inherent physical and material fabrication constraints.

The second creates two NURBS surfaces from two distinct pairs of splines, extracting a lattice structure based on repetitions of the following pattern: short supporting segment, diagonal downward segment, short supporting segment and diagonal upward segment. We consider the curvature contrast between surfaces, one maintaining curvature in the U direction, and the other in the V direction. The potential error in fabrication presented by curvature differences is balanced by an algorithm that weaves the lattices connecting their nodes (Figure 5).

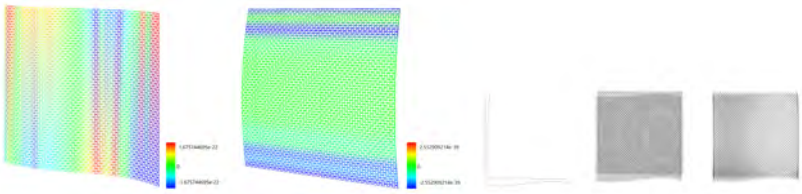


Figure 5. Design Process for Lattice Structures.

3.2. FABRICATION

A tectonic approach that considers affordances and limitations of material, and the physical tool is recommended. However, anticipating constraints does not ensure clean and fail-safe fabrication. The main challenge is that the nozzle has to respect material already printed in order to prevent collisions. For instance, in the cellular structure algorithm, collision detection between voxels is checked. To overcome unforeseen problems, a feedback loop between the design and fabrication processes is implemented. For efficiency, an offset in the Z direction higher than the voxel's height is applied to the first and last points of the polyline at each cell. This ensures that the nozzle never collides with already printed geometries during non-printing motions.

4. Case Studies

Two case studies have been tested to accommodate both structures. The cellular structure is tested by conventional 3D spatial printing, locking the nozzle at the

negative Z axis; the lattice structure is tested at different orientations using two configurations: implementing a dynamic multi-robot workflow, and printing over a 4m height ceiling, locking the nozzle at the positive Z axis.

4.1. CELLULAR STRUCTURE

A volume is discretized into smaller units using a multi-resolution approach. The underlying 3D grid stores information such as material and geometry at each voxel. Testing a range of printable polylines from simple to complex give insights into the type of design nomenclature feasible for this fabrication technique.

Acute angles present a lower fidelity to the digital model than obtuse angles. Consecutive segments shorter than 10mm start to blur the overall appearance of the cell. Printing temperatures above 220C for PLA result into sagged segments. Otherwise, an excess of cool temperature, below 180C, yields rigid segments that produce undesirable low-fidelity outcomes. These constraints might be overcome by changing feed-rate flow, wait times and the motion of the robot; it is also necessary to find a contextualized balance between design limitations and time cost. The variability of the results compromise the clarity of the relation between parameters and geometrical path. However, the relation between the robotic arm speed and air pressure yields a clear distinction. An increase in speeds beyond 4mm/s requires design re-adjustment (see Figure 4b). It is important to note that material texture is less smooth when the PLA spool has higher humidity levels.

4.2. LATTICE STRUCTURE

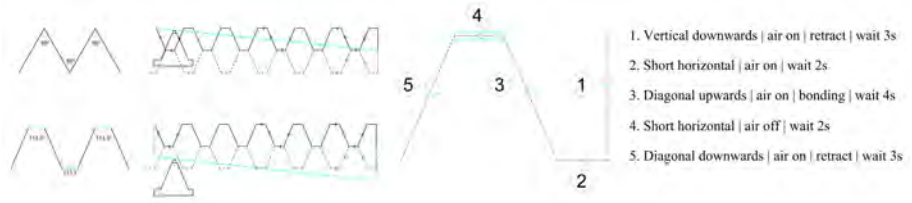


Figure 6. Physical constraint feedback into design process.

Lattice structures are generally organized by rows of repeated patterns. The results provided by the cell structure method informs the design of the pattern for the lattice structure. Consider a proper equilateral-triangular pattern. Although within a printable range, it presents drawbacks such as a lack of horizontal support for upper rows, as well as a risk of decrease in the height of the triangle, since acute angles are prone to bow towards the direction of printing due to the tensile strength carried by the nozzle. A workaround is to introduce small horizontal segments at the vertices, so that the acute 60° angles are converted to a 113° obtuse angle. To avoid collisions, this typology requires adding an offset point at the beginning and end of each row (Figure 6).

The material behavior was tested at a smaller scale by the use of two robotic arms synchronized so that an ABB IRB 4400 arm grips an MDF base at a given

orientation. An ABB IRB 6640, which holds the printing tool, starts printing the lattice structure until the first robot changes the orientation and position of the board. The printing robot readjusts its position to continue printing from the last point printed at the previous position (Figure 7). This test provides two major breakthroughs:

- The algorithm adjusts the flowrate and applies a retraction force based on the orientation of the tool. This immediately nullifies gravitational forces in the print process.
- The same lattice structure has been tested over horizontal, vertical and other four different orientations. With the right parameters relative to each orientation, no difference in material quality nor geometry deformations are presented.



Figure 7. FOAM technique tested over a dynamic variable setting.

For the final case study we created a fully automated set-up using an ABB IRB 6640 arm, with a maximum reach of 2.55m and a wrist torque of 1324 Nm. The workpiece bounding box dimensions are 2x1x0.3m, fabricated as a single piece, having its base on an MDF board attached to a metallic beam structure on the ceiling at a 4.20m height. The robotic arm lies on a 6m track.

The lattice structure is divided into main patterned rows, a continuous cord that lies over each patterned row, and diagonals that connects the nodes of each side of the lattice. The robot is then actuated so it varies its motion velocity depending on these three parts and on the grammar of the pattern, following the instructions given in Figure 6.

The piece was completed in 40 hours, printing each patterned row in 18 minutes, each continuous cord in 8 minutes, and each weaving sequence in 35 minutes at its maximum dimension. Different wait times were implemented depending on geometry and context of the process; intermittent air unit was crucial in this process. This test demonstrates that the scalability problem of 3D printing can be overcome by printing in-situ a single piece, reducing logistic and assembly costs. Due to the lightweight nature of thermoplastic polymers, the FOAM technique can print large single structures that might support greater overhangs than other manufacturing processes.

5. Results and Discussion

This research used a 6-axis ABB robotic arm mounted on a 6m length track, which can reach any point within the robotic work-cell, with any given orientation, making the printing optimal for the adaptability to 3D print on complex geometric settings. The main authors have previously tested similar tool-path algorithms on

normal horizontal settings, where the referenced parameters were tested built on top of other research works (Liu et al. 2018). In our tests, PLA proved to be a more successful print material as compared with ABS or PETG. One of the challenges for spatial printing is synchronizing robotic arm motion, stepper feed-rate, wait times and cooling system. Overall, a 3mm/s speed and 1/8 motor step has proven to yield successful filament thickness when printing horizontally. We have found that, accommodating these variables to the orientation of the piece, the printed structure maintains a 7% difference from its digital version in all tested orientations. Thus, gravity does not have a major effect on the deformation ratio.

Improvements to the design tool and fabrication algorithms resolve fabrication hurdles that are inherent to FDM. We acknowledge that despite using a relatively simple printing tool, a sophisticated computational control system is required to print using this technique, since it is the algorithms as outlined that contribute to FOAM's success and advancements over fundamental printing techniques.

There are still drawbacks present in the FOAM process:

- Time cost is still inefficient. This might be overcome by reducing wait times at each node and speeding up the robotic motion, however, more extensive research is required.
- Thermoplastic polymers, although lightweight and cost-effective, have deficient ecological footprint, and present a lack of tensile strength and durability for direct construction application. Correctly assessing anisotropic mechanical behavior in FDM is a general challenge. The incorporation of reinforced plastics or metals (Blonder & Grobman 2015, Kwon et al. 2019, Mitchell et al. 2018) is a step forward to applying FOAM to construction.
- There are limits to designs reflected by the limitations of the tool. The nozzle should be optimized to avoid collisions with already printed material. A thinner nozzle has a larger printable angle range than a thicker nozzle. We focusing on an improved tool with a thinner nozzle for printing with reinforced thermoplastic materials.

FOAM provides a novel fabrication technique for architectural applications in previously unexploited spaces, providing the means for reconfiguring and bonding new qualities to existing non-necessarily planar nor horizontal infrastructures. This entails a reduction in logistic and assembly costs. It also opens up possibilities for new design methodologies in practice and academic institutions. Using robots in pedagogical frames can speed up research in design, creating new aesthetic sensibilities that right now are difficult to assess due to the lack of precedents, as we are in the shift of using new science with old machines (Carpo 2017).

Acknowledgments

This research was supported by The Frank Ratchye Fund for Art @ the Frontier and Consejo Social de la Universidad Politécnica de Madrid (UPM). The authors would like to thank the advising team, Professors Josh Bard, Daniel Cardoso, and Mary-Lou Arscott from Carnegie Mellon University (CMU). Also, we would to thank Prof. Jesus Anaya from UPM, and the head of the school of architecture of CMU, Prof. Steve Lee, for making possible this international collaboration.

References

Ackoff, R.L.: 1974, Redesigning the future, *Proceedings of an IFORS Specialized Conference on Operational Research and the Social Sciences*, New York, 29.

Blonder, A. and Grobman, Y.J.: 2015, Design and fabrication with fibre-reinforced polymers in architecture: a case for complex geometry., *Architectural Science Review*, **59**, 257-268.

Bock, T.: 2015, The future of construction automation: Technological disruption and the upcoming ubiquity of robotics., *Automation in Constructiotn*, **59**, 113-121.

Carpo, M.: 2017, *The Second Digital Turn: Design Beyond Intelligence*, MIT Press.

Felbrich, B., Wulle, F., Allgaier, C., Menges, A. and Verl, A.: 2018, A novel rapid additive manufacturing concept for architectural composite shell construction inspired by the shell formation in land snails, *Bioinspiration & biomimetics*, **13**(2), 26010.

Jimenez Garcia, M., Retsin, G. and Soler, V.: 2017, A Generalized Approach to Non- Layered Fused Filament Fabrication, *ACADIA 2017*, 562-571.

Haas, C., Skibniewski, M. and Budny, E.: 1995, Robotics in civil enegineering, *Microcomputers in Civil Engineering*, **10**, 371-381.

Hack, N.H., Lauer, W.V.L., Gramazio, F.G. and Kohler, M.K.: 2014, Mesh Mould: Differentiation for Enhanced Performance, *Proceedings of CAADRIA 2014*, Hong Kong, 139-148.

Huang, Y., Carstensen, J., Tessmer, L. and Mueller, C.: 2018, Robotic Extrusion of Architectural Structures with Nonstandard Topology, *ROBARCH 2018*, Zurich, 377-389.

Kwon, H., Eichenhofer, M., Kyttas, T. and Dillenburger, B.: 2018, Digital Composites: Robotic 3D Printing of Continuous Carbon Fiber-Reinforced Plastics for Functionally-Graded Building Components, *Robotic Fabrication in Architecture, Art and Design*, 363-376.

Liu, S., Li, Y. and Li, N.: 2018, A novel free-hanging 3D printing method for continuous carbon fiber reinforced thermoplastic lattice truss core structures, *Materials and Design*, **137**, 235-244.

Mitchell, A., Lafont, U., Holynska, M. and Semprimoschnig, C.: 2018, Additive Manufacturing-A Review of 4D Printing and Future Applications, *Additive Manufacturing*, **24**, 606-626.

Mueller, S., Im, S., Gurevich, S., Teibrich, A., Pfisterer, L., Guimbretière, F. and Baudisch, P.: 2014, WirePrint: 3D Printed Previews for Fast Prototyping, *Proceedings of the 27th annual ACM symposium on User interface software and technology - UIST*, Honolulu, 273-280.

Ngo, T., Kashani, A., Imbalzano, G., Nguyen, K.T.G. and Hui, D.: 2018, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, *Composites Part B: Engineering*, **143**, 172-196.

Oxman, R.: 2008, Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium, *Design Studies*, **29**, 99-120.

Oxman, N., Laucks, J., Kayser, M., Tsai, E. and Firstenberg, E.: 2013, Freeform 3D printing: Towards a Sustainable Approach to Additive Manufacturing, *Green Design, Materials and Manufacturing Processes*, **479**, 479-483.

Garcia de Soto, B.G., Agustí-Juan, I., Hunhevicz, J., Graser, K., Habert, G. and Adey, B.T.: 2018, Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall, *Automation in Constructiotn*, **92**, 297-311.

Tam, K. and Mueller, C.: 2017, Additive Manufacturing Along Principal Stress Lines, *3D Printing and Additive Manufacturing*, **4**, 63-81.

Warszawski, A.: 1984, Application of Robotics to Building Construction, *Proceedings of the 1st International Symposium on Automation and Robotics in Construction (ISARC)*.

Willmann, J., Gramazio, F., Kohler, M. and Langenberg, S.: 2013, Digital by Material, *Rob|Arch 2012*, Vienna, 12-27.

Yuan, J., Jianke, D., Yong, H. and Guiqiang, F.: 2017, Modeling and Process Planning for Curved Layer Fused Deposition, *The International Journal of Advanced Manufacturing*, **91**, 273-285.

THE NATURE OF DATA IN EARLY MODERN ARCHITECTURAL PRACTICE.

CHRIS BAMBOROUGH
[1]*The University of Technology Sydney*
[1]*chris.bamborough@uts.edu.au*

Abstract. In contemporary data-driven society, forces of capital increasingly seek risk-averse decision making through data and digital calculation, aligned to this the discourse around design intelligence in architecture has begun to embrace the role of data and the technical non-human as much as the human. In parallel, the cultural understanding of data, in technologically mediated societies, has become tied to the digital representation of information experienced in everyday life, which in turn influences human practices. A problem exists in the dominance of scientific thought around data in architecture that exerts disciplinary bias towards quantity rather than quality. In contemporary digital practice, data is assumed to offer an objective characterisation of the world and have faithful representation through the mechanisms of the computer. From this shift, a macro question exists concerning the influence of data's conceptualisation on the physical products of architecture. To contribute to this overall question this paper considers the register of data in early modernism identified as a moment when scientific abstraction and the mapping capacity of the machine combine to afford recognisable data practices and infrastructures.

Keywords. Data; Design Practice; Infrastructure; History; Theory.

The alignment of human decision making to the insights born from computational pattern recognition in data, labelled "data-ism" (Lohr 2015), increasingly provides a source of trusted information that influence the material world, and organises everyday life (Greenfield 2017). As architecture's expertise lies in the design and realisation of material assemblies towards the spatial organisation of social life, data-ism is a context that influences how the built products of architecture are both conceptualised, produced and experienced. Influenced by software studies that has exposed the inherent political control designed into the internet through software protocols governing "the architecture of the architecture of objects" (Galloway 2004, p. 75) architecture has become increasingly interrogated through a lens of infrastructure. Such a view characterises architectural space as an information technology that facilitates communication through spatial organisation but materialises through planning protocols and organisational standards (Easterling 2014). This focus on architecture as an infrastructure presents the material outcomes of architectural practice as an emergent assemblage governed by immaterial forces in decision making.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 343-352. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

This paper contributes to a larger research question regarding the influence of data on the material assemblies produced through architectural design practice. This paper explicitly considers how data has emerged in past architectural practice see understand if it is registerable in the physical products of architecture during this time. The question this paper asks is - what is the nature of data in early modernist practice and is it associated with patterns of material outcomes through its use? The overall hypothesis presented is that data practice is detectable in the early modernist avant-garde and the cultural project of a "new architecture". The research finds that data becomes used in wider practice but is applied as a rhetorical device, and that data is used to compress and transmit the ideas of modernism internationally through the data assemblage of a handbook.

1. Lens of Data

In order to progress with the above hypothesis, it is necessary to define data and provide a lens through which it is possible to analyse its emergence in architectural practice, the sub-question, therefore, is what is data?

Rob Kitchin provides a useful starting point – "data are commonly understood to be the raw material produced by abstracting the world into categories, measures and other representational forms - numbers, characters, symbols, images, sounds, electromagnetic waves, bits - that constitute the building blocks from which information and knowledge are created" (Kitchin 2014, p. 2). However, where does data come from? From an epistemological perspective, data is regarded as the detection of "putative fact regarding some difference or lack of uniformity within some context" (Floridi 2017).

However recently it has become regarded by scholars that data does not exist as a raw and presumed fact, data is not a natural occurrence, rather than a given it is a cultural construct as it is a sampled version of reality (Gitelman 2013; Kitchin 2014; Shah 2013). What is more, depending on the informational agent that observes and processes data, data provides a set of affordances determining the space of information possibilities available (Floridi 2017). Therefore, for this research, data is understood as a material through which information is constructed, while also contributing to an environment of human practice that invites or resists certain constructs of information. From an architectural point of view, data is closely tied to the epistemological framework applied to understand reality for design, and registers in the communication and materials employed towards built outcomes.

2. Data Between Art and Science

Although data is detectable in the digitised representation of Leon Battista Alberti (Carpo 2011) and in the measurement, analysis and teaching of Jean-Nicolas-Louis Durand (Goudeau 2015), it is not until the 1900s that the idea of measuring and representing difference through data starts to become embedded into the wider architectural culture. This moment is traceable in the shift in pedagogy at the Bauhaus from a "new art of building", to an engagement with industrial mass production and wider "nature research", nature as a proxy for functionalism,

through scientific methods (Siebenbrodt & Schöbe 2009). Data in the form of measurement and calculation shifts in significance between an architecture of expressive subjectivity, and a desire for scientific objectivity to operate in the new context of industrial production and to contribute to a broader political drive for knowledge and technology (Pommer & Otto 1991).

With Walter Gropius's replacement by Hannes Meyer in 1927, research became embedded into the Bauhaus's curriculum as a basis of design required to accurately determine the need of use and context through an analysis of social and economic questions (Siebenbrodt & Schöbe 2009). Gropius's "nature research" gave way to Hannes Meyer's more radical scientific functionalism introducing data to objectively describe patterns of difference existing in the context of the project. Meyer's techno-scientific-rationalism quickly established a design approach based on the perceived superiority of statistical certainty rather than human intuition (Siebenbrodt & Schöbe 2009). This duality between certainty and human intuition is recognisable in modern-day attitudes towards data-driven design (Deutsch 2015). In addition, the manner with which Meyer employed data in design communication is useful for a contemporary comparison.

To understand the status of data in Hannes Meyer's time at the Bauhaus, (1927 to 1932), requires reference to the work completed by Meyer and his students. Although it is evident from the literature on Meyer about the importance of research in understanding the needs of architecture (Hays 1995), data is also recognisable in his schematic organisation of function through diagrams. The relationship between data and function is evident in Meyer's San Carlos Academy lecture when he states "for without hygiene or climatology or the science of management he will have no functional diagrams, i.e. no data on which he can elaborate his architectural forms." (Wolfe 2018). However, when considering Meyer's architectural schemes more closely, data appears more as a rhetorical device to aid his communicative aims (see Figure 1). Additionally, this application of data is confirmed in Meyer's teaching where the visual display of quantities and scientific techniques of representations indicate a body of knowledge rather than drivers of architectural form (see Figure 2). Instead, data appears to culturally appropriate the legitimacy of science onto the proposition and suitability of the architectural scheme.

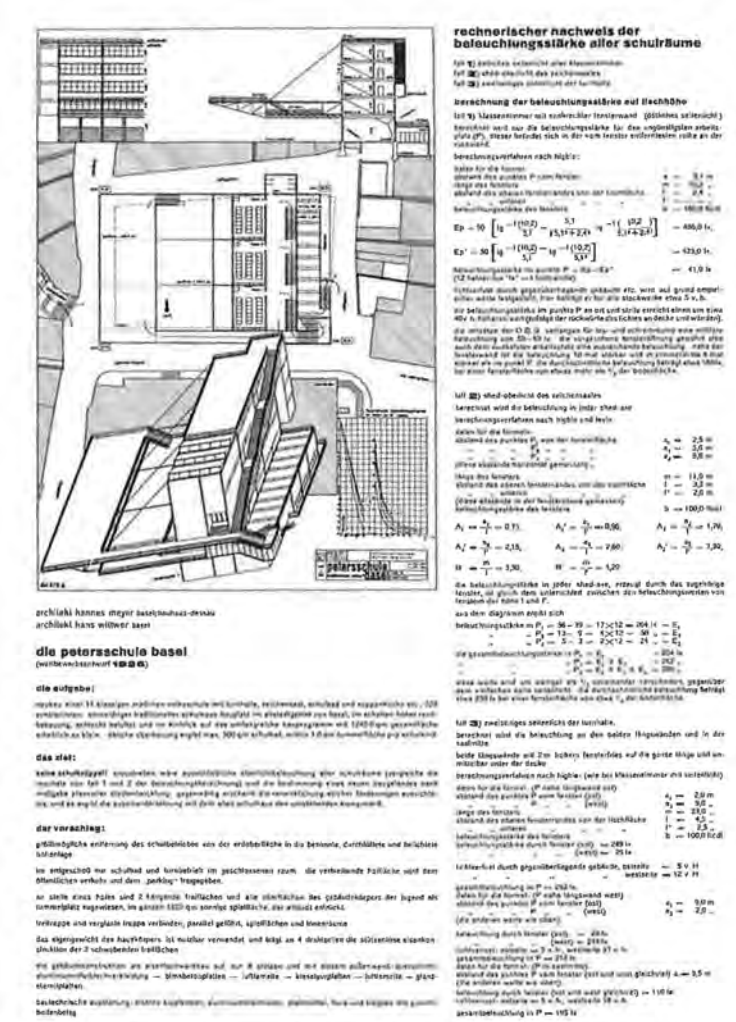


Figure 1. Hannes Meyer - Petersschule project with data related to the schemes lighting system (Hays 1995).

Through the lens of data as described above, it is possible to locate a shift in data as a concept through the Bauhaus as it sought to reconcile artistic production with industrial mass production. Data shifts from a subjective understanding to an objective and scientifically rational view of the world for design. What emerges from this examination is a nature of data as a source of communicative aesthetic and visual style that appropriates the authority that science held at the time. An understanding of the world through data presumed that the scientific intelligence encapsulated in the method of knowledge generation would enrich architectural ideas; this was particularly the case in the modernist project of a "new architecture".

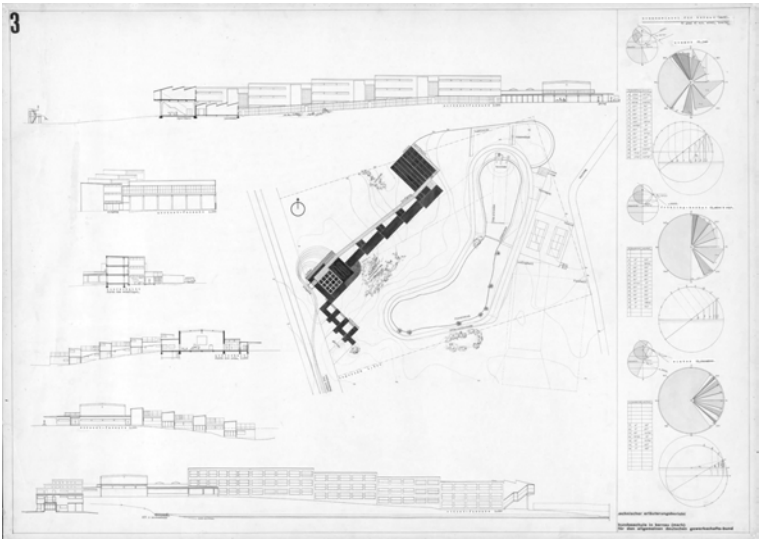


Figure 2. page from a study dossier by Heiner Knaub, from Hannes Meyer's Bauhaus course in 1930.

3. A New Architecture

Although the pedagogy of the Bauhaus seemed radical in academic terms, it sat within a broader European architectural avant-garde that argued for a material and spatial response to the social impacts of industrial mass production, through its technology. Within this context, the modernist project of "a new architecture" sought to assign architecture with the responsibility for elevating the quality of life through improved living and working conditions. As the first projects began to materialise in the 1920s, it is possible to identify a concept of data that became a means of cultural transmission, a medium as much as a message, under the guise of design method and supported by the infrastructure of the printing press and publishing logistics.

The Weißenhofsiedlung exhibition organised by the Deutsche Werkbund is readable as a moment that the ideas within a "new architecture" were materialised toward addressing German housing affordability. From an analysis of discourse surrounding the project, there is little reference to data in design, however, the use of data is present in the visual kitchen planning guidelines issued to all participants by Ludwig Mies van der Rohe.

As part of the project brief, Mies had shared Margarete Schutte-Lihotzky's research and design proposal for the "Frankfurt Kitchen". The Frankfurt Kitchen design absorbed the principles of Christine Frederick's scientific management of the house into a design for the "optimal" kitchen, centred on efficient energy usage in household activity (Kirsch 2013). Lihotzky's drawings communicated the kitchen layout through measurement and a set of guiding proportions and proximities (see Figure 3), distilling organisation of the room through an overlayed

set of governing data and rules. The Frankfurt and Stuttgart kitchens are detectable in many of the schemes as a repeatable spatial and material arrangement (Lupton & Miller 1996). Therefore communication of material arrangement through a set of given measurements, and encapsulated within the idea of an objectively optimal design outcome, operates as a mode of cultural transmission whereby ideas propagate through the visual overlay of data rather than a discourse or material experience.

A more extensive application of data as cultural infrastructure exists in Neufert's Bauentwurfslehre (Building Design) book published in 1936. What was later translated into English and renamed "Architects data handbook", represents a larger scale mobilisation of data and visual language found initially in the Frankfurt kitchen. The combination of the organising capability of a book, and Neufert's abstraction of architecture into data described spatial arrangements, compressed an architecture suitable for international publishing (see Figure 4). However, it is Neufert's design method, termed "Schnellentwerfen" (rapid design), that ties together data and management into a mode of synthesis (Vossoughian 2014). Neufert's rapid design, a response to the increased speed in industrial production and the parallel pressure on the architect's time and energy, introduced the idea of data as a material in design combinable at the architect's decision but dictated by functional demands. The book provided a mechanism through which to "work" the data material through design routines based on architectural types. Neufert's book provides a moment when data meets an environment for design contained within the rapid design theory and the organisational capacity of the book.

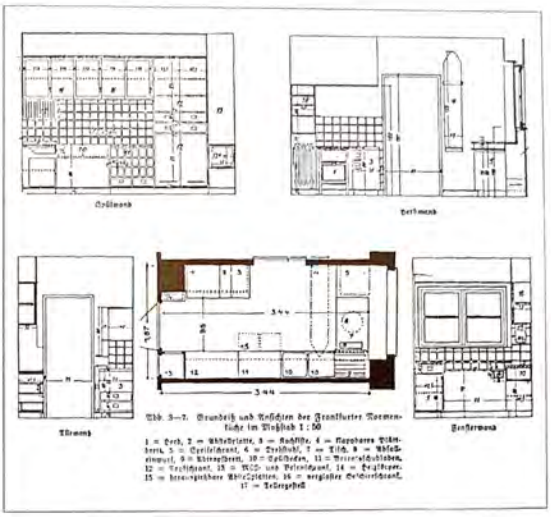


Figure 3. design drawings of the Frankfurt Kitchen, Margarete Schutte-Lihotzky (Kirsch 2013).

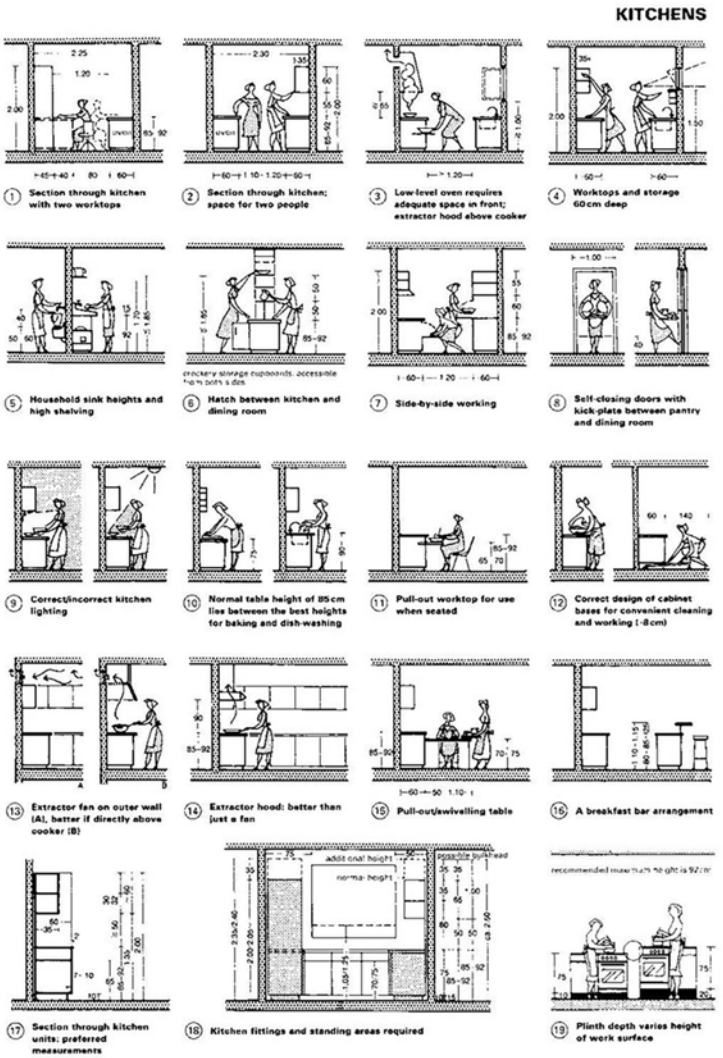


Figure 4. Ernst Neufert – Architects Data Handbook – English Edition (Neufert 1970).

Although Neufert's book initially focused on Germany, there were similar efforts such as Charles Ramsey and Harold Sleeper's Architectural Graphic Standards in the United States, and subsequent English translations. Both books have been shown to operate as instruments within their respective state-driven industrial standards projects that were used to stimulate industrial and military production in the interwar period (Vossoughian 2014). Data and its organisation through a book, set within the broader project of standardisation, condensed and centralised intelligence into a system for architectural communication and design

justification. Neufert's book provided architects with a centralised and static assemblage of data, that facilitated a process of intelligence towards rapid form making. The data handbook promoted a materialisation of ideas through functional use to avoid the stylistic formalisms criticised in modernism (Banham 1960). However, given that the international style would be one of modernism's distinct legacies shows how an architecture communicated and justified through data, set within industrial standardisation and paired with a material infrastructure and method of design synthesis, produced architectural products that tended towards a specific aesthetic and spatial organisation.

A consideration of the modernist project of "a new architecture" shows how data's rhetorical utility, became transferable via physical infrastructures of representation, namely a housing exhibition, and a handbook. In the Weißenhofsiedlung, it is possible to detect the reliance of data as a set of "ideal" and "optimal" conditions accepted into a design as a given. Most important here is the spreading of the Frankfurt Kitchen across the project, easily expressed and absorbed into the housing designs due to its data description. Finally, Neufert's Handbook provides an example of how data became mobilised, providing a routinised approach to design through the organisational capacity of the book. This combination provides an example where data operates as a material but restricts possibilities as the book provides an environment for design. Data, as a result, is characterised as an immaterial infrastructure that influenced action through the ideas and routines held within the way the handbook presented and processed data.

4. Conclusion

This paper has argued that in order to critically consider architectures capacity to operate in increasingly data-driven contexts it is beneficial to understand data's historical conceptualisation and absorption into design practice. By examining early modernism through the lens of data as infrastructure, it is possible to trace an attitude towards data and detect an effect on the physical outcomes of architectural production. From the research the following key points arise;

The main findings in this paper relate to the increased use of data in early modernism to apply scientific objectivity to design decision justification and the use of science's cultural legitimacy to bolster the avant-garde's push for a "new architecture". The key point made is that the discourse around data in education and then practice is identifiable in the transition from artistic to scientific modes of knowing as a basis for design. The contrasting data practices in the Bauhaus, either side of 1923, show how data moved from a personal understanding and artistic response to an objective scientific measurement. This shift from subjective art to objective science enabled architecture to engage with mechanised industry as a new mode of production and means of material expression. Despite the detectable shift to data aligned design decisions it is possible to point to examples where data operates more as a rhetorical device than a driver of design. This rhetorical use is recognised in the modern movements wish to materialise their ideas, requiring an aesthetic for political and cultural engagement. Scientific representation, therefore, acts to contribute to knowledge and technology for a discipline without the traditional techniques to do so.

Within the framework of data as a rhetorical device, the connection of scientifically based architectural planning with efficiency and optimisation provides a moment where data begins to operate as a means of transmission in architectural ideas, using the authority of science to influence culture. The Frankfurt and Stuttgart kitchens within the Weißenhofsiedlung project offers a repetitive material precursor to Neufert's Bauentwurfslehre that helped propagate the homogenising effects of international modernism. However, it is not possible to claim that data within Neufert's book had a causal relationship to internationalism as both industrial production and industrial standardisation also contributed, but the description of objectively optimal functional spatial arrangements presented architecture in alignment to the repetitive and homogenising capacity of mass production. Neufert's book and approach to rapid design represent how design intelligence could emerge through a design synthesis of data as a building block, routinised by categories of function and architectural type.

This paper contributes to a macro question regarding data's influence on the material products of architecture. Four trends have emerged that require closer interrogation to understand data's material influence in more depth. Firstly the uncritical use and acceptance of data in design that can serve as a rhetorical device through the cultural conditioning of scientific epistemology. Secondly the infrastructural influence of data bound to material formats used in practice which is applicable to the use of software and file formats in contemporary computational design. Lastly there is a need to further understand the deterministic influence of data choice and availability on the material organisation of architecture.

This paper has aimed to introduce a historical lens to data use in architecture to better comprehend data in contemporary architecture, however, in doing so it must acknowledge its limitations. The research restricted archival sources to those concerned with post-1900 events and focussed on a predominantly German context of early modernism, therefore is unable to conclude about data in design practice before this time or across other geographic contexts. Further research taking in earlier periods, and other national and cultural responses would help clarify the relationship between data and the material outcomes of architecture.

References

Banham, R.: 1960, *Theory and Design in the First Machine Age*, Architectural Press, London.

Carpo, M.: 2011, *The Alphabet and the Algorithm.*, MIT Press, Cambridge, Mass..

Deutsch, R.: 2015, *Data-Driven Design and Construction*, John Wiley & Sons Inc, London/New York.

Dourish, P.: 2017, *Stuff of Bits*, MIT Press, Cambridge, Massachusetts.

Easterling, K.: 2014, *Extrastatecraft: the power of infrastructure space*, Verso, London / New York.

Floridi, L.: 2017, "Semantic Conceptions of Information, Stanford Encyclopedia of Philosophy Archive" . Available from <https://plato.stanford.edu/archives/spr2017/entries/information-semantic/> (accessed 27th October 2018).

Galloway, A.R.: 2004, *Protocol: how control exists after decentralization*, MIT Press, Cambridge, Mass..

Gitelman, L.: 2013, *"Raw data" is an oxymoron*, The MIT Press, Cambridge, Massachusetts ;

London, England.
Goudeau, J.: 2015, The Matrix Regained: Reflections on the Use of the Grid in the Architectural Theories of Nicolaus Goldmann and Jean-Nicolas-Louis Durand, *Architectural Histories*, **3**(1), 1-17.
Greenfield, A.: 2017, *Radical Technologies: The Design of Everyday Life*, Verso, London / New York City.
Hays, K.: 1995, *Modernism and the Posthumanist Subject: The Architecture of Hannes Meyer and Ludwig Hilberseimer*, MIT Press, Cambridge, Mass..
Hyde, R.: 2016, "Architecture in the coming age of Artificial Intelligence, Architecture Australia" . Available from <https://architectureau.com/articles/architecture-in-the-coming-age-of-artificial-intelligence/> (accessed 15th November 2018).
Kirsch, K.: 2013, *The Weissenhofsiedlung: Experimental Housing Built for the Deutscher Werkbund, Stuttgart, 1927*, Edition Axel Menges, Fellbach.
Kitchin, R.: 2014, *The Data Revolution: Big Data, Open Data, Data Infrastructures and Their Consequences*, SAGE Publications, London.
Lohr, S.: 2015, *Data-ism*, Harper Business, an imprint of HarperCollins Publishers, New York, NY.
Lupton, E. and Miller, J.: 1996, *Bathroom, the Kitchen, and the Aesthetics of Waste*, Princeton Architectural Press.
Neufert, E.: 1970, *Architects' data*, Crosby Lockwood Staples, London.
Pommer, R. and Otto, C.F.: 1991, *Weissenhof 1927 and the modern movement in architecture*, University of Chicago Press, Chicago.
Shah, N.: 2013, "Big Data, People's Lives, and the Importance of Openness" . Available from <https://clalliance.org/blog/big-data-people-s-lives-and-the-importance-of-openness/> (accessed 20th November 2018).
Siebenbrodt, M. and Schöbe, L.: 2009, *Bauhaus, 1919-1933*, Parkstone International, New York.
Vossoughian, N.: 2014, Standardization Reconsidered: Normierung in and after Ernst Neufert, *Grey Room, MIT Press*, **Winter**(54), 34-55.
Wolfe, R. L.: 2018, "Hannes Meyer, Marxist and modernist, The Charnel House" . Available from <https://thecharnelhouse.org/2013/08/10/hannes-meyer/> (accessed 20th November 2018).

AUGEMENTED ARCHITECTURE

Interplay between Digital and Physical Environments

SURAPONG LERTSITHICHAI
[1]*Faculty of Architecture, Chulalongkorn University*
[1]*surapong@cuinda.com*

Abstract. In an increasingly connected world where computers are everywhere, surrounding us in embedded small portable devices, appliances and inside buildings, implementing these interconnected and embedded computers have now become common practice in the design of smart spaces and intelligent environments of today. Digital information is constantly being collected and distributed by a network of digital devices communicating with users and vice versa. New behaviors and activities that may have not been considered before in the design of architectural building types are now commonly found in public and private spaces throughout the world. In an attempt to explore and experiment with the concept of interplay between digital and physical environments, an option studio was proposed to 4th year architecture students to develop a new type of augmented architecture that corresponds to changes in human social behavior due to digital technologies. Five pilot projects are presented with experiments conducted to question three social activities commonly found in everyday lives using Arduino prototypes installed in real physical locations. The prototypes were then used as a basis for the development of large-scale projects proposed as augmented architecture.

Keywords. Human-Computer Interaction; Ubiquitous Computing; Virtual / Augmented Reality; Computational Design Research; IoT for Built Environments.

1. Introduction

We live in an age where multiple computers are everywhere, surrounding us in embedded small portable devices, appliances and inside environments where we live and conduct our daily life routines. The concept of interconnected and embedded computers or "ubiquitous computing," described this future scenario when it was first coined in the late 1990s, is becoming a commonplace in the design of smart spaces and intelligent environments (Wieser 1991). We are now witnessing the impact of such integration where useful information is offered to users within a space to enhance their periphery perception beyond the physical space itself.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 353-362. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Today, digital information is constantly being collected, connected and communicated between computers and users or vice versa, and can become tangible feedback as the analog and digital world collide seamlessly (Ishii 1997). Through various intelligent sensors and Internet of Things (IoT), it is also possible to analyze and get insights of undiscovered human behaviors. However, as architects living in the digitally divided world with those who are constantly connected online and those who are not, what does the future bring to the world of physical architecture when the rest of the world is connected to the digital realm? How can we then transform digitally connected architecture and enhance user experiences in a meaningful way?

This scenario can be summarized as an interplay, one in which users, human or nonhuman, are coupled to computational interfaces and networks of physical and virtual environments creating new architecture of speculation (Bratton 2016).

1.1. OBJECTIVES

To investigate this interplay between digital and physical environments, an option studio is offered to 4th year architecture students under the title of "Augmented Architecture" as the premise of the design brief. The studio questions the creation of architecture that is fundamentally formed by its user behaviors that later turn into common activities and if frequent enough, become permanent or dedicated spaces for such activity. However, changes in social behavior of people in the past decade due to digital technologies has been so rapid that we can no longer keep up with new typologies of hybrid spaces or new health syndromes related to the impact of digital technology towards the human body.

The objectives of the studio are to question the existence of architectural typologies in the digital world today, observe new behaviors enabled by digital technologies and ultimately challenge students to create a combined hybrid or augmented architecture that embodies the best of both worlds.

1.2. SCOPE AND LIMITATIONS

The scope of the studio is divided into two phases. The first phase encourages students to research relevant case studies and projects to understand how digital technologies impact user behaviors in a physical space and similarly, how physical spaces can be enhanced with digital technologies to change user behaviors. Students are then required to explore and identify certain behaviors impacted by digital technologies and vice versa. The behaviors selected are then put to test with built prototypes using Arduino microcontrollers, various input sensors, visual and audio feedback, and combined with a physical interface in real world situations. Feedback is collected and analyzed for the effectiveness of the hypothesis and the prototype.

The second phase challenges students to propose novel ideas for an augmented architecture developed from prototypes proposed during the first phase. The transition from prototype to architecture must be relevant and coherent in order to assess the scalability of the behavior that is converted into actual spaces. Limitations of the project include time and expertise of students, since students

participating in the studio had no previous experience in Arduino programming and the 15-week long project is divided into two phases allowing a limited time to produce, test and evaluate each deliverables.

2. Digital and Physical Interplay

There is no question that if our behavior changes i.e., how we work, play, learn, rest, eat, read, contemplate, conference etc., then our activities in space is no longer constrained by past tectonics and classical typologies of architecture. On the other hand, if one looks into how changes in behavior can alter our use of space, it is also possible to explore how digital technologies can alter user behaviors in the space to become aware of digital information that is communicated through user interactions or within the border of digital and physical interplay (Mitchell 1995).

Three selected case studies showcase how digital and physical environments can be combined to create a new unique and meaningful user experience. Users can interact with physical, virtual or mixed realities, each having their own pros and cons in responding to human behaviors.

2.1. TANGIBLE MEDIA

Tangible media with physical input and output in various scales can be easily perceived and understood by users. Interactions are straightforward and reflect upon common human behaviors and responses and therefore require no prior explanations. For example, the "Fun Theory" campaign experiments conducted by Volkswagon in 2009, presented a project called the "Piano Stairs" by embedding muscial notes on plates disguised as piano keys on a physical staircase at the Odenplan subway station in Stockholm. The project encouraged users to walk up the staircase instead of standing on the adjacent escalator by means of "fun" play as an incentive and hence changed user behavior through tangible media interactions. Another example is the Network Sensory Landscape that creates geographically dense web of sensors, which produce data to enhance a sense of space and presence (Dublon & Paradiso 2014). Incorporating environmental sensor networks platform embedded in the landscape can provide real-time sounds and visualizations (Mayton et al. 2017) as augmented components in architecture for end-user applications.

2.2. VIRTUAL REALITY

On the virtual reality side, one can argue that in the future, the physical environment is no longer relevant to people and humans can spend most of their lives online and assume a virtual avatar representation similar to the Hollywood film, "Ready Player One." Total immersion in virtual environments can leave users isolated and incapable of leaving the virtual world to spend time living in the real world. The presence experience through virtual reality may eventually equal to consciousness (Sanchez-Vives & Slater 2005) when selective attention, perceptual fidelity and other sensory factors all interact (Witmer & Singer 1998). However, in the virtual environment, there is much flexibility with less physical risks involved unless it ties back to natural human life cycles and social norms.

The question then comes back to what is considered the right balance for present times during this critical social transition.

2.3. MIXED REALITY

Finally, in mixed reality and the use of Internet of Things (IoT) to create smart environments can provide personalized experiences based on user movement and interactions paired with smart devices in a museum (Hashemi & Kamps 2017). For example, teamLab's commercially successful interactive installations, "Borderless" and "Planets" exhibited at Odaiba, Tokyo are examples of the future of exhibitions that offer a unique mixed reality experience to visitors combining continuous virtual projections with physical interactions and tangible object displays. teamLab is a group of interdisciplinary professionals combining the creativity of artists, programmers, engineers, animators, architects and designers that form one "ultra-technologist" team. Their artworks move in and out of rooms freely, forming connections and relationships with people, communicate with other works, influence and sometimes intermingle with each other, and creating a unique sensory experience for visitors like no exhibition in a typical museum. Their collective aim is to achieve a balance between art, science, technology and creativity.

3. Project Prototypes

Five pilot projects were explored in this studio with five distinct experiments proposed by ten architecture students from Thailand, Japan and France. Students were asked to identify a unique set of human social behaviors that have changed in the past few years and create new activities using new digital technologies within an architectural space. These behaviors include waiting for a bus, dining at a restaurant, jogging in a park, crossing an underground tunnel and meeting strangers at a lift lobby. Then, with no prior knowledge in computer programming and electrical engineering, students were required to create physical prototypes using Arduino and various sensors and output to interact with users in real situations and spaces of choice. The five projects can be grouped and categorized into three main activities consisting of waiting, exercising and meeting.

3.1. WAITING

The act of waiting for someone or something is usually accompanied by conducting some kind of activity to kill time. A common waiting experience that was identified is waiting for a bus at the bus stop and the most common killing time activity observed was using a smart phone to do various small tasks. With this premise, one of the projects titled "Sumaho Secchi" or put down your phone in Japanese, was developed to encourage users to put down their phones and to be aware of their surroundings and notice people next to you.

The prototype is situated between two seats at a local bus stop in the university campus. The system is activated when a user puts down a smart phone to wirelessly charge the battery. Once a user puts down one phone, the red display is turned into green and blinks inviting a second user to do the same action and pair up with the

first user. When both users are free from their phones, a simple game of Pong is activated and can be played by both users bouncing the cursor from one side to another until one player misses. The game stops when someone loses or picks up their phone and leaves on a bus. The prototype built by students was based on two Arduino units and utilizing switches, LEDs, buzzers and a simple numeric display. Power is supplied for the wireless battery charging stations as well as the microcontrollers (Figure 1).

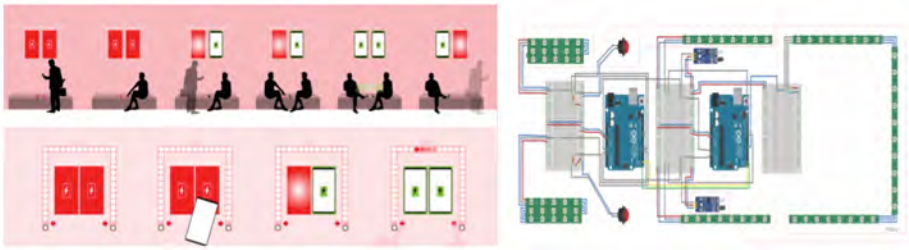


Figure 1. Diagram showing user interaction while waiting for a bus and the design of the microcontroller unit. .

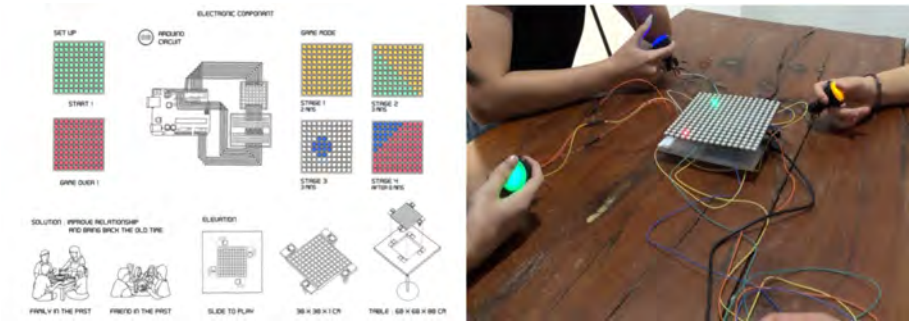


Figure 2. Diagram of the game design with a single Arduino unit and testing the prototype game with four concurrent users.

Another project is also an act of waiting at a coffee shop. The time spent while waiting for coffee to be served can be easily wasted on personal mobile phones rather than to socialize with friends and family that accompany oneself. The site of this project is located in a local coffee shop and the prototype is designed to be an interactive game embedded in the coffee table itself with an interactive game to be played by one to four users at the same time with three levels of difficulty (see Figure 2). The game is designed to allow maximum participation of users paying attention to each other's moves in synchronization. Feedback from initial user tests has been positive as users find the game to be a social activity that engages users to communicate more.



Figure 3. Diagram showing the system components installed in a jogging track and a live demonstration of the prototype in studio. .

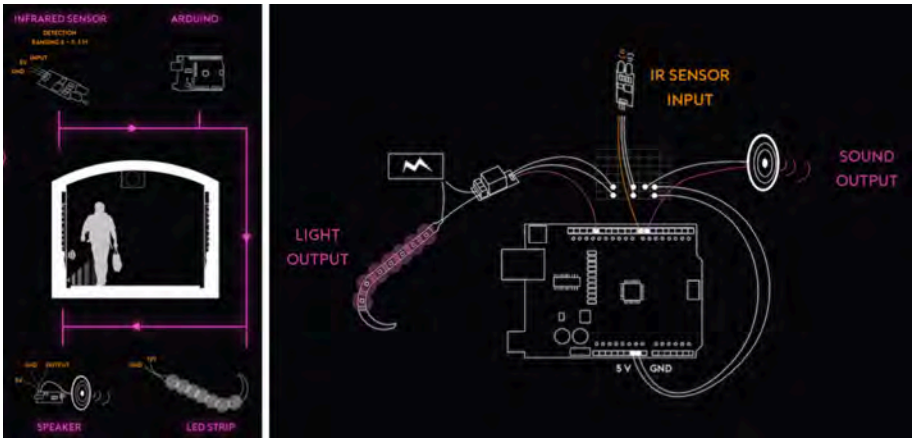


Figure 4. The interactive tunnel system to encourage users to move in synchronization with the light and sound features. .

3.2. MOVING

The second group focuses on the act of moving or human movement. One project was the jogging correction assistant system. Students took notice of an activity of jogging that is usually conducted incorrectly by people who try to maximize the length of their jogging strides. The correct way to jog is actually to minimize the length of each stride so as to step on the forefoot rather than the heel. Doing so will decrease possible risks of damaging the knee and increase the effectiveness of exercising to the runner. An interactive system is therefore designed to assist runners in landing their feet at the right position from a guiding laser light on the ground. The jogging correction assistant system comprises of several Arduino units connected in chains throughout the length of the jogging

track. For experimental purposes, the prototype was limited to a length of five meters with an average stride of 30 centimeters each (see Figure 3).

An additional moving project focuses on the behavior of people crossing an underground tunnel beneath a road separating a university campus in two sides. The investigation takes place during peak operations in the morning, lunch, and evening hours observing how people move from one side to the other and walking chaotically to avoid colliding with one another. The project then proposed a system to encourage users to walk more in line within one side of the wall rather than in a zigzag pattern. To do so, the prototype incorporated proximity sensors along the tunnel to detect movement of users from one side and activate lights on the wall and audio sounds to visualize the sequence to users (see Figure 4).

3.3. MEETING

The last group was the act of meeting. The project is called "Let's Meet, Neighbors" focusing on the activity of greeting a stranger in front of an elevator lobby in the international student residence. The goal of the project was to use an interactive game to initiate small talk among strangers and encourage international students to meet new friends. Users will see a light panel installed around the elevator buttons. When users touch the elevator button, a sensor will detect proximity and activate the light panels with light and sound. Users will have to touch the lit panels in a correct sequence similar to Simon Says in order to complete the game (see Figure 5). The actual prototype system was installed in the elevator lobby of the international residence as proposed and user tests were conducted with real residents. Initial responses were puzzled by the real purpose of the game but users found it intuitive enough to play along with the interactions.



Figure 5. Proposed interactive system to encourage meeting new friends and actual prototype installed in the international student residence. .

As all the small prototypes were completed, installed, and tested, the next phase of the project was to transition from simple prototypes and scale them up to a larger architecture scale. The transition although seemed deliberate, was more challenging for students and therefore only two projects succeeded in linking both phases together coherently.

4. Augmented Architecture

Architecture is fundamentally formed by user behavior that turn into common activities and if frequent enough, become permanent or dedicated spaces for such activity. Behavioral changes of people in the past decade due to digital technologies has been so rapid that we can no longer keep up with new terminologies for health syndromes related to the impact of digital technology towards the human body. Physcial architecture is also no exception. We have witnessed the fall of physcial retail businesses such as bookstores, video rental, banking and healthcare due to new digital behaviors. Architecture must cope with this paradigm shift in order to remain relevant throughout its century lifespan.

The studio project in phase two deals with the transitioning of a simple prototype that responds to a single interaction based on a single behavior of either waiting, exercising and meeting. The projects developed from hereone were proposals into the definition of an augmented architecture project. Two projects are showcased here.

4.1. PARASITIC FITNESS HUB

The Parasitic Fitness Hub project transitioned from the behavior of exercising or jogging into the activities inside a fitness hub. The project proposed a modular fitness framework of activities attached to an existing building, in this case, a high-rise complex, as a parasitic architecture capable of moving and reconfiguring its units to adapt to users and its building host. Also, environmental sensor networks can be deployed inside the units to render real-time visual and audio landscapes within the space and enhance user experiences. The topic was intriguing as a project but raised many concerns about the construction and mechanics behind the mobility of units that are physically attached to a building façade (see Figure 6).

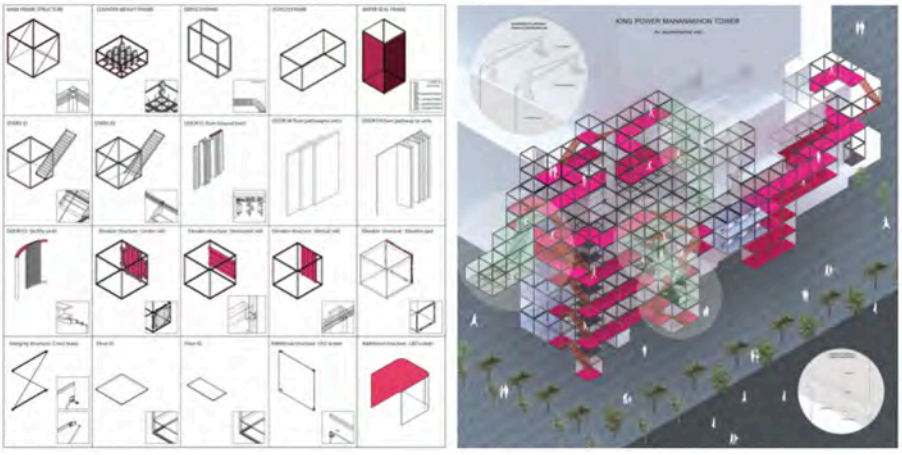


Figure 6. Parasitic Fitness Hub with an array of exercise modules combined into an interconnected augmented architecture. .

4.2. PARKOUR EXTREME PARK

The last project also transitioned from the behavior of exercising and developed the project into an extreme sports park specifically for Parkour, and created an interactive extreme sports environment where the building surfaces can be reconfigured internally and externally to accommodate the multiple levels of difficulty of the sport. The floor platform and walls are comprised of interactive units that can push in or out and reconfigure its continuous surface depending on its users. Each unit has an air pump system in a channel pushing or pulling its top cushion where it is used as a gripping object or stepping platform (see Figure 7). Customization of the obstacles can be programmed using personalized intelligent sensors combined with user behavior analysis to help shape an adaptive game (or play) setting and alternative scenarios to the players in real-time.

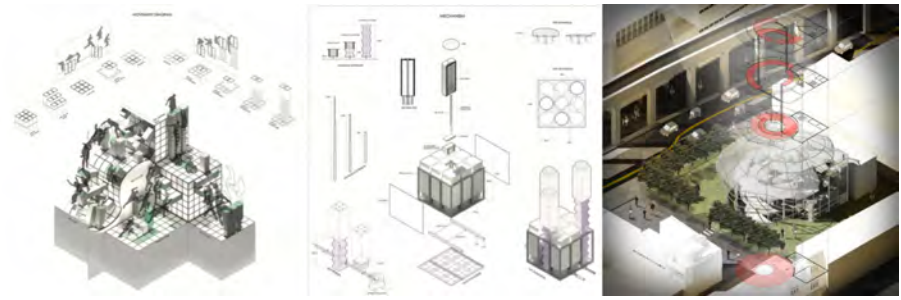


Figure 7. Diagram of internal spaces with three levels of difficulty and detail drawings showing the internal interactive surfaces.

5. Conclusion

Augmented architecture explores human behaviors that have changed due to digital technologies and how they impact activities and the design of spaces. In this option studio, students are required to rethink how these new behaviors impact the design of spaces in architecture as well as experiment how the design of a space with embedded digital technologies can change human behaviors purposely. The first phase of the project experimented with Arduino prototyping was a good experience to inquire human behavior changes and learn simple programming with microcontroller. Students paired up and learned from making, planning, and testing. All prototypes completed were at a satisfactory level. The second phase of the project however, transitioning from prototype design to architectural design may prove to be a challenging for students. Especially those who did well in first phase were not so successful in second. This is due to the lack of meaningful interactions within the spaces chosen and the hesitance of students to take the leap of faith into new design possibilities. Nonetheless, augmented architecture can be explored further in other aspects of computational design education and practice. Looking into novel construction applications, performative facades, kinetic building envelopes, and interactive and transformative architecture are possible future research directions for continuation of this option studio.

Acknowledgements

The author would like to acknowledge the participation of Panat Triwattana, Lucile Uda, Natchapongtorn Gaesornsuwan, Pierre Alexandre Pommerol, Thanapon Harnpattanapanich, Parisorn Itsarapanich, Thanatcha Pojthaveekiat, Kittpon Sanitwong Na Ayuthaya, Jun Jashiro and Nana Mori with contributions from Preechaya Sittipunt, Deborah Lopez, Sorachai Kornkasem and support from the International Program in Design and Architecture, Faculty of Architecture, Chulalongkorn University.

References

Bratton, B.: 2016, *The Stack*, MIT Press.

Dublon, G. and Paradiso, J.A.: 2014, Extra Sensory Perception, How a world filled with sensors will change the way we see, hear, think and live., *Scientific American*, **311(1)**, 36-41.

Hashemi, S.H. and Kamps, J.: 2017, Where To Go Next?: Exploiting Behavioral User Models in Smart Environments, *Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization*, Bratislava, Slovakia.

Ishii, H. and Ullmer, B.: 1997, Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms, *Proceedings of CHI*.

Mayton, B., Dublon, G., Russell, S., Lynch, E.F., Haddad, D.D., Ramasubramanian, V., Duhart, C., Davenport, G. and Paradiso, J.A.: 2017, The Networked Sensory Landscape: Capturing and Experiencing Ecological Change Across Scales, *Presence: Teleoperators and Virtual Environments*, **26(2)**, 182-209.

Mitchell, W.: 1995, *City of Bits: Space, Place, and the Infobahn*, MIT Press.

Sanchez-Vives, M.V. and Slater, M.: 2005, From presence to consciousness through virtual reality, *Nature Reviews Neuroscience*, **6(4)**, 332-339.

Weiser, M.: 1991, The Computer for the 21st Century, *Scientific American, 265, 94-104*.

Witmer, B.G. and Singer, M.J.: 1998, Measuring presence in virtual environments: A presence questionnaire, *Presence*, **7(3)**, 225-240.

ADAPTIVE MODULAR SPATIAL STRUCTURES FOR SHOTCRETE 3D PRINTING

NORMAN HACK[1], HENDRIK LINDEMANN[2] and HARALD KLOFT[3]
[1]*Institute of Structural Design | Junior Professorship for Digital Building Fabrication, Technical University Braunschweig*
[1]*n.hack@tu-braunschweig.de*
[2,3]*Institute of Structural Design, Technical University Braunschweig*
[2,3]*{h.lindemann|h.kloft}@tu-braunschweig.de*

Abstract. This paper presents a modular, digital construction system for lightweight spatial structures made from reinforced concrete. For design and fabrication, a digital workflow is presented, which includes the rationalization of a freeform geometry into adaptive spatial modules made up entirely of planar components. For fast and precise fabrication, these components are 3D printed using a novel 3D concrete printing technology called "Shotcrete 3D Printing". The ongoing research is demonstrated by an initial real-scale prototype of one exemplary spatial module. Lastly, the paper provides an outlook into future research, which is necessary to make this digital construction system applicable to the real-scale construction of large, wide-spanning structures.

Keywords. Robotic Fabrication; Digital Construction Systems; Shotcrete 3D Printing; Modular Structures.

1. Introduction

Spatial structural systems, such as lattice structures and space frames, are highly efficient load-bearing structures, which are characterized by a good ratio of material consumption to space spanned. This feature makes them particularly suitable for long-spanning, column-free constructions, as for example halls, terminals, or hangars. Moreover, as spatial structures consist of a large number of discrete structural members, they are geometrically well adaptable by locally altering the length and angle of individual members. Accordingly, spatial structural systems are particularly well suited for the realization of free-form geometries as for example recently demonstrated in the Heydar Aliyev Center by Zaha Hadid Architects (Zaha Hadid Architects 2012), the ArcelorMittal Orbit by Anish Kapoor and Cecil Balmond (Studio Balmond 2012) or the Shenzen Bao'an International Airport by Studio Fuksas (Studio Fuksas 2013). Due to the reason that the elements of a spatial structure must bear both, tensile as well as compressive forces, they are today predominantly constructed using isotropic construction materials like steel or aluminum. Spatial structures constructed in reinforced concrete, on the other hand, are less common (Schätzke 2015). There

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 363-372. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

are mainly two reasons for this: On one hand, this is due to the high costs involved in constructing the geometrically complex formwork, and on the other hand due to the constructive and visual "heaviness" of concrete structures, which is caused by the minimum concrete cover necessary to protect the steel reinforcement. Today technological innovations like computational design and calculation tools, novel robotic fabrication techniques, as well as innovative material composites like textile reinforcement (C3 - Carbon Concrete Composite e. V. 2017) and high performance concrete (Ductal 2015), could possibly pave the way for the application of reinforced concrete for geometrically complex spatial structures. However, despite the technological innovations, the challenge today remains to develop adequate digital construction systems, which seamlessly integrate these innovations and which negotiate between interdependent factors like structural efficiency, fabrication efficiency, and material properties. The goal of this ongoing research project is the development of an integrative digital construction system for adaptive modular spatial structures in reinforced concrete, which equally considers fabrication constraints, structural performance, material properties, construction site logistics, as well as economic and ecological aspects. In view of that, this paper describes a digital construction system and a digital workflow, in which a freeform geometry is first rationalized into planar panels, secondly developed into spatial modules, and which can finally be fabricated rapidly and without causing construction waste using 3D concrete printing technology.

2. Background

Today a number of research groups investigate the use of reinforced concrete for the realization of structurally optimized and hence geometrically complex lattice constructions. For the realization of such structures, most fabrication approaches today focus on the fabrication of the concrete lattice formwork. Three different approaches are described in the following paragraphs: The research project "Hedracrete" of the "Polyhedral Structures Laboratory" of the University of Pennsylvania investigated spatially complex polyhedral structures developed on the basis of three-dimensional static graphics (Figure 1a). This method is exemplary for structural efficiency, expressive forms and the minimal use of material. Tectonically, the Hedracrete Pavilion consisted of 129 individual Glass Fibre Reinforced Concrete elements, including 54 compression members, 30 tension members as well as 45 three-dimensional concrete nodes. The formwork of the individual lattice elements was CNC milled, whereas each of the 129 parts was composed of at least two CNC milled parts (Akbarzadeh et al. 2017). The project indicates, that realizing highly efficient structures, still involves considerable efforts in the fabrication of the lattice formwork, and moreover that form-work waste remains an inevitable aspect when realizing highly differentiated constructions. Maintaining fabrication efficiency while being structurally highly efficient was the starting point of the Opticut research project (Søndergaard et al. 2019). This research project explored methods for efficiently fabricating topologically optimized structures by applying robotic abrasive wire cutting techniques for EPS formwork. Here, the individually cut lattice formwork parts serve as inserts for standardized concrete formwork. As the final demonstrator, the

research group realized a geometrically complex, topologically optimized pavilion with dimensions of 20 x 3 x 5 m (Figure 1b). Compared to multi-axis milling, the hot wire cutting process is more than 100 times faster and provides smoother surfaces. However, despite the considerably improved fabrication efficiency, also here large quantities of formwork waste are created. A strategy for eliminating formwork waste to the largest extent possible was recently demonstrated in a project by Xtree (Gaudillière et al. 2019). For this project, the formwork and temporary support structure for a 4 m high, truss-like column, was 3D printed with concrete in four individual segments. After curing, the segments were stacked on top of each other, filled with concrete and the temporary support structure was removed (Figure 1c). The structure´s high geometric complexity made the integration of conventional reinforcement challenging. Hence, the structure was filled with Ultra-high Performance Concrete, which provided, sufficient tensile strength for this particular application. For the proof of the load-bearing capacity, the printed lattice formwork was structurally treated as lost formwork. Despite being one of the first applications of 3D printing with concrete in construction, the project also makes two of the major challenges evident: Firstly, integrating structural reinforcement into the additive manufacturing process remains problematic, and secondly, 3D printed construction elements are not yet approved for the application as structural elements.



Figure 1. Contemporary examples for spatial structures in reinforced concrete(decreasing complexity, increasing fabrication efficiency): (a), Heptacrete; (b) Opticut; (c) column in Aix-en-Provence.

The three examples show that, despite the technological advancements, the fabrication of spatial structures in reinforced concrete still remains labour, time, and waste intensive. However, for a fabrication and material efficient design of spatial structures in reinforced concrete, clues can be taken from the past. Pier Luigi Nervi, for example, developed a series of aircraft hangars for the Italian Air Force based on a highly efficient lattice shell system composed of prefabricated, spatial truss girders (Greco 2008). For the construction, Nervi developed a system of 3 m long and 90 cm deep, planar, prefabricated concrete trusses which were assembled on site to form a diamond-shaped vault structure.

After assembling, the trusses were monolithically joint by casting concrete into the gaps between the trusses (Figure 2).



Figure 2. Pre-fabricated Airforce hangars, Pier Luigi Nervi, Orvieto, 1939: (a) interior view of the lattice shell before the planking; (b) prefabricated truss girders during assem-bly; (c) detail of the joint before casting.

By exclusively using identical, planar truss girders, Nervi was not only able to save considerable amounts of material, weight and time but also he was able to reuse the formwork and hence reduce construction waste. The drawback of using merely identical components is clearly a restriction of design freedom. However, with new digital design and optimization tools, novel high-performance materials and novel robotic fabrication methods, this particular limitation can be dissolved. As such, this research takes Nervi‘s system as a reference and proposes a spatial structural system, that equally considers structural efficiency, fabrication productivity, as well as ecological and economic factors.

3. Methods

The overall concept of the construction system is based on the following digital workflow: Firstly, a freeform geometry is rationalized into spatial modules, consisting of planar components. Secondly, the spatial modules are digitally unfolded, the fabrication paths are generated, and the components are 3D printed as planar elements. Preconfigured reinforcement is manually placed during the printing process. Thirdly the edges, along which the components are connected are post-processed while the concrete is still in its green state. Subsequently, the components are assembled into spatial modules which can finally be assembled into a shell configuration.

3.1. COMPUTATION:

3.1.1. Segmentation and planarization

Based on the constraint that all elements in the structure have to be planar, a workflow was developed that rationalizes a given freeform NURBS surface into spatial modules consisting of exclusively planar components. Initially, a given input surface is divided into quadrilateral components, which results in predominantly double curved components (Figure 3a). In the next step, the components are planarized using a physics solver implemented in Kangaroo 2 for Grasshopper. Each of the newly created planar quadrilaterals subsequently serves as the basis for the development of the spatial modules. For this, the mean curve of the long surface edge is generated and subsequently offset in the direction of the surface normal. Based on the edge curves and the newly created mean curve, two additional surfaces are created, providing structural depth. These surfaces, however, are yet again not planar (Figure 3b). Hence, the two resulting surfaces also have to be rationalized, however this time with two additional boundary conditions. First, the resulting surfaces have to be connected to the initial planar quadrilateral and secondly, the module has to be connected to the next module on all edges (Figure 3c).

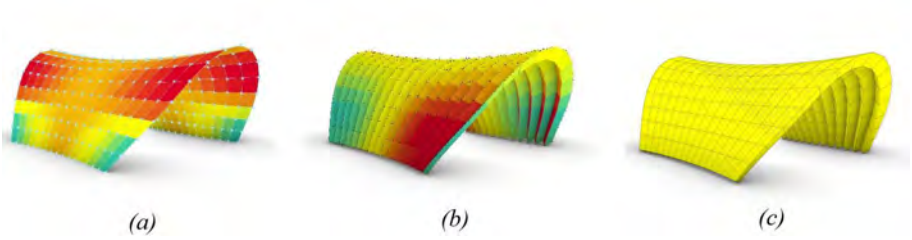


Figure 3. Module generation: (a) initial surface subdivided into double curved quad-rilaterals with colours indicating the double curvature; (b) planarized quadrilateral grid with double curved surfaces providing structural depth (c) planarized quadrilat-eral grid with planar spatial structure, the single colour indicates planarity.

3.1.2. Optimization and Preparation

In a final stage, the planar quadrilaterals are transferred into a spatial lattice structure, which is locally adapted to the specific loading condition. For this, the module edges are extracted and the stresses are calculated using Karamba for Grasshopper. Depending on the structural load, the thickness of the element is calculated and the geometry is generated for all modules (Figure 4a). In a final step, each module is unfolded, positioned and translated into fabrication data. For this, an offset of the outlines creates the input for the robot path. In order to simulate the robot‘s movement, the plugin “Robots” for Grasshopper is used (Soler 2017). The coordinates and the tool speed are translated into a G-code legible for the Siemens Sinumeric, which is controlling the robot and CNC mill.

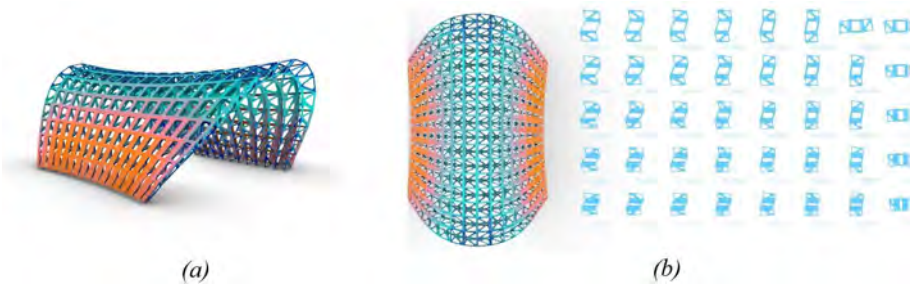


Figure 4. Final geometry: (a) Planar and structurally adapted structure with thicker parts marked in orange and more slender members in blue; (b) top-view of the structure and digitally unrolled modules.

3.2. 3.2. FABRICATION:

3.2.1. Robotic setup:

For fabrication, the unique Digital Building Fabrication Laboratory (DBFL) of the Institute for Structural Design at TU Braunschweig was used. The DBFL is a large scale robotic fabrication facility consisting of a gantry system with two independently controllable manipulators, firstly a six-axes Stäubli TX 200 robot, and secondly a three-axes Omag milling application. The overall cooperative build space embraces 10.5 x 5.25 x 2.5 meters. As such, the DBFL facilitates the production of largescale structures, both by subtractive machining, as well as by additive manufacturing processes.

3.2.2. Printing method:

For the printing process, the Shotcrete 3D Printing (SC3DP) technology, which was previously developed by the authors was applied (Lindemann et al. 2019). This novel technique differs from conventional 3D concrete printing by the fact that the material is not simply extruded, but spayed with pressure in order to build up a three-dimensional structure. The advantages compared to conventional 3D

printing are, firstly, a superior layer adhesion, secondly, the ability spray around, and hence integrate, reinforcement, and thirdly, the potential to spray against vertical surfaces and overhangs.

3.2.3. Fabrication:

Prior to printing, a planar wooden baseplate was installed in the workspace of the DBFL. The fabrication data for each of the module‘s components was uploaded, and the concrete mixing process was started. Each of the module‘s three components was printed separately in three consecutive layers. After the first two layers were printed, 8 cm wide and 100 cm long strips, cut from a larger carbon fiber reinforcement grid (sglgroup 2017), were manually placed on the top layer. Subsequently, the last layer was sprayed on top of the previous layers, embedding the carbon fiber reinforcement into the structure (Figure 5a).



Figure 5. Fabrication process: (a) Spraying of the elements; (b) cutting of the edges in the green state of the concrete; (c) smoothing of the mitered surface-edge.

3.2.4. Green post-processing:

After initial curing of the concrete, the long edges of the elements were post-processed in order to create a dry joint. For this, a steel disc with a diameter of 200 cm was mounted to the spindle of the milling head. With a rotation of 200 rpm and a feedrate of 3000 mm/min, the edges were first cut to miter (Figure 5b), the excess material was removed, and the edge was subsequently smoothed in a second pass (Figure 5c).

3.2.5. Assembly:

After curing for two days the planar elements were detached from the wooden baseplate by laterally moving them. Due to the low weight of each element of merely 60 kg, the elements were lifted into place by only two persons (Figure 6).

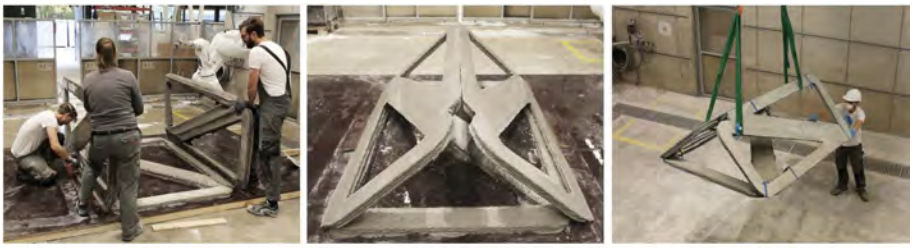


Figure 6. Assembling process of one module: (a) assembly with three people; (b) as-sembled element; (c) positioning using a crane.

4. Results and Reflections

The experiment resulted in a 2.2 x 1.5 x 1m prototype, which is part of the larger structure depicted in Figure 4. The prototype was fabricated in 25 minutes excluding waiting time, whereas the spraying process took 12 minutes and post-processing lasted 8 minutes. Assembling of the module consumed another 5 minutes. During the fabrication process, the following observations were made: Spraying resulted in good compaction, was fast and offered consistent height control. However, the starting and stopping procedures of the spraying process are not yet precisely controlled, requiring to extend the starting and ending point of the contour. With regards to the reinforcement, it became apparent, that using pre-cut strips of carbon fiber mats is an effective measure to reduce the structural thickness of the elements. However, the manual placement did not prove to be not sufficiently precise, causing collision conflicts during the cutting of the edges during post-processing. The subtractive post-processing of the green concrete is a novel approach in itself. It proved to be fast and with little energy consumption compared to cutting cured concrete. Moreover, it proved to be sufficiently precise at least for wet joining techniques using a thin bed of mortar. However, for force-locking dry joints, the precision should be improved. Due to the low weight of the components, the assembly was possible with only three persons. As no connection mechanisms were integrated in this first prototype, lashing belts were used to connect the components.

5. Conclusions and future work

This initial prototype represents the first proof of concept for a just starting research project. Yet, it already demonstrates a high potential for efficiently fabricating lightweight loadbearing 3D printed spatial structural systems in reinforced concrete. However, in order to realize the full potential of this method and make it applicable for largescale, free spanning constructions, further investigations have to address the following aspects: At this stage, the computational workflow starts by rationalizing any given, arbitrary surface. This will be further developed to also cover the automated, computational generation of a structurally informed surface geometry. Moreover, the current module design is still at its most basic

stage. As such, the modules have to be developed further specifically in two regards: Firstly, in respect to the overall typology, and secondly, regarding their functional integration. The former concerns, for example, the load transfer in both directions, longitudinally as well as laterally. Here the key challenge will be the development of more sophisticated module typologies, allowing for improved connectivity and multidirectional load transfer between neighboring modules. The latter concerns the automated integration of functional features, as for example interlocking mechanisms like finger joints, the incorporation of pre-stressing tubes and structural reinforcement, as well as the integration of precast couplers in order to structurally connect the elements on the component level, as well as on module level. Accordingly, additional fabrication steps, including, rebar cutting, tube bending, as well as pick and place processes for the precise placement of the precast couplers will be implemented into the overall fabrication process. Additionally, strategies for an automated assembly of the components into modules will be explored in further research. In the next phase of the research, the goal is to realize larger spatial structures consisting of several modules and use those to perform a structural test. Only in that way the overall performance, ranging from design and fabrication to assembly logistics and structural efficiency can be evaluated and compared to current standards in the fabrication of spatial structures. In summary, the examples of Nervi´s aircraft hangars are early demonstrations, how the modularization of spatial structures into planar components can yield in highly material, fabrication, and structurally efficient constructions. Against the background of new design and calculation tools, new production technology as well as new materials, it becomes evident that these developments today dramatically widen up the design space of this approach.

References

"Ductal" : 2015. Available from <https://www.ductal.com/en> (accessed 15th February 2019).

"C³ – Carbon Concrete Composite e. V." : 2017. Available from <https://www.bauen-neu-denken.de/en/#about-c3> (accessed 2nd February 2018).

"sglgroup" : 2017. Available from <http://www.sglgroup.com/cms/international/innovation/future-carbon-technologies/sustainable-construction/index.html?__locale=en> (accessed 15th February 2019).

Akbarzadeh, M., Mahnia, M., Taherian, R. and Hossein, A.: 2017, Prefab , Concrete Polyhedral Frame : Materializing 3D Graphic Statics, *Proceedings of IASS 2017*, Hamburg, 8-11.

Zaha Hadid Architects, initials missing: 2012, "Heydar Aliyev Centre" . Available from <http://www.zaha-hadid.com/architecture/heydar-aliyev-centre/> (accessed 15th February 2019).

Studio Balmond, initials missing: 2012, "Arcelormittal Orbit" . Available from <http://www.balmondstudio.com/work/arcelormittal-orbit.php> (accessed 15th February 2019).

Studio Fuksas, initials missing: 2013, "Shenzen Bao" . Available from <http://fuksas.com/?p=196> (accessed 15th February 2019).

Gaudillière, N., Duballet, R., Bouyssou, C., Mallet, A., Roux, P., Zakeri, M. and Dirrenberger, J.: 2019, Large-Scale Additive Manufacturing of Ultra-High-Performance Concrete of Integrated Formwork for Truss-Shaped Pillars BT - Robotic Fabrication in Architecture, Art and Design 2018, *Robotic Fabrication in Architecture, Art and Design 2018*, Zurich.

Greco, C.: 2008, *Pier Luigi Nervi: Von den ersten Patenten bis zur Ausstellungshalle in Turin 1917-1948*, Quart-Verlag, Luzern.

Lindemann, H., Gerbers, R., Ibrahim, S., Dietrich, F., Herrmann, F., Dröder, K., Raatz, A. and Kloft, H.: 209, Development of a Shotcrete 3D-Printing (SC3DP) Technology for Additive

Manufacturing of Reinforced Freeform Concrete Structures BT - First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018, *First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018*, Zurich.

Schätzke, C.: 2015, *Stabnetze Aus Textilbeton*, Ph.D. Thesis, Rheinisch-Westfälischen Technischen Hochschule Aachen..

Soler, V.: 2017, "Robots" . Available from <https://github.com/visose/Robots/wiki> (accessed 15th February 2019).

Søndergaard,, A., Feringa, J., Stan, F. and Maier, D.: 2019, Realization of Topology Optimized Concrete Structures Using Robotic Abrasive Wire-Cutting of Expanded Polystyrene Formwork, *Robotic Fabrication in Architecture, Art and Design 2018*, Zurich.

INFLUENCES OF A NEW DIGITAL CULTURAL LAYER ON DESIGN AT VARYING SCALES

JAMES HOLTH[1], SCOTT MEEKINGS[2],
MARC AUREL SCHNABEL[3] and TANE JACOB MOLETA[4]
[1]*PLUS Architecture & DARA*
[1]*james.r.holth@gmail.com*
[2]*DARA*
[2]*s.m.meekings@gmail.com*
[3,4]*Victoria University of Wellington*
[3,4]*{MarcAurel.Schnabel|Tane.Moleta}@vuw.ac.nz*

Abstract. Architects work with data daily. Spatial metrics, building codes and client requirements form the main considerations for many designers, yet new layers of data are impacting the way cities and inhabitants interact with each. This data can be used to more effectively analyse and predict patterns and behaviors to produce environments better suited to users.This paper reviews a selection of ideas from across digital architectural discourse by discussing tangible outcomes from a practitioner point of view and advocates for a greater integration of this digital cultural context into the design process. This paper considers a city-wide digital logic, rather than a new-age technological zeitgeist, that is as much a part of a city as its buildings are and through this provides a lens into our environment and devices that can be used to influence design at multiple scales.

Keywords. Big Data; Digital Identity; Built Environment; Authenticity.

1. Big Data, Small World

"The future of architecture is culture." - Philip Johnson

A cities culture is a product of the lifestyle of its people. It is an organic system that reacts to and in turn influences people. Architecture and the built environment form an intrinsic part of this system. Not only does the designed environment provide the physical amenity for many of a cities activities, they keep a record of a cities past. The built environment has an important role to play by being receptive to and enhancing a cities culture in order to help guide its future. This requires a proactive approach by architects that considers how architecture is situated in a cultural timeline by developing academic considerations into additional constraints and motivators for practice.Today's society collects data on an unprecedented level (Neef, 2014). Interaction with data has moved from a purely practical level, i.e. maps, bus schedules, to include more whimsical uses, i.e. location based mobile games. Data collection has become a normalised

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 373-380. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

aspect of many peoples lifestyles (Mayer-Schonberger, 2013). Lifestyle apps have enabled large scale personal data collection, analysis and comparison; with many of these apps tied to location, see Figure 1 for an example of simple user location tracking.These data collection apps are becoming increasingly linked to social media, providing means to interact and connect with nearby users. In the same way that a park, or a popular bar, may have connected a cities people in the past, these apps are connecting people to different locations in a new way. As this becomes more prevalent, and reaches an international scale, traditional wayfinding techniques will blur with more data driven approaches that can be harnessed by viable developments.

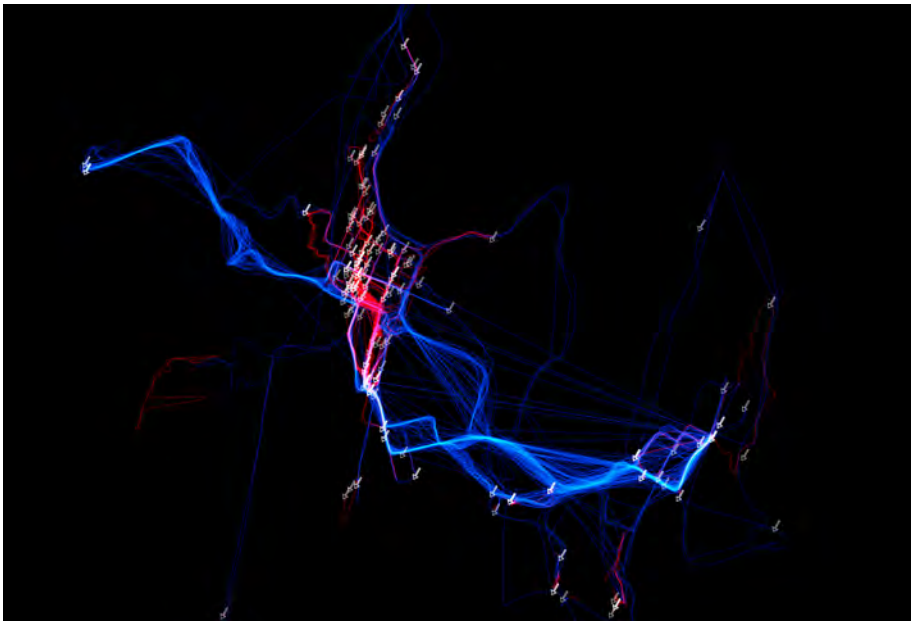


Figure 1. Exploration of personal datasets within cities Source: Author.

There is room for greater integration of the digital environment into the design process in order to create spaces that are better integrated into a digital cultural context. Each city has its own intelligence in the form of patterns, and it is important to view this data not simply as sets of disparate data, but as a layer of aggregated culture.

As the way we interact with the environment has shifted, so too have the environments themselves. Businesses are putting more information online. Tourist destinations are being artificially framed for social media, see Figure 2.

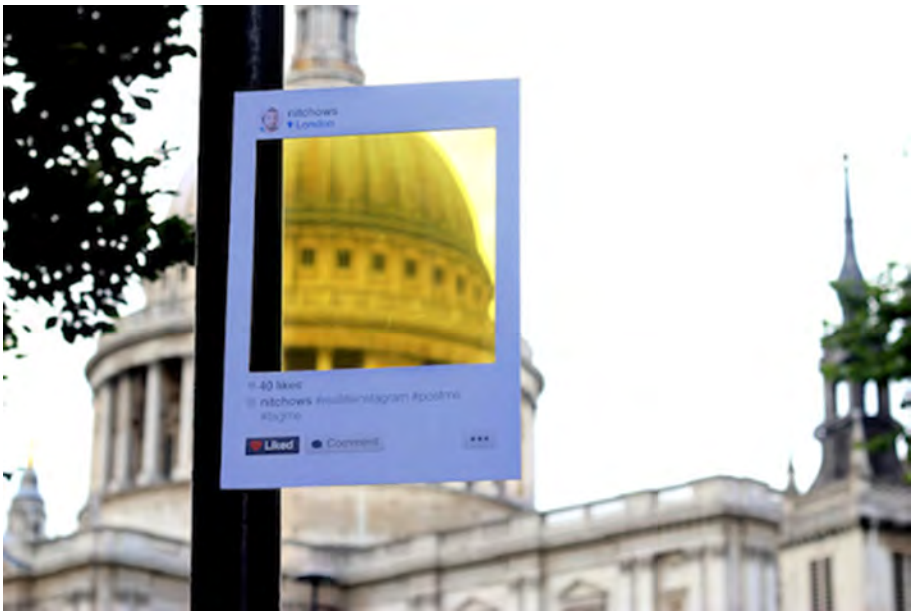


Figure 2. Real Life Instagram project Source: Bruno Ribeiro.

Cafe's are including USB ports to charge devices, and WiFi to browse social media. Even public spaces are beginning to incorporate aspects of our increasingly digital culture (Figure 3). Our environments are showing signs of adapting to this shifting cultural paradigm.

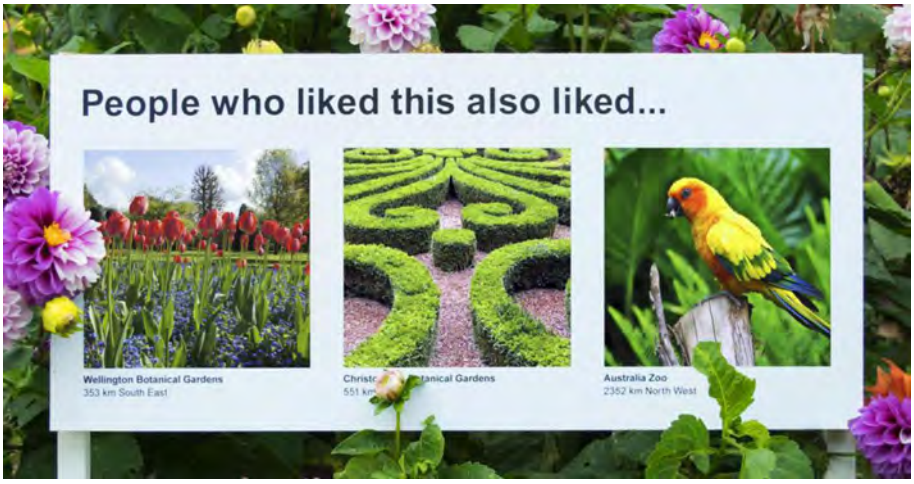


Figure 3. Signs of the Times project Source: Scott Kelly and Ben Polkinghorne.

In order to explore this concept, two scales have been considered; urban scale and human scale. The first scale questions the influence of this cultural layer when

applied on a city scale, where people are represented as data points and trends. This section discusses the strengths and weaknesses of a holistic data-driven planning perspective. The second scale introduces a relationship between buildings and people through data centred interaction. The idea of a digital culture layer is examined at an impersonal as well as a personal level.

2. Urban Scale

Data has been collected at an urban scale for a long time; however, the level of available data is much greater than before. This allows for insights to be gained into different aspects of how people live in a city. Large amounts of data and layers of information are becoming integrated into city programs in a network of interoperability but that is still only on the fringe of practical usage. Shifts in the scale and interoperability of this digital network are constantly changing the applications for this data, and providing increasing possibility to influence design at a greater scale.

Site and context are key factors to consider for a successful architectural outcome, and the digital cultural layer provides additional tools and complexities for engaging with site. Aggregate data of digital interaction can quantify conventional values such as mood, age, sex and wealth. More importantly, aggregate data can attempt to provide additional considerations such as a communities shared personality traits (Chittaranjan et al., 2013). Similarly the ability to derive a sense of a communities aesthetic taste is increasingly possible as the digital cultural layer comiles individual preferences. Through aggregate data, site can be informed by digital data at an urban scale in much the same way as traditional site influences.

This is exhibited in projects such as the Hemnet Home by Tham & Videgård Arkitekter where the ‘ideal’ house was designed based on the browsing and buying habits of users of Swedish property buying website, Hemnet (2015). This provided data on preferences such as prefered colours and configuration of rooms. Additional digital datasets can be integrated with these location specific information sources to provide a macro-scale context which can see wider societal changes such as year on year declines in searches for apartments. These patterns can be compared across cities giving context to any location, see Figure 4. This use of aggregated data can allow a city to make an informed response to growing trends using the digital space before the’re manifested physically. The ability to integrate a quantitative view of trends or tastes allows for a more direct relationship to clients and developer goals.

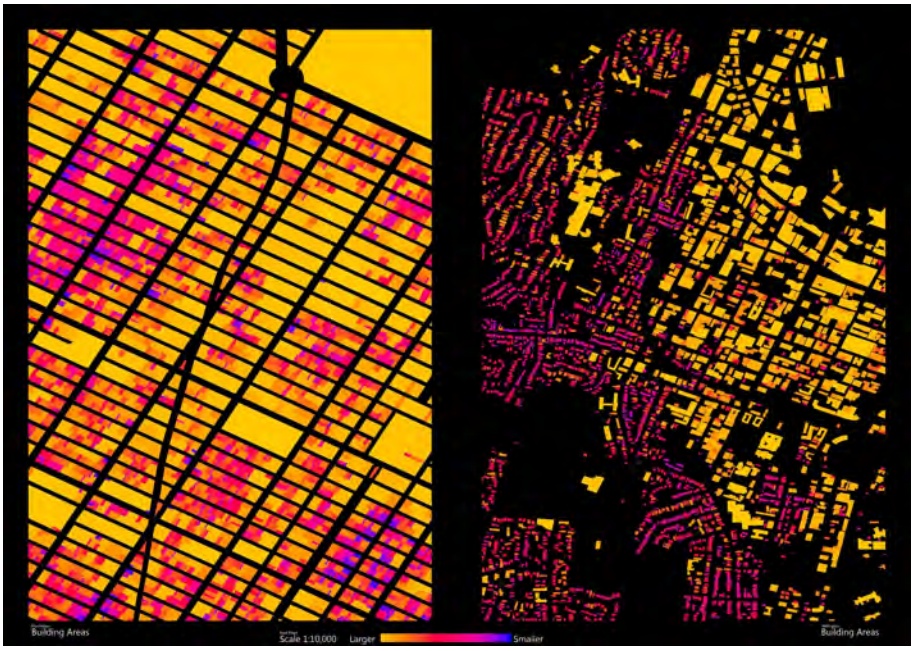


Figure 4. Exploration of patterns and datasets within cities Source: Author.

A data driven approach is not without its pitfalls. The dichotomy of a need for, and danger of, a centralized framework is one area that needs careful consideration. Privacy issues around the widespread use of personal data also create an ethical element to its use (Neef, 2014).

There are difficulties associated with aggregating data such as creating a dashboard or visualization to make sense of a cities complexity under the guise this will make for easier decision making - however this view advocates for a framework that is designed, operated and controlled without conscious input from those affected (Ciuccarelli, et al., 2014). By ignoring these stakeholders the outcome is likely to diminish the culture which it is based upon. This is the inherent risk in the filtering stage of data-driven design. In doing so, user bias can allow for pre-conceived results to be falsely justified. It is important that the use of data is a transparent process that allows organic solutions to form, where people act more as observers and less as operators.

Contrary to the issues of too much centralized control is the inherent reliance on existing centralized infrastructure frameworks. This reliance puts these intermediary government or private organisations (governmental or private) in the powerful position of influencing the built environment, due to their ability to curate and diseminate the aspects of the digital cultural layer known as “gatekeepers” (Segev, 2010). Alongside the need for centralized frameworks is the need for oversight of data, as unexpected issues can arise from the release and publicization of data which has not been vetted. An example of these issues was spurred by Strava publicizing popular running routes and unknowingly identifying US

military base locations (Ruser, 2018).

A further issue with centralizing control is the need to anonymize data without removing key outliers. Design professions differ from typical data-driven professions in that we deal with the creation and reaction to unusual and atypical inputs as opposed to considering them irrelevant and removing them as outliers. This makes privacy more difficult to maintain as uniqueness is quintessential to the built environment but is also directly antithetical to maintaining privacy (Meekings and Schnabel, 2016).

3. Personal Scale and Agency

Connection and interactivity help make a space successful. Personal interaction with the digital cultural layer is changing as it becomes a part of the built environment. Typically users have agency over their digital interaction and profile, often referred to as an avatar. As data is being collected and curated to reflect individuals this agency is removed. Explored here is an opposition to this reduced agency through the ability for individuals to filter how data's influence is manifested in physical space.

When interacting with the digital environment, individuals have become accustomed to the concept of a digital avatar that represents them in a digital setting. The separation of data into an 'avatar' to represent an individual is common throughout digital technology; a set of preset details that, for convenience's sake, carry across multiple media. This concept can be seen in physical space through profiles used in home automation systems that enable occupants to adjust lighting per room, monitor their home from other locations and set presets that recognise an occupants personalized settings. This avatar typically gives agency to the user, as they have the ability to modify or control how their avatar represents them.

As the built environment adapts to incorporate digital culture, it too will start to connect with these digital identities. As lifestyles become so intrinsically linked with digital personas, the distinction between 'avatar' and individual will become blurred. Once digital interaction becomes a part of physical space, the need for an avatar disappears, as data can be directly associated with the individual.

Through leveraging existing methods of profiling, smart buildings and automation will be able to associate data with individuals without the need for user input. This is different to a user-created avatar in that the profile is created without agency from the user. These existing methods are currently used in moderating and curating the digital cultural layer by internet-based marketing and social media companies, which rely on their ability to extract data from digital interactions and use this to form a profile representing an individual. This profile can help digital organizations make assumptions on the preferences of an individual and deliver a personalized experience within a wider framework. Despite there being no agency in creating this profile, this data is still being made accessible to individuals; google for example provides a webpage for reviewing their assumptions about you while spotify will allow you to download a list of every song you have listened to via their service. By leveraging these existing data-sources and algorithms a plethora of architectural outcomes become available. Examples vary widely from simple

ideas such as intuitively dimming and reducing the blue-wavelength of lights based on an individual's typical sleeping patterns ("blanched" melatonin levels are an increasing problem due to the digital cultural layer and it's current reliance on constant connectivity and backlit screens) (Scott, 2016). More complex options are made available with more data, examples include real-estate or apartments being coordinated to create symbiotic communities of people based on these profiles, or recommending areas to live based on facilities and locations most visited as recorded by phone GPS (Meekings, 2017).

As an individual's agency is removed through the replacement of 'avatars' with automatically generated profiles, this agency could be restored by giving the user increased input into how data influences the built environment around them; likely in the form of reducing the data that is available to them in physical space rather than the inclusion of more data. In the past this area of research has largely focussed on overlaying and increasing the amount of data that is made available through architectural space, with early examples such as MIT tangible media groups Ambient Room which utilised interactions that were novel for the time such as projections and physical icons referred to as phycons (Wisneski et al., 1998). This has been a continual theme in this specialism such as the more recent BMW Museum by ART+COM (Dalton, et al. 2016). Increasingly there is a sense that 'data overload', limitless access and constant connectivity can have negative emotional or physical outcomes. It is increasingly impossible to be 'fully-informed' as the internet-enabled pool of data and information becomes vastly deeper than ever before. If data and information become synonymous with the built-environment around us this sense of 'data-overload' will reach new heights. This 'data' overload' can have profound effects on wider society, politics and productivity; factors that are often associated with the built environment but often only sparingly considered by designers (Andrejevic, 2013).

It is important to understand a personal digital context to both facilitate and provide relief from data driven interactions. This could be a way to give agency back to users as it does not focus on reducing the data that is associated with a profile. Environments designed to create a relaxed atmosphere could act as filters for some of this information. Existing examples of a data-restricted environments are no-reception zones within offices and libraries to ensure certain areas are free from phone calls and an increasing awareness of designing for quiet work (Cain, 2012). Through a moderated level of agency, spatial occupants can consciously review and edit how they interact with their environments and provide an experience that both protects and enhances the way they experience their surroundings.

4. Conclusion

Successful architecture as a discipline and built work should interface with the digital cultural layer at multiple scales. The evolution of a digital cultural layer provides a basis for changes to the architectural discipline, structured around academic ideas of urban and human interaction. A cities culture is tied to its built environment, therefore the built environment should be responding to shifts in digital as well as physical culture.

This paper assesses the way digital culture has and can influence the built environment, and in what way advances in digital architectural knowledge can influence practice. At an urban scale, this paper puts forward ideas centered on the role of centralized frameworks and associated pitfalls. Issues discussed at a personal scale center on changing dynamics of agency and the role of 'avatars'.

Overall this paper seeks to promote the further exploration of the myriad of ways our increasingly evolving digital culture has impacted our cities, and our buildings. It advocates for a considered approach to both urban planning and building design as the digital cultural layer makes its way into mainstream practice. Interaction with a cities culture is a key to the designed environments success at any scale. Our culture is shifting; as are our cities, in order to continue designing successful spaces we must too.

References

Andrejevic, M.: 2013, *Infoglut*, Routledge. 2013..

Tham & Videgård Arkitekter, N./A.: 2015, "The Hemnet Home" . Available from <http://www.tvark.se/the-hemnet-home/>.

Cain, S.: 2012, Quiet: The power of introverts in a world that can't stop talking, *New York: Crown*.

Chittaranjan, G., Blom, J. and Gatica-Perez, D.: 2013, Mining large-scale smartphone data for personality studies, *Personal and Ubiquitous Computing*, **17**(3), 433-450.

Ciuccarelli, P., Lupi, G. and Simeone, L.: 2014, *Depicting the Data City*, Springer.

Dalton, N.S., Schnädelbach, H., Wiberg, M., Varoudis, T., Dalton, N.S., Schnädelbach, H., Wiberg, M. and Varoudis, T.: 2016, *Architecture and interaction : human computer interaction in space and place*, Switzerland : Springer. 2016..

Kelly, S. and Polkinghorne, B.: 2017, Sign of the Times, *[Artwork]*.

Mayer-Schönberger, V. and Cukier, K.: 2013, Big Data-A Revolution That Will Transform How We Live, Think and Work, *N/A*.

Meekings, S. and Schnabel, M.A.: 2016, Big Data on Individuals in the Architectural Design Process: Combining Individual's Data with the Architects Toolset, *International Journal of Parallel Emergent and Distributed Systems*, **32**, 66-72.

Meekings, S. and Schnabel, M.A.: 2017, *Datatecture: Creating a real home for a virtual identity*, Master's Thesis, Victoria University of Wellington.

Neef, D.: 2014, *Digital Exhaust: What Everyone Should Know About Big Data, Digitization and Digitally Driven Innovation*, Pearson Education.

Ribeiro, B.: 2013, Real Life Instagram, *[Artwork]*.

Ruser, N. [@N.R.G.8000]: 2018, "Strava released their global heatmap. 13 trillion GPS points from their users (turning off data sharing is an option). It looks very pretty, but not amazing for Op-Sec. US Bases are clearly identifiable and mappable [Tweet]" . Available from <https://twitter.com/nrg8000/status/957318498102865920?lang=en>.

Scott, L.: 2016, *The four-dimensional human: Ways of being in the digital world*, Random House.

Segev, E.: 2010, *Google and the digital divide: The bias of online knowledge*, Elsevier.

Wisneski, C., Ishii, H., Dahley, A., Gorbet, M., Brave, S., Ullmer, B. and Yarin, P. 1998, Ambient displays: Turning architectural space into an interface between people and digital information, *in* N. Streitz, S. Konomi and H.J. Burkhardt (eds.), *Cooperative buildings: Integrating information, organization, and architecture*, Springer, 22-32.

AGENCY OF INTERACTIVE SPACE IN SOCIAL RELATIONSHIP

KRISTINA BOYCHENKO
[1] *University of Queensland*
[1] *k.boychenko@uqconnect.edu.au*

Abstract. Embedded computation allows built space to be intelligent and get smarter, becoming interactive and gaining agency with ability not to merely adapt to changing conditions, but to process information and react, observe and learn, communicate and make decisions. The paper investigates agency of interactive space based on interpretation of input data, like users' response to the spatial agency, data from environment or other actors, and ability to change its performance accordingly. The research is focused on the role of interactive space as an active participant in social relationship communicating with users, constantly changing and having its' attitude. The research is aimed at defining social role of interactive environments and explains how they interact with users, what qualities are enabled by interactive behaviour and how do they influence space perception, revealing the significance of bi-directional communication between society and smart spaces. Interactive space does not just providing location for activities and facility for lifestyle, but influences these activities. Users and interactive space constitute one social network being constantly aware of each other establishing bi-directional communication.

Keywords. Interactive architecture; computation; programmable; design; social.

1. Introduction

The main key words of the modern life is the motion and the information. Nowadays it has become more obvious because of the development of information sources and ability to get any information fast and easy, and our habits to live in well-organized space full of devices becoming more fantastic day after day. The further the technologies and development go - the more requirements they meet and more questions they have to answer. Static architecture is limited in its ability to interact with the changing circumstances and what is more important, with the users. It is frozen in one state while nowadays there is an ability to make it fluent, changing, and communicating with people. Users seek an immediate response from the surrounding area and the modern technologies are able to provide it. Now the built environment can understand itself and better perform its function. It can understand people within it and outside, furthermore it can help them to understand themselves better. (Boychenko, 2017)

Interactive design is aimed at engagement of social and cultural dimensions of space, spatially defining interaction as a mechanism to understand, shape and

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 381-390. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

promote social interaction. The physical space can be used to include or exclude people from one another, to facilitate, dissipate, or focus crowds. In this way, in the realm of physical architecture, interactive public spaces can have a profound effect on social interactions. It is important to point out that a lot of projects in public sphere play big role in testing the durability of materials as well as the time frame of particular interactive strategies within the context of unpredictable participants. (Boychenko, 2017)

2. Approach

Interactive environment is a recent phenomenon that is related to the development of new technologies. Interactive environment transformed into stream of information, claims its continuous metamorphosis in space and time, it affirms the permeability between the body and the technology, between the subject and the space. This reminds the conception of the Flesh of Merleau-Ponty, as the interactive space effaces the border between object and the subject. The body is considered as an interlacing of vision and of movement. (Mahdalickova, 2009)

There are a lot of tools in modern technologies and design for the efficient exchange information between built environment and users. When the message is clear it deals not just with intelligence but with emotions and feelings. The environment responds to demands that appear and even more - it leaves a desire to continue a conversation between a user and an impression this building made. Sending appropriate message and having a continuous dialogue with users is one of the main aims that architect should keep in mind during the progress of designing, choreographing the movement and actions of the built environment to create a clear and appropriate response on a foreseen request the way it will be understood correctly. This enables the space to be a fully-valued part of society, an active participant of communication. (Cohen, 1998)

Public space design can also benefit greatly from implementation of interactive behavior. The space becomes one of the actors in social relationships, enhancing public involvement in common activities or reflecting their emotions, behavior or needs. With its ability to attract attention interactive public space gathers people around and lets them act together, see what do the others do and perform together.

Many applications of human-computer interaction embrace an communication component, in which a new kind of kinesthetic learning and space awareness are combined with unique experiences. Such applications enable users to utilize their bodies as well as their minds in collaborative ways. It has an entertaining interactive component; they are engaged through the aspect of controlling the event narrative. While Interactive entertainment is rapidly moving into the physical realm, it is a concept born out of electronic media. Marshall McLuhan lists “three key pleasures” that are uniquely intensified in electronic media:

- immersion
- rapture
- agency

Immersion he says, is the sense of bang transported to another reality, rapture is the entranced attachment to the objects in that reality, and agency is player's delight in having an effect on the electronic world, in the world of entertainment, when an environment is engaging. It is by definition successful.

2.1. AGENCY

With fast development of new technologies built environment transitioned from a silent background of activities performed by users to another participant of those activities. Embedded computation allowed environment to become intelligent and it gets smarter day after day with technological advance, it becomes interactive and gains agency. Architectural space now is able not to merely adapt to changing conditions, but to process information and react, observe and learn, communicate and make decisions. Agency of interactive space is based on interpretation of input data, like users' actions, their response to the spatial agency, data from environment or other actors, and changing its performance accordingly. Therefore interactive environment becomes an active participant in social relationship, communicating with users and learning, trying different modes of interaction and making decisions, constantly changing and having its' attitude. Within the context of this research interactive space is considered as a participant of social relationship along with its uses through the network framework constituting one common network in which both human and non-human actors have agency.

Interactivity essentially means that both people and architectural components of the space have agency, enabling the creation of conversations between the two in real-time. The main difference between responsive environment and interactive is the agency. Interactive means the dialogue between space and users *space* forces where they both have agency enabling real-time multiple loop dialogue while responsive environment gathers data and responds to it but has no agency.

3. Methodology

When adopting a cybernetic perspective, the idea of architectural agency can be appreciated even more comprehensively. Assuming every interactive system is expected to have some sort of internal goal, without which feedback structures are not conceivable, then every single system will also display some degree of intrinsic agency, even if it does not involve complete autonomy or intelligence. Thus, if every space or architectural element can manifest extrinsic agency (in Bruno Latours' conception of the term), equivalently every interactive setting can also manifest intrinsic agency.

The agency of interactive space in social relationship can be defined through a network framework as it proposes amalgamation of human and non-human participants of this relationship, hence all of the participants influence each other. Users and interactive space constitute one social network being constantly aware of each other establishing bi-directional communication.

The role of interactive environment in social relationship can be considered within the network. It frames relationship between people and interactive space as a system that contains components of human and non-human origins, all

components are socially constructed and society shaping. All components of a system interact with each other and contribute to the common system goal. Within the context of this research on-human components are represented by interactive spaces, experiences or interactive architectural components that have agency, forming a system or a network that facilitates their social communication. (Figure 1)

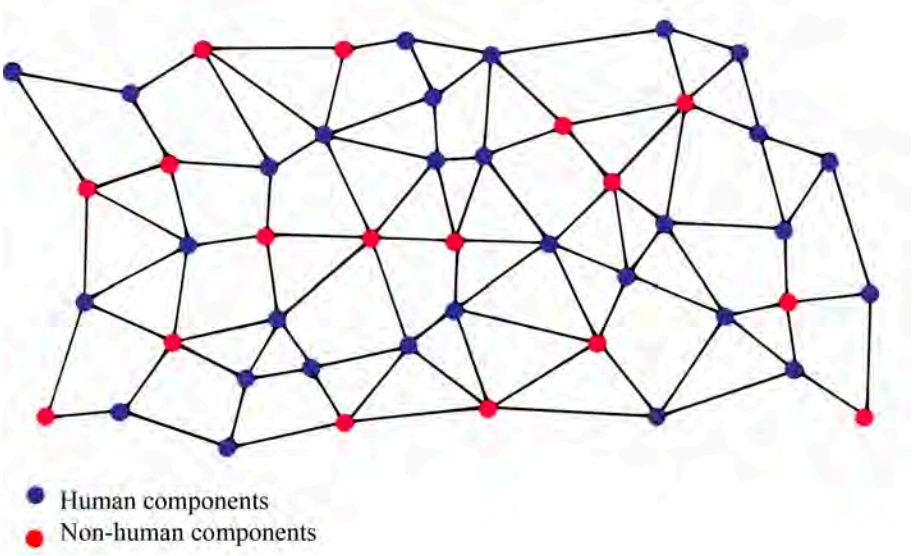


Figure 1. Uniform network of human and non-human components.

As Thomas P. Hughes argues while non-human components are generally aimed at problem solving functions, human components mostly act as providers of feedback in order to establish connection between the system performance and the system goal, shaping its behaviour and determining its agency. Degree of actors' autonomy or freedom within a system relies on the system complexity and goal and differs from on case to another. (Wiebe E. Bijker, 1989)

4. Case studies

4.1. INTERACTIVE ADA SPACE, SWISS NATIONAL EXHIBITION EXPO02, 2002

Interaction mechanism has three main modes:

Exploration mode

As an individual enters the playground they are introduced to the system, they both learn rules of communication. The system understands the degree of responsiveness and the user learns how to play, trying different moves and actions

and seeing how the playground responds. For example a jump means changing the colour of tracing light, waving hands means changing the figure on the screen, joining another user and running together results in special effect projecting om the playground and assigned figures on the screen start communicating, etc. Meanwhile the system analyses the responsiveness of users and cues them or persuades them to move and engage in a game by introducing visual effects on the playground.

Play mode

When rules of the game are learnt users can follow the cues from the playground and create their own scenarios reflected on the screen. They all act individually and watch the changes on the screen caused by their movement. They can choose to interact with other users and see how it is reflected on the screen. The playground encourages active behaviour by projecting special rewarding visual effects to those who follow the cues and react faster.

Group or story telling mode

After individual activities users get introduced to a new interaction scenario when they are able to create new shapes on the screen by moving in groups. Users now communicate not only with playground but with each other as well in order to make the figures on the screen move. The playground provides hints on new/unexplored actions to be performed so that the users in groups are always engaged and discover something new/interesting for them.

4.2. ELECTROLAND - ENTERACTIVE, LOS ANGELES, CALIFORNIA, 2006

The project demonstrates a link between two remote spaces and how can the action taken in one environment alter performance of component in different location. The project integrates interaction between people and the city. An interactive playground constituted of tiles with LED lights senses visitors and displays interactive light patterns in response. LED lights on the building facade display the same light patterns that are on the interactive playground in real time. Environmental intelligence and surveillance of human activity are combined with a video-game sensibility.

4.3. IDVA GALLERY, BROOKLYN, NEW YORK, 2015

The project was designed as a virtual model yet can be feasible using a system of actuators and motors. IDVA gallery is conceptual project designed to host Virtual Art Exhibitions and Interactive Design Installations. The project site is located in Brooklyn, New York at the end of Brooklyn Bridge Park Pier 3 where the museum has a great view toward the Manhattan Skyline and also has clear visibility from downtown Manhattan. The waterfront pier which has been heavily activated central areas for transportation and manufacturing in the past has significant meanings in that it symbolizes the transforming social paradigm and urban structure. The gallery is programmed to have flexible space usage utilizing operable wall panels and ceiling grids to adapt to diverse spatial formations and activities. Each wall panel and ceiling grid has diverse formations

pre-programmed into the system which can be flexible and interactive during the exhibition hours. Open Plans will be provided for Virtual Exhibitions where viewers can utilize headset VR monitors with motion & position tracking devices to view the digital exhibits while walking around into the space. For the given project, one pre-animated single formation is assigned to each unit with which can be activated while the viewer enters and stays within the preset trigger zone. Due to the size of the data for this virtual model, limit the formations to one per unit was tested for the model, however there are future potentials to add more diverse pre-animated spatial scenarios to each wall panel. This can be rearranged to fit the given conditions for the exhibition.

5. Behaviour of interactive space

Within the discourse of this research behavioural design is introduced as design able to handle various users' needs throughout time and their feelings that adjust to the lifestyle and the way they use this space, demonstrating awareness of the social structure of their communications, a dynamic movement together in time. It includes behavioural considerations in the design of communication with the architecture as a facilitator of the human behaviour or vice versa.

According to Combs and Brown (Digital Behavioural Design) behavioural design works best when it's ethically-aligned with three criteria: transparency, social good and users' desires and is considered as a set of techniques for persuasion that respects person's intrinsic rights to freedom of choice, autonomy and dignity.

According to Ramsey and Combs, human habit system is a set of learned behaviours (default actions) that are performed unconsciously. Considering a habit is a learned behaviour, the designers could control the consequences of user behaviours via CAR Model.

Cue → Action → Rewards (CAR) Model is a proven design framework for inducing user habits that drive continued engagement and retention.

A user senses the cue in their environment that they can learn to associate with an action (behaviour), which leads to a reward (consequence). A behavioural designer knows how to intentionally construct synthetic cues to induce a particular action.

6. Learning mechanism

Three main types of rewards are used to delight users, including Rewards of the self (desire for self-mastery & proficiency), Rewards of the Hunt (desire for conquest), and Rewards of the Tribe (desire for belonging). (Kong, 2018)

How can interactive space learn to influence users' behaviour? By using learning mechanism (such as distributed adaptive control) smart environments can learn effective cues to influence users' behaviour and guide them through space and set preferred directions. Truly interactive intelligent space incorporates a bi-directional symbiotic approach to human-environment communication, being able to affect users' behaviour as well as be affected.

The research aims to explain:

Language of communication between environment and users

Instead of using gesture or voice based language it could use non-verbal language of ambience alteration like sound and light as output and tracking as input. These means of communication are used in order to avoid antropomorphization of the space as it would happen with utilizing language-based features like spoken or written words.

"Intelligence" in this context refers to the perception of space as the defining capacity of users, but it is the smart ability that is now extended in its efficacy by the sensibilities of affect. Figuring the Human in Intelligent Space relates to, arises from, or deliberately influences emotions.

Users are naturally active learners and explorers if they have a proper motivation. The major part of interactive space behaviour depends on users' performance or other external stimuli. Interactive environment can provide cues for visitors on how to act within it, a target to move towards, possible routes, options of space use. The space tracks users and assesses their responsiveness to cues from the space, learning how to communicate effectively. In case of distributed adaptive control (DAC) the learning scheme is based on two simple rules of trial and error learning: if something works, do it again; otherwise try something else at random.

Affective design

Affective refers to emotional, but may, perhaps usefully, be confused with effective. Emotion is another component, then, needed for effective rationality. More generally, discourses of affective computing evidence some shared starting assumptions: "Affect" comprises a distinguishable domain of cognition that can be analysed into universal, component parts. Affect is the expression of an underlying emotional "state." Affective interaction can be achieved through the replication of behaviours understood to comprise it, made up of units assembled into a catalogue of affective expressions, productions, recognitions, and normative responses. Emotional states and their affective expression can be understood in terms of their (evolutionary) utility, as a kind of primal but still functional ancestor of contemporary reason. (Suchman, 2007)

7. Interactive space and social relationship

Built space has to be linked to other environments, analogue as well as digital. For instance, the building is crossed with another location. Interestingly, the aesthetic experience may be collective as well as individual. By implementing multimedia approach and designing a new type of interface that offers selective worthwhile exchange, the new type of spatial extensibility into another dimension. Architecture now accommodates not just static construction components, but moving situations.

In connection with other systems' networks, architecture becomes reprogrammable in meaning that the built space gain ability to play an important cultural and social role throughout longer period within their life cycle. Ability

to be updated is not a question of adaptation to new functions anymore, but the essential component in architectonic performance of static object.

The architecture now can reflect the social performance in multiple ways:

- it can change its shape according to users desire
- it can adapt itself to different types of activities
- it can be linked to remote device or other environment (virtual or physical)
- it can become a possible modality of Network activity

With these new abilities architecture now can be updated in order to communicate with the society on qualitatively new level. Architecture becomes a form of time transmission. This time can be filled with any content desired, so the architecture now offers not just the space, but also the time and the information. "The result is the rise of Digital Gothic", as Kas Oosterhuis puts it.

8. Conclusion

Interactive environment that triggers various senses is proven to be immersive and stimulate further communication. Using unique space qualities and tangible means of interactive behavior users can be guided through space and engaged into various activities as the part of communication with the space. Users are invited to explore the space and what it does, they are offered to perform certain tasks in order to continue this communication and during this process they can be brought through different modes of space cognition requiring their active or passive participation in this dialogue.

Interaction of users and interactive space is usually considered on individual level and targeted on communication of one person with the space. Within the context of this research environment architecture communicates not only with individuals but with groups of people becoming a part of their social relationship. Both individuals and groups of people can be considered as actors of one network depending on the mode of interaction and its' final goal.

Space without interactive qualities was always a facilitator of communication between people providing a background for their relationship and letting them to pass through it, accommodating them and serving a certain function.

Interactive properties allow the space to take part in social relationship, becoming a part of it and being the driving force of their communication with each other within the space and with the space itself. Interactive space does not only provide unique experience but can also create situations engaging users and groups of users in common activities, requiring them to act independently or in groups. Space and users communicate in real time, defining further modes of this interaction and shaping the experience.

Interactive behavior has multiple qualities that assigns it as the new type of built environment such as ability to communicate with users providing unique space experience. Comparative analysis includes exploring how interactive environment can understand users and interact with them providing immersion into this communication and committing to its' rules. It refers to learning mechanisms

of interactive space on one hand and implementation of this information in defining its' behaviour on the other hand. It refers to affective design and focuses on building the most comprehensive engagement of users and space, learning their behaviour patterns and utilizing this analysis to foster communication. The space acts as alive being and it invites users to communicate, observing their response and changing its' performance accordingly.

In behaviouristic perspective interactive space can has various modes of communication determined by its function and position within the network of human and non-human actors. It depends on the rules of communication and heavily relies on response of the users and their desired degree of engagement. The ultimate goal of this interaction is to provide certain experience while allowing all users to feel comfortable within it and communicate, therefore continuous analysis of users behaviour allows the building to understand them and create beneficial and pleasant relationship.

Acknowledgments

This work was supported by the PhD scholarship of the University of Queensland, School of Architecture, Faculty of Engineering, Architecture and Information Technology, Brisbane, Australia

Special gratitude to Dr. Fred Fialho Leandro Alves Teixeira.

References

M. Alexenberg (ed.): 2011, *The Future of Art in a Postdigital Age: From Hellenistic to Hebraic Consciousness*, Intellect Books/University of Chicago Press, Chicago.

W.E. Bijker, T.P. Hughes and T.J. Pinch (eds.): 1989, *The Social Construction of Technological Systems New Directions in the Sociology and History of Technology*, The MIT Press , Cambridge, Massachusetts .

Boychenko, K.: 2017, Interactive Architecture: development and implementation into the built environment, *European Journal of Technology and Design*, **5**, 20-25.

Boychenko, K.: 2017a, Edutainment in Interactive Environment Framework, *Science, Technology and Education*, **5**, 101-105.

Brown, G. and Kronnenberg, R.: 2003, *Transportable Environments 2*, Spon Press, London.

Cohen, M.: 1998, Design Principles for intelligent Environments, *Proceedings of the Fifteens National Conference on Artificial intelligence*.

Iishi Hiroshi, U.B.: 1997, Tangible Bits: Towards Seamless Interfaces between people, bits and Atoms, *ACM CHI 97 Human Factors in Computing System Conferrence March 22-27*, Atlanta, Georgia, 234-241.

Kong, J.: 2018, "What is behavioural design" . Available from <https://uxplanet.org/what-is-behavioural-design-8d2790a9d624> (accessed September 2018).

Mahdalickova, E.: 2009, New Experiences Of The Body Through Space, *Implications philosophiques*, **L'habitat, un monde à l'échelle humaine**, 1-2.

Mancilla, R.G.: 2011, Introduction to Sociocybernetics (Part 1):Third Order Cybernetics and a Basic Framework for Society, *Journal of Sociocybernetics*, **9**, 35-56.

Oosterhuis, K.: 2003, *Toward an E-motive Architecture*, Testo & Immagine, Turin.

Salingaros, N.A.: 2004, Towards a Biological Understanding of Architecture and Urbanism: Lessons from Stephen Pinker, *Katarxis*, **3**, 1.

L. Suchman (ed.): 2007, *Human–Machine Reconfigurations: Plans and Situated Actions, 2nd Edition.*, Cambridge University Press, New York.

E. Weibe and T.P.H.T.J.P. Bijker (eds.): 1989, *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, Massachusetts & London: MIT Press,, Cambridge.

DESIGNING FOR SHAPE CHANGE

A Case study on 3D Printing Composite Materials for Responsive Architectures

ELENA VAZQUEZ[1], BENAY GURSOY[2] and JOSE DUARTE[3]
[1,2,3]*The Pennsylvania State University*
[1,2,3]*{emv10|bug61|jxp400}@psu.edu*

Abstract. This paper presents the initial stages of a research that aims to develop hydroactive architectural skin systems that respond to environmental humidity. As part of this study, we have developed wood-based bio-composite materials that are 3D printed with wood filament. Shape-changing behavior is not predictable in advance. We developed customized 3D printing protocols to systematically study shape-changing behavior. The paper presents this systematic material study and the prototypes that we have developed.

Keywords. Smart materials; responsive architecture; 3D printing; material computation.

1. Introduction

Smart materials are designed to adapt and transform in response to environmental stimulus, reversibly altering their properties. They can act as sensors, actuators, and regulators at the same time, without the need for any additional energy for mechanical or electronic control. In shape-changing smart materials, a stimulus (i.e. heat, water) causes a strain in the material, thus changing its shape. Over the past years, architects have become increasingly interested in smart materials, envisioning lighter, more efficient and adaptable systems. Researchers argue that these materials can be built into responsive building systems to achieve improved performance through their actuation capabilities in response to shifting environmental conditions (Juaristi et al. 2018). This opens up a new conceptual and practical framework for architects to design "truly environmentally responsive" architectural systems (Kretzer 2016).

Incorporating shape-changing materials in the design process, however, has several challenges. The dominant ontological and epistemological frameworks in design usually rely on final products, as opposed to processes of material formation. Designing with shape-changing materials, on the other hand, is designing with the flows and transformations of materials. As pointed out by Kennedy (2018), shape-changing transformations take place over time and the behavior is usually unpredictable in advance. The unpredictability can give way to unexpected discoveries and emergent material outcomes. As designers, in addition to quantifiable properties that are more suitable for exact simulations, we are

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 391-400. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

interested in sensory aspects that can be discovered through material engagement, such as emergent visual (forms, shapes and textures), and tactile qualities. The question, then, is how to design with this dynamic behavior, and how to have control over it?

In this study, we intend to develop methodologies for designing for shape-change, and propose ways in which a material-based approach can facilitate the knowledge transfer of shape-changing materials into design fields. We present the initial stages of a research to develop a hydroactive architectural skin system that responds to the relative humidity in the environment. As part of this study, we have developed wood-based bio-composite materials by 3D printing with a special wood filament that is humidity-sensitive. We customized the 3D printing protocols in order to explore the shape-changing behavior. The shape-changing behavior is not predictable in advance since the transformation mechanics is defined by the geometry and printing settings. A systematic material exploration is required to have control over this behavior. The section below provides a background on bilayer materials in shape changing systems. Afterward, we present a systematic material exploration studying the shape-changing behavior of bilayer composite materials developed through 3D printing. Finally, we discuss the early prototypes of an architectural skin system.

2. 3D Printing Bilayer Composite Materials

2.1. BACKGROUND ON BILAYER COMPOSITE MATERIALS IN SHAPE-CHANGING SYSTEMS

Wood, being a natural fiber-reinforced composite, presents hygroscopic properties. There is a considerable amount of studies that explore the use of wood to construct shape-changing systems, including biomimetic building skin designs (Reichert et al., 2014), and wood-based bio-composites used for actuation purposes (Le Duigou et al. 2016). One strategy for leveraging wood's hygroscopic properties is the use of the bilayer principle. In a bilayer configuration, two tightly bonded layers that have different swelling coefficients present a bending response when activated with humidity or water. Previous studies have used this principle to create, for instance, autonomous shading devices (Vailati et al. 2018) and large-scale material explorations (Wood et al. 2018). In these studies, manipulating the orientation of wood-fibers in the bilayer system leads to a designed shape-change.

A similar strategy for creating shape-changing bilayer composites relies on additive manufacturing. The precise control over the tool path geometry and printing settings allows for embedding localized anisotropic behaviors into composite materials and lead to shape-change. This strategy has been explored in manufacturing shape-changing systems using different materials, including hydrogels (Gladman et al. 2016), and thermoplastics (An et al. 2018). In the case of wood-based composites, 3D printing enables the design of specific patterns for layers that lead to differential swelling and then to shape-change. In a recent study, Correa et al. (2015) explore creating multi-material wood-based composites by 3D printing with wood filament and non-humidity responsive polymers, such as ABS and nylon. They developed custom tool paths to 3D print controlled patterns and

embed anisotropic behaviour into wood-based composite materials.

2.2. CASE STUDIES

Building on this existing body of work, we developed methodologies to program shape-change using 3D printing, and discuss the mechanisms for controlling the shape-changing behaviour. In this section, we present case-studies where we explore the shape-changing behavior of bilayered composite materials that we have developed through 3D printing: 1) a preliminary study to understand the principles of 3D printing bilayered thermoactive composite materials using PLA, 2) a study on 3D printing bilayered hydroactive composite materials using a wood-based filament that is humidity sensitive. In both cases, in order to have control over the shape-changing behavior, we pursued a systematic material exploration where we defined the parameters and explored their implications on the process, and the product systematically and comparatively. Figure 1 presents the framework of this material exploration under three main categories: digital model, printing, and activation.

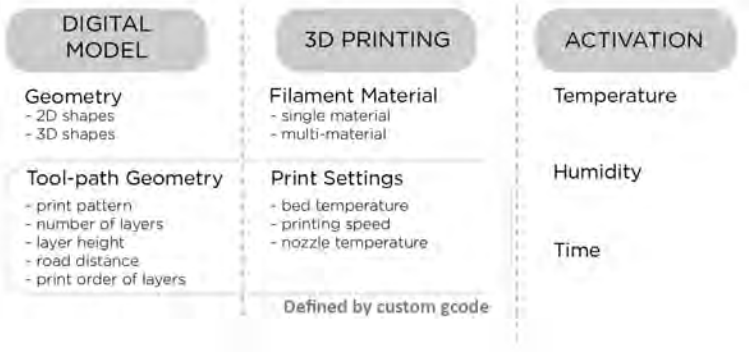


Figure 1. The framework for systematic explorations in 3D printing bilayer composite materials.

The digital input parameters include the base geometry of the object to be 3D printed, and parameters for the custom gcode design. Customizing the gcode enables having control over the tool path that the 3D printer nozzle follows, hence defining the print pattern. Controlling the tool path is especially crucial in this study as the print patterns define the *fiber orientations* and directly affect the shape-changing behavior. We have used *Silkworm* (a plugin for Grasshopper in Rhino) to customize gcodes for 3D printing. Additional parameters that we have identified related to the tool path geometry are the total number of print layers, layer height, the order in which *active* and *constraint layers* are printed in the bilayer configuration, and the road distance which controls the porosity of the 3D printed objects. The 3D printing settings that we control also through custom gcode include bed and nozzle temperatures and the 3D printing speeds. Another parameter that is in play while 3D printing is the filaments used, and whether the objects are printed using a single material or with multiple materials. The

two *activators* for the 3D printed bilayer composite materials are temperature for thermoactive composites, and humidity for hydroactive composites. The duration in which the 3D printed samples are exposed to these *activators* also defines the shape-changing behavior.

2.2.1. 3D printing thermoactive bilayer composite materials with PLA

In the preliminary study, we explored 3D printing bilayer composite materials using a single material, PLA, by changing print patterns from one layer to the next. PLA is a shape-memory polymer that, when printed, high temperatures during extrusion cause alignment and stretching of the polymer chains along the direction of extrusion (Van Manen et al., 2017). The rapid cooling of the polymer filament fixes the temporary shape, and the application of heat triggers the return of the chains to the original unstretched state. This directional strain that PLA parts exhibit is the material principle that enables shape-change.

For the first set of explorations, the base geometries are defined as rectangles of 3 different dimensions: 55 x 55 mm, 85 x 55 mm, and 115 x 55 mm. Figure 2 shows a summary of our material explorations. In order to produce bilayer composites with a single material, the tool path geometry is designed by adjusting printing patterns per layer to create a differential expansion between layers. The total number of printed layers (4), layer height (0.35mm), road distance (0.70mm), bed temperature (25°C) and nozzle temperature (215°C), as well as the printing speed (1500 mm/min) are kept constant while exploring with different geometries. Following the work by An et al. (2018), we immersed the 3D printed composite materials in hot water (80 °C) for the duration of 2 minutes to *activate* the shape-change.

The distribution of *constraint layers* (CL) and *active layers* (AL) in the bilayer configuration considerably affect the shape-change. As can be seen in Figure 2, the sample shown in Figure 2-D and and the sample shown in Figure 2-F have the same base geometry (rectangles of 85x55mm) and total number of layers (4). While in the sample in Figure 2-D all the four layers are printed with the same angle (90°), in the sample shown in Figure 2-F, the first three layers are printed with the same angle (90°), and the last layer is printed with a different angle (0°). This last layer acts as a constraint layer when immersed in hot water that triggers the shape-change. The active layers, on the other hand, define the main direction of curvature as it shrinks along the direction of the print pattern longitudinally when heated. Since the sample in Figure 2-D does not have a constraint layer, when heated the entire geometry is affected by thermal expansion and does not bend. The proportions (length to width ratio) of the printed samples also affect the bending angle, as also noted by (An et al. 2018). The bending angle increases as the length of the rectangles increase, while the width is kept constant. The comparison of samples shown in Figure 2-E and 2-F highlights how the length of the rectangles affects the curvature angle when the direction of the print pattern is aligned with the long edge. Also, varying the printing angles with reference to the main geometry leads to complex geometries when activated. The samples shown in Figure 2-B and 2-C have different angles, and when activated one presents a simple single curved shape and the other a hyperbolic paraboloid, respectively.

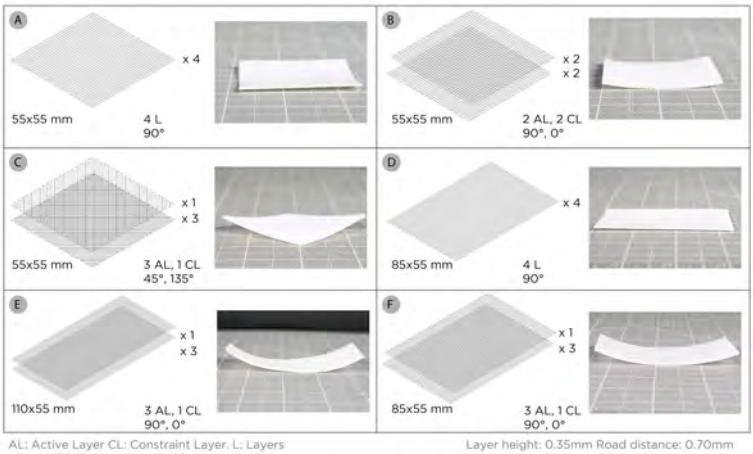


Figure 2. Six 3D printed bilayer composite samples of PLA with varying tool path geometry and their response to being immersed in hot water.

2.2.2. 3D printing hydroactive bilayer composite materials with wood filament

The first set of explorations using PLA set a basis for the next set of explorations on 3D printing bilayer wood-based composite materials. This section describes the second set of explorations using a commercially available wood filament under the name of *Laywood*. As mentioned in Correa et al. (2015), wood filaments are developed by combining different polymers with micro-scale wood fibers. Since the wood fibers remain hygroscopically active, the 3D printed objects swell or shrink in response to humidity changes. As specified by the manufacturer of *Laywood*, the material composition of *Laywood* has 40wt% wood fibre, and the objects that are 3D printed with *Laywood* can present an elongation rate of 106% when exposed to higher levels of humidity.

In this second set of explorations with *Laywood*, the base geometries are defined as isosceles triangles with a base and height of 55mm. The triangular geometry is kept constant in each sample. Total number of printed layers (4), layer height (0.35mm), bed temperature (25°C) and nozzle temperature (240°C), as well as the printing speed (1500 mm/min) are also kept constant. This time, we focused on exploring the effects of various print patterns (print angles) and road distances (porosity) on the final shape of the activated samples. All the samples have 3 active layers (AL) and one constraint layer (CL) as can be seen in Figure 3. The number of AL and CL are defined according to the previous study where we observed more bending with the 3 AL-1 CL configuration. The samples A and D; B and E; and C and F have the same print angles on the active and constraint layers: 45°/135° ; 60°/150°; and 90°/180° respectively with reference to the symmetry axis of the isosceles triangles. While the samples A, B, and C have a road distance of 1.5 mm, the samples D, E and F have a road distance of 1 mm. This makes the samples A, B, and C more porous when 3D printed.

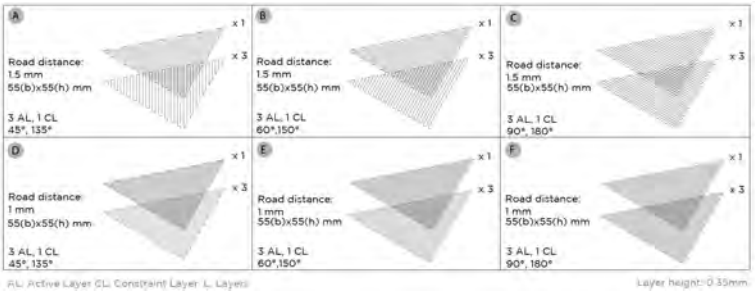


Figure 3. Toolpaths of six bilayer composite samples to be printed with wood filament.

We built a humidity chamber in order to create a controlled environment to document and capture the shape-change in the samples. We kept the temperature within the humidity chamber constant while increasing the relative humidity levels up to 100%. We used an ultrasonic cool mist humidifier for this purpose and periodically captured the shape-changes in the samples. Duration of exposure to the stimulus (i.e. heat, humidity) is a significant parameter affecting the shape-change. While with the previous set of explorations with PLA, the response of the samples to heat change was almost instant and the samples usually reached their final forms in about 2 minutes, the wood-based composites required longer exposure times to high levels of humidity. Even when the humidity levels within the humidity chamber reached the peak point, the shapes of the samples kept changing as long as the the samples were exposed to humidity. Figure 4 shows the shape-changes in the 3D printed samples with 10 minute intervals for a total duration of 40 minutes.

As can be seen in Figure 4, the change in road distance, hence porosity, considerably affects the shape-changing behavior. All the parameters for samples A and D are the same except road distance: sample A is more porous than sample D. Under same relative humidity levels, and over the same duration, the shape-change in sample A is more drastic than the shape-change in sample D. This is also true for samples C and F: sample C is more porous than sample F, and the transformation is more remarkable. On the other hand, no significant shape-change is observed in sample B. We speculate that this is due to an unexpected outcome of 3D printing: the initial print layers melted more than predicted on the heat bed and resulted in thicker lines in the print pattern. This prevented sample B to bend. As we have mentioned as part of the previous set of explorations with PLA, even though the base geometry is the same, different print patterns (print angles) result in different shapes when the samples are activated. The samples extend in the direction following the print angle of the active layer, and the print angle of the constraint layer defines the bending direction. The effect of print angles on the shape-change of the activated samples can be observed when samples D, E, and F are compared. Also, in the first set of explorations with PLA, the shape-change was not reversible once activated, whereas in this second set of explorations with wood filament the shape-change is partially reversible, mainly due to “mechano-sorptive degradation” as noted by Le Duigou et al. (2016).

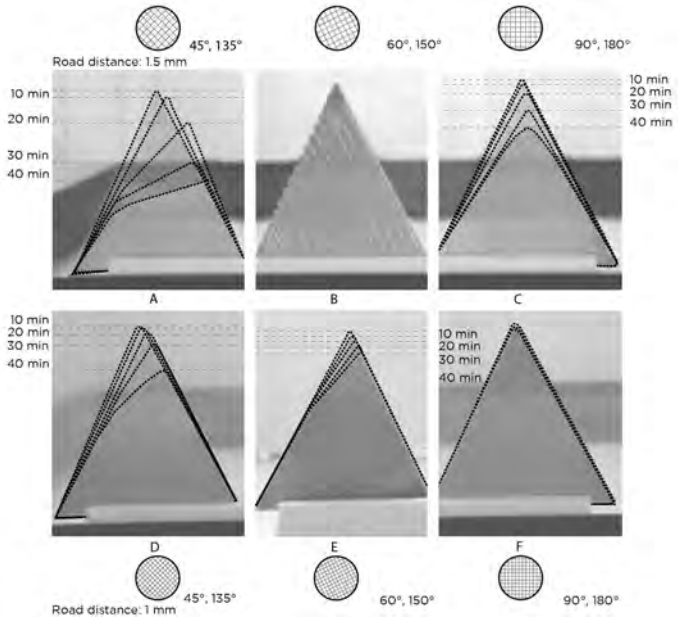


Figure 4. The shape changes of the six bilayer wood-based bio composite samples with 10 minute intervals for a total duration of 40 minutes.

2.3. INITIAL PROTOTYPES FOR HYDROACTIVE ARCHITECTURAL SKIN SYSTEMS

This section describes the initial prototypes that we developed for a hydroactive architectural skin system that responds to the relative humidity in the environment. Building upon the set of experiments described in the previous section, we designed the tool paths and customized the 3D printing settings to fabricate the prototypes. Through the previous set of explorations, we have discovered that the print patterns (print angles) and porosity significantly affect the shape-change. Porosity is defined by road distance, and, as pointed out previously, the more porous the sample, the more rapidly it changes shape when exposed to high levels of humidity. Print angle, on the other hand, defines the bending behavior and the final *activated* shape. Playing with these two parameters, we designed simple 175 x 75mm prototypes by combining multiple triangles that have the same dimensions as the previous samples on a tessellated surface. The main idea here is to test how various shape-changing pieces interact within a system. Figure 5 illustrates the two prototypes designed (A and B) and the definition of the toolpath geometry. The five triangles shown in the figure are inscribed in a frame. The frame and the triangles have different levels of porosity: while the triangles are intended to change their shape, the frame would be less affected by humidity; while the triangles are more transparent, the frame would be opaque. Similar to the previous samples, the triangles in the system have 3 active layers and one constraint layer. The frame, on the other hand, has 4 layers printed in 0°- 90°- 0°- 90° angle

order. The layer order of the frame is intended to generate a more isotropic condition with interlocking layers. The triangles, on the other hand, are printed in 90°(AL)-180°(CL) angles for prototype A, and 45°(AL)-135°(CL) angles for prototype B.

Prototypes are then placed in the humidity chamber. For prototype A, we captured images every 10 minutes to record the shape-change as can be seen in Figure 6-A. The shape-changing of the prototype is more noticeable from a perspective view, therefore we registered from that viewpoint. The entire prototype significantly deforms from minute 70 onwards, causing both the frame and triangles to bend. This indicates that other non-humidity responsive materials should come into play while 3D printing the static parts that can serve as the frame.

As indicated previously, the shape-change within a hydroactive system occurs over time. With prototype A, we have captured shape-change over a period of approximately 70 minutes. However, in most cases, the transformation continues when the samples are kept in the humidity chamber. To assess how the samples keep changing shape over hours instead of minutes, we recorded shape-change of prototype B over a period of 7 hours. Figure 6-B shows the shape-change of prototype B on intervals of 2 hours. The shape-change is significantly more substantial this time. One challenge with prototype B is that when the triangles bend, they collide with the frame and with each other because the bending direction is defined by the printing angle. In prototype B, the triangles have a 45-135° printing angle, therefore the triangles bend asymmetrically to the side. This indicates the need for developing a simulation tool that allows to visualize the transformations over time, to prevent the pieces of a system to collide due to shape-change. As discussed previously, the shape-change is partially reversible when the humidity levels decrease. Figure 6-A also presents the reverse change that take place over 40 minutes.

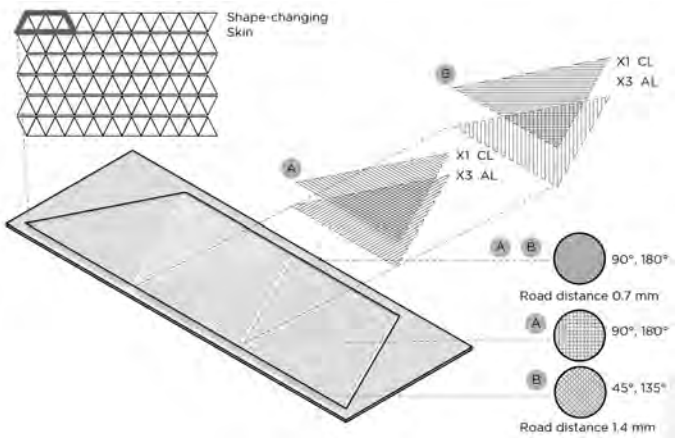


Figure 5. Prototype design for a hydroactive architectural skin.

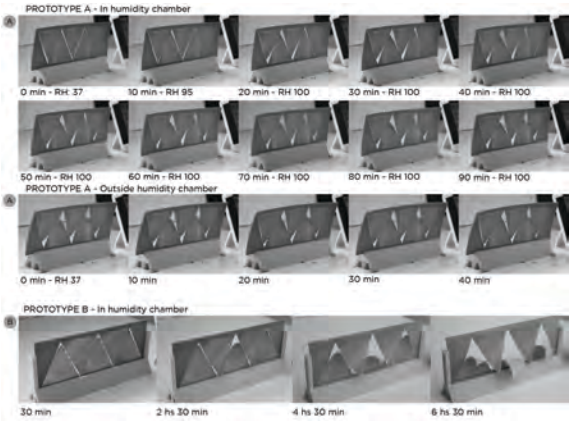


Figure 6. A) The shape-changes of the Prototype A with 10 minute intervals, B) The shape-changes of Prototype B with 2 hours intervals.

2.3.1. Results and Discussion

The studies highlight the direct connection between tool path geometry and shape-change. 3D printing enables the creation of anisotropic conditions within the bilayer composite materials thus leading to shape-change. By developing software to design the tool path and customizing the gcode, we are able to program and control the direction of bending within the structures. The use of 3D printing as the fabrication method also enables to rethink the design of shape-changing structures. Rather than rebuilding common wood veneer sheets, through 3D printing, we can modify the level of porosity of the printed samples, and use this as a strategy to control both the shape-changing behavior. Further, we can use the parameters identified in this study such as porosity and layer count to design and control transparency in architectural skins. 3D printing also could enable the creation of more complex geometries than other approaches using wood veneer to fabricate architectural skin system. For instance, a multi-step folding could be explored in future studies using the described strategies for controlling shape-change. Finally, when the prototypes are printed using a single material, the whole prototype is affected by humidity over time and gets deformed. A multi-material approach where humidity-responsive materials are used together with non-humidity-responsive materials, similar to the study by Correa et al. (2015) will be explored to solve this issue in future prototypes.

3. Conclusion

This paper is part of a research agenda to explore how to design for the dynamic behaviour of shape-changing materials. While arguing for the need to develop methodologies for designing for shape-change, we propose ways in which a material-based approach can facilitate the knowledge transfer of shape-changing materials into design fields. Our ultimate goal in this research is to design hydroactive architectural skin systems by 3D printing bilayer composite

materials that respond to environmental humidity. This paper reports the early prototypes developed towards that goal, and presents a systematic, bottom-up material-based exploration. The approach presented in this paper differs from other studies for developing responsive materials in that it is centered in how design decisions condition the dynamic behavior of shape-changing architectures. In the explorations conducted, design decisions orchestrate the interdependence between geometry -from tool path to overall form-, 3d printing settings, and time, as the added dimension in the design process. Time, in this study represents shape transformation, and we argue that a systematic material exploration and computation brings us one step closer to controlling this dynamic behavior in designing for shape-change.

We postulate that once the shape-changing behavior is formalized through systematic material explorations, material intelligence can be embedded in parametric computer models. This constitutes a next stage in this research, and can enable us to explore design variations in the computer prior to materialization. It will also allow us to create computer simulations to assess the performance of the architectural skin designs in controlling air flow, daylight and interior temperature.

References

An, B., Tao, Y., Gu, J., Cheng, T., Chen, X., Zhang, X., Zhao, W., Do, Y., Takahashi, S., Wu, H.Y., Zhang, T. and Lining, Y.: 2018, Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces, *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*.

Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Reichert, S., Menges, A. and Tibbits, S.: 2015, 3D-Printed Wood: Programming Hygroscopic Material Transformations, *3D Printing and Additive Manufacturing 2*, **2**, 106-116.

Le Duigou, A., Castro, M., Bevan, R. and Martin, N.: 2016, 3D printing of wood fibre biocomposites: From mechanical to actuation functionality, *Materials and Design*, **96**, 106-114.

Gladman, A.S., Matsumoto, E.A., Nuzzo, R.G., Mahadevan, L. and Lewis, J.A.: 2016, Biomimetic 4D printing, *Nature materials*, **15**, 413-419.

Kennedy, S. 2011, Responsive Materials, *in* S.c.h.r.öp.f.e.r. T (ed.), *Material Design*, DE GRUYTER, Basel, 118-131.

Kretzer, M.: 2016, *Information Materials: Smart Materials for Adaptive Architecture*, Springer.

Van Manen, T., Janbaz, S. and Zadpoor, A.A.: 2017, Programming 2D/3D shape-shifting with hobbyist 3D printers, *Materials Horizons*, **4**, 1064-1069.

Menges, A. and Reichert, S.: 2012, Material Capacity: Embedded Responsiveness, *Architectural Design*, **82**, 52-59.

Miren, J., Gómez-Acebo, T. and Monge-Barrio, A.: 2018, Qualitative Analysis of Promising Materials and Technologies for the Design and Evaluation of Climate Adaptive Opaque Façades, *Building and Environment*, **144**, 482–501.

Reichert, S., Menges, A. and Correa, D.: 2014, Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness, *CAD Computer Aided Design*, **60**, 50-69.

Vailati, C., Bachtiar, E., Hass, P., Burgert, I. and Rüggeberg, M.: 2017, An Autonomous Shading System Based on Coupled Wood Bilayer Elements, *Energy and Buildings*, **158**, 1013-1022.

Wood, D., Vailati, C., Menges, A. and Rüggeberg, M.: 2018, Hygroscopically Actuated Wood Elements for Weather Responsive and Self-Forming Building Parts – Facilitating Upscaling and Complex Shape Changes, *Construction and Building Materials*, **165**, 782–791.

DATA INFORMED BRANCH TYPOLOGIES FOR STRUCTURALLY OPTIMISED CURVILINEAR SURFACES

3D Printed Mesh Density System (MDS) as Formwork for Concrete Shell Structures.

MARYAM HOUDA[1] and DANIEL DIAS-DA-COSTA[2]
[1,2]*University of Sydney, Australia*
[1,2]*{maryam.houda|daniel.diasdacosta}@sydney.edu.au*

Abstract. This research sheds light on the advancement of additive fabrication and its relevance to the construction of curvilinear surfaces. The Mesh Density System (MDS) explored in this paper, is a novel 3D printed dual formwork and reinforcement system for free-form complex concrete geometries. It offers an alternate method to current formwork systems, essentially for thin shell structures. By using multi-cellular distribution and optimised branch structural arrangements, the system optimises form and concrete flow.

Keywords. Additive Fabrication; Concrete Shells; Evolutionary Algorithms; Permanent Formwork; Structural Optimisation.

1. Introduction: Structural Patterns

The tree leaf, the most common found shell-form in nature, span outwards to obtain energy from the sun simultaneously providing shade below (McMillen & McClendon, 1979). Such behaviour found in nature has been transmitted as fundamental structural lessons for shell construction, where the key geometric principle of these structures is their long-spanning curvatures providing both strength and stiffness (Calladine, 1983). A vast number of existing shell structures have been built using concrete since the Pantheon, 126 AD, and reinforced concrete as a successor for thin-shell forms, namely the work of Candelas from the 1950's as significant construction feats. A decreased appearance of these shell structures however, has been linked to the high costs and erection times of formworks and falsework (Huijben et al., 2011). The revival of these forms can arise from a collaborative approach between the designer and builder to not only resolve costs, but also to reintroduce shells as a viable structural solution (Meyer & Sheer, 2005) that can span space using a singular surface.

In recent years, interests in shell structures and advancements in digital fabrication technologies (Asprone et al., 2018) have led to increased studies in developing dual formwork-reinforcement systems, aiming to relieve customised formwork from complex assembly processes and associated costs. Innovative large-scale 3D printing techniques using grid-like structural patterns have been

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 401-410. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

used in projects for double-curved concrete geometries as seen in Mesh Mould, ETH; prototypical research into fiber composite surface moulds for concrete casting in the NGV Pavilion, 2016; and dense lattice structures in the Flotsam and Jetsam pavilion by SHoP Architects and Branch Technologies (Daas & Wit, 2018). While these have renewed interest in curvilinear forms, there are yet to be significant research findings on the behavioural relationship between permanent formworks and concrete and geometric optimisation in terms of the distribution and angle arrangement of grid-pattern formworks for shell structures.

2. Methodology

This paper investigates the development of a novel branch and node structural system, titled 'Mesh Density System' (MDS), for the application of a 3D printed dual formwork-reinforcement system for concrete shell structures. The paper extends research on 3D printing data informed branch patterns derived from a multi-cellular distribution of Voronoi cells, for structurally optimising curvilinear geometries (Houda & Reinhardt, 2018). With a custom-designed shell as the overall geometry, this paper extracts two surfaces in a test cube arrangement for a micro-pattern analysis for the larger shell geometry.

A simultaneous process of digital design and simulated FEA analysis is carried out to achieve optimal structural performance, and an appropriate cell and branch distribution for ideal concrete flow and containment within the porous mesh density. The research tests the capacity of the formwork system to work as reinforcement using a suitable thermoplastic to resist tensile stresses, as well as contain a concrete mixture with appropriate viscosity to bond with the reinforcement and resist stresses developing after hardening for a structurally optimal curvilinear form. Various geometric outcomes are explored in a series of experiments varying in cell distribution and branch pattern criteria to achieve optimal arrangements of 45-degree branch angles using evolutionary algorithms.

The novel system outlined in this paper is part of ongoing research towards an alternative application to current formwork methods for complex concrete shell structures. It explores optimised branch typologies for improved structural performance of a permanent thermoplastic formwork system. Future work will explore the robotic extrusion of fiber-reinforced polymers for large-scale deployment. This will anticipate behavioural simulations of different structural moments of the global shell, determining multi-scalar cell distribution for a varied branch pattern arrangement, and varying shell thickness and branch angles relative to concrete thrusts for large-scale 3D printing.

3. Mesh Density System (MDS)

3.1. CELL DENSITY ARRANGEMENT

The MDS formwork system is experimented at a test cube scale to investigate cellular strategies relative to the performance of a fluid material. As a permanent, porous skeleton module, it varies in surface cellularity to accommodate for the viscosity of concrete, the ability to retain liquid to semi-solid liquid, and to relieve hydrostatic pressure.

The surface is proportionally zoned in the u-direction at a ratio of 1:20 of the u-distance, and divided in the v-direction in three equally sized zones: high density, medium density and low density in an upward progression. Each zone is populated with a certain amount of cell points for functional cellularity. The test cube scenario discussed in this paper, consists of six vertical rows, where the two outer rows have double the amount of cell points than the inner rows. Increased densities retains concrete towards the edges of the test cube working as stop-ends to relieve built up pressure. Each original cell creates a branch, where having extra cells towards the edges allows for easier concrete flow as branch density is reduced towards the core of the geometry.

The repopulation of points to the test cube specimen was necessary due to the difficulty to retain concrete in the second cellular arrangement, as surface openings were too large. In this case, additional points do not amount to extra branches but operate at a cellular level for surface treatment alone, re-exploring structural optimisation of cellular porosity discussed in Houda, 2018. The overall structure in relation to openings was differentiated in size, for a gradient distribution of cell openings and essentially branch arrangement to the viscosity of concrete. While on one hand, the mesh required to be dense to retain concrete, cell sizes were optimised to reduce the possibilities of void occurrences during concrete pour around branch nodes, resulting in segregation of concrete.

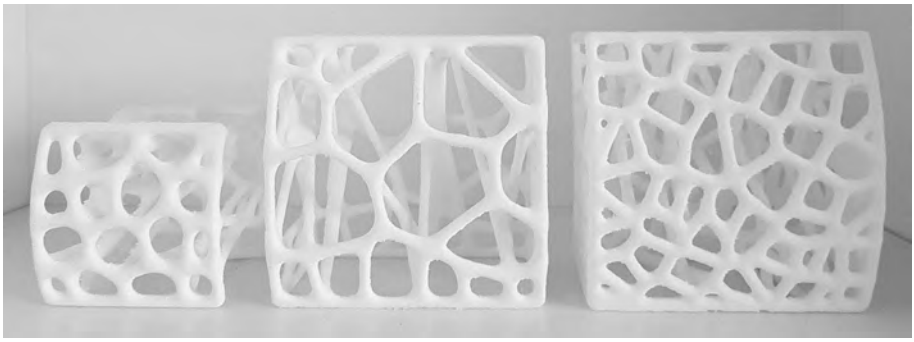


Figure 1. Cellular porosity and arrangement strategies over two scales.

Current leaky formwork systems exist, where concrete is poured into perforated modules that are either fully exposed such as Forma-Tech walls or COFFOR panels, or retained within two flat walls with the perforations in between such as Dincel Panels and AFS Rediwalls. These contemporary systems have moved away from conventional metal and timber formwork systems, in terms of their material and process, however in the context of concrete shells or complex curvatures, regular modularity poses limitations in geometric complexity, surface curvature and structural behaviour, as outlined in previous research (Houda & Reinhardt, 2018). Essentially the Voronoi grid proved to be structurally and geometrically more befitting than a regular linear grid.

3.2. BRANCH PATTERNS

This research is concerned with the structural performance of free-form curvilinear geometries. The cell point arrangement is calculated using an algorithmic solver, Galapagos, for a structurally optimised branch pattern connecting two curvilinear surfaces. Essentially, the branches work as reinforcement. Every second cell alternates in the inner rows (Houda & Reinhardt, 2018) and the solver runs through every point of a Voronoi polygon to result in an optimal arrangement that meets a minimum 45-degree branch angle, for 3D printing without supports, producing truss-like configurations to withstand loads during the pouring and curing process. A denser branch arrangement for the stop-ends and for the two outer rows in the u-direction, aim to relieve built up hydrostatic pressure during the wet pouring stage. By connecting two branches together, the branches are strengthened by a nodal intersection, to relieve stresses once the concrete has cured.

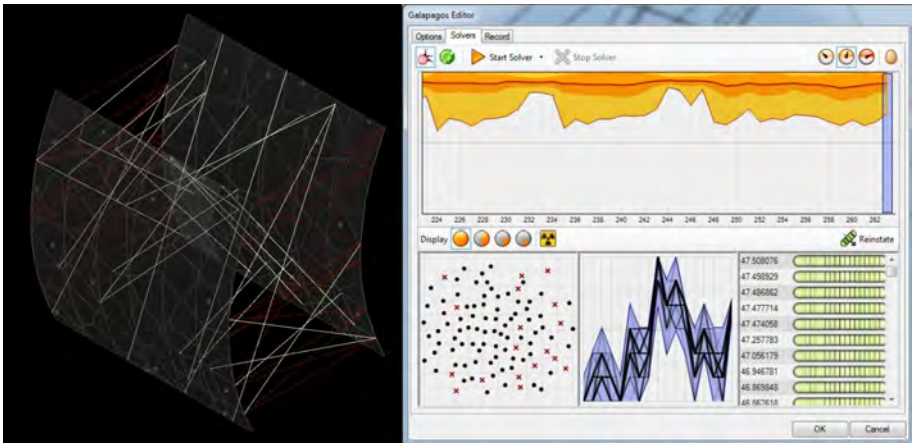


Figure 2. Surface point arrangement for optimised branch pattern via Galapagos.

The branching structures of the MDS are inspired by fractural assemblies found in nature that exhibit biological and structural functions. If we take the example of the tree, the branch arrangement is intentional, optimising form by distributing the load within a hierarchy of branches, increasing progressively in an upward manner (Rian et al. 2018). In the test cube specimen, this strategy is implemented where more branches and cell openings are organised towards the bottom or foundation.

A variety of branch thicknesses from 2-5mm were experimented with to test the ideal thickness against structural behaviour, print time, mesh infill and minimal support, for optimised branches with reduced print time, weight and minimal material use. A 5mm PLA branch configuration with a 10% infill was optimal, where the test cube specimen, 120mm (l) x 80mm (w) x 120mm (h) was printed within 8 hours on a desktop 3D printer, using 117g of plastic.

4. Structural Analysis

4.1. DIGITAL SIMULATION

A series of differentiated mesh densities varying in cell and branch pattern, were produced to select the most structurally optimised test cube. Displacement and utilization levels were digitally analysed using Karamba, where a dead load was applied using the properties of a standard concrete mix with a density of 23.5kN/m3, to investigate forces acting on the geometry. Under a compressive load, the test cube results in the majority of the form resisting compressive forces. The upmost edges along the stop-ends dealt the most displacement, 0.0693cm (Figure 3). The use of 3D printed PLA is a proof of concept for the MDS formwork system for, form-finding, testing concrete flow and geometry optimisation. The mesh skeleton can adopt other additive processes, such as metal extrusion, and hybrid additive processes including fibre-reinforced composites. Where tensile forces are in action, this research will look into a multi-material application with enhanced mechanical properties such as carbon fiber.

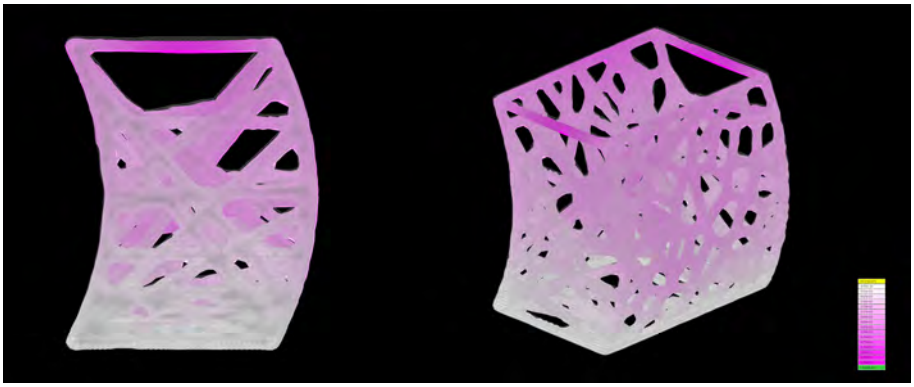


Figure 3. Load and displacement relationship.

It is difficult to simulate an in-situ-concrete pouring load using Karamba. Physical testing will be implemented in current developing progress for a numerical comparison to calculate an average structural performance of the test cube specimen, to compare digital and physical results and the deviances between the two processes of data analysis. Alternatively, fluid flow analysis using computational fluid dynamic testing may be an option worth investigating in following stages to simulate and predict flow rates and pressure within the design stage.

Testing the MDS on curvilinear forms not only widens the possibilities to apply the formwork system on non-standard geometric expressions, but varied cellularity and curvature exhibited in natural forms are structurally more effective than linear, rigid forms. If we take for example cellular differentiation in developmental biological systems, we understand that cells develop into different types to perform specific, specialised functions (Slack, 2013). In the same manner, the Voronoi grid developed in this system, varies in cellularity for specific functions in relation to

concrete flow and geometric structural principles. Without the development and variation of the cell as a unit, the system would fail. Voronoi is not only used for its aesthetic qualities, but the ability to produce optimised volumetric geometries through adaptive cellular typologies performing as connected structural members, and allowing for an effective transfer of load forces.

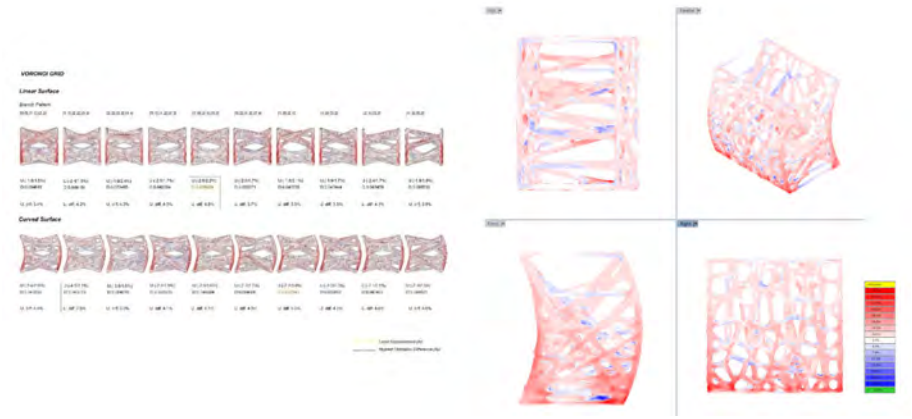


Figure 4. FEA results using Karamba for dead load of concrete (left); FEA simulation of compressive and tensile loads using Karamba (right).

5. Concrete Mix Design

Concrete after water, is the most abundantly used material on earth (Agrawal, 2018). Its flexibility and resilience to mould into any form provides many benefits to the creative designer. The limitations to geometric complexity in concrete buildings however, is not because of the material itself, but essentially, what shapes the concrete, which is typically linear formwork systems that simplify form. This research demonstrates the potentials in architecture of unlocking the opportunities associated with the fluidity of concrete. Through the process of 3D printing customised formwork and reinforcement, the MDS can produce complex geometries with minimal material and waste.

One of the key challenges of conducting a wet concrete cast to a porous geometry is successfully retaining the material within the mesh density. To address the issue, several experiments were conducted with various cellular apertures and distribution as well as branch arrangement to investigate the relationship between solid form and fluid material. In the first set of experimentation, wet concrete casting was performed to a mesh density with large cell openings. Although the process was somewhat successful, the successor had a varied cellular integration strategy to minimise the amount of concrete leaking at concave moments of the geometry.

Another main factor contributing to a successful and non-segregated cast is the concrete mix design. The size of aggregate as well as the rheology played an important role in how the concrete deposited in the mesh density. Three standard

ready mixes were prepared to visually compare flow and workability. A standard ready mix with large aggregates was the least successful as the aggregates were too large and lodged in between and under branches. Alternatively a standard sand and cement mix successfully flowed through the mesh density, however, without the presence of an aggregate cracked at the surface and failed to successfully adhere to the PLA. The same sand and cement mixture was used on the varied cell mesh and demonstrated successful flow and concrete containment. Minimal concrete was lost which proved that the varied cell openings were effectively distributed to address to the viscosity of concrete. The cellular surface treatment was able to reduce the amount of concrete leaking even at concave moments and the stop ends effectively relieved hydrostatic pressure. In all scenarios, concrete is poured from the top of the geometry, with the use of a vibrating needle to support an even concrete flow and smoothened for a thin, trough finish.

Essentially, the aim is to reduce the water-cement ratio for lightweight and structural attributes, but simultaneously, allowing the mixture to be liquid enough for an even flow within the dense mesh. By reducing the water content, structural properties of the concrete increase. Developing experiments will use a superplasticiser as well as the introduction of fibers and lightweight aggregates to the mixture to assess the flow of concrete in relation to the structural performance of the concrete mix design.



Figure 5. Sand and cement mixture in large cell openings (left); varied cell openings (right).

6. Discussion

The research conducted in this paper proved that a varied cellular distribution provided better containment of concrete than a single cell opening size. Through differentiation of branch angle and cellular size and distribution as well as a varied global geometry thickness, the branch and node system structurally optimises complex free-form geometries at the local scale, which would not be able to physically produce and cast with conventional concreting methods. The MDS has the ability within the one system, to effectively cast concrete into a porous geometry without external helpers such as timber stop ends to reduce concrete leaking and relieve hydrostatic pressure. The research investigates form finding and the structural capacity of the formwork system to compressive loads, however

successive experiments will introduce a variety of materials and a multi-material application to enforce tension reinforcement as a substitute to steel rebar through non-layer based robotic fabrication. Further studies will explore a variety of concrete mix designs to better suit the system for shell structures such as the use of finer aggregates and lightweight concrete to reduce the weight.

There is a strong trend in industry and academia outputs in concrete extrusion as an alternate material system for non-standard concrete construction, such as Contour Crafting and 3DCP Technology. However, the amount of concrete used and weight are still two main disadvantages of concrete 3D printing as well as the need to reinforce these forms with steel. Thermosetting polymers alternatively, can be modified as composites to work like steel, such as fiber reinforced polymers (FRP), but have the advantages of being lightweight, flexible in formwork design as it can be melted and extruded into an intended shape and produces minimal waste as material deposition is precise with no off cuts. With the integration of digital design and structural simulation coupled with physical testing, concrete rheology and structurally optimised formwork design no longer become separate entities, but work as a mutual system dependent on one another.

Formwork and reinforced material and labour in typical concrete production is approximately 70% of the total cost (Robert, 2007). The result is simplification of architectural geometries to linear, repeated forms to minimise costs with concrete fabrication and assembly. There is a demand for a new formwork system and fabrication process that unveils the structural and aesthetically versatile potential of concrete. With robotic fabrication, research objectives involve the precise deposition of polymers to fabricate building components, irrespective to the complexity of form.

As the system works with algorithms and design is performed parametrically, the formwork system is customised specifically for each module. Cell ratios and branch arrangement can be applied to larger scales. Where the branch patterns rely on evolutionary algorithms, based on a set rule of one branch per alternated cell, Galapagos calculates the most optimal arrangement to meet a 45-degree angle to the cell's normal. These parametric rules developed and structurally analysed at a test cube scale can then be applied to different modular arrangements and scales.

Larger implications of MDS will consist of full-scale system deployment for curvilinear design, where modules are fabricated and welded together on-site, readied for a single concrete fill. A gradient of high, medium, and low density cellular and branch distribution will be implemented across the shell to resist forces from upward concrete thrust in a vertical concrete cast. Other forces to take into consideration will be wind load especially up-force wind usually observed in open shell structures. The versatility of the branch pattern angles of the MDS formwork can be designed according to the concrete application of a shell-like form. This process opens up new opportunities to not only combine formwork and reinforcement as one system, but also the ability to design and build more structurally effective, optimised habitable and non-habitable forms via functionality of material processes.

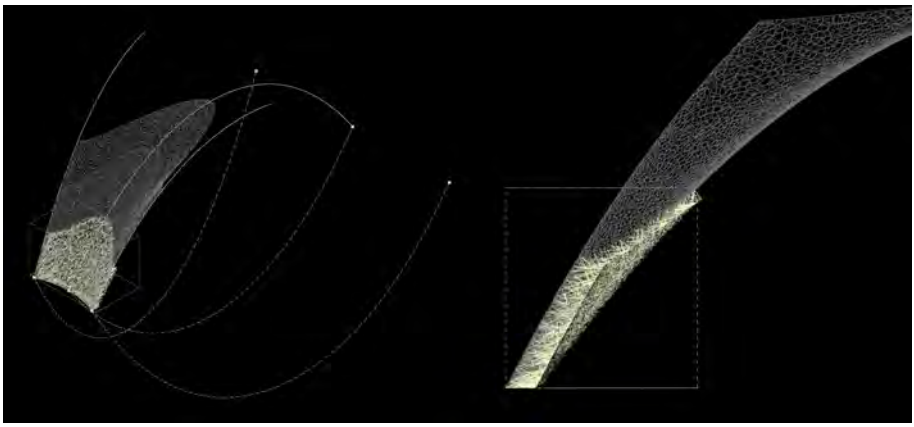


Figure 6. Deployment of MDS to shell structure.

The research presented in this paper is part of a larger project interested in robotic fabrication of a novel composite polymer formwork system for free-form concrete geometries. Whereas the paper explains the development of the Mesh Density System, progress will build on the structural testing of the system such as bending moments and the ability to reduce strain by revisiting composite material strategies that may allow for more flexibility while effectively resisting compressive and tensile loads.

The findings in this research will disseminate into different applications of the formwork system, varying in spans, geometries and typologies, to test the capacity as well as the limitations of the system, as well as explore different scales of application. Development will look into robotic 3D printing to investigate scalability of the MDS at an architectural scale. This will explore differentiation and organisation strategies of the formwork system for various forms and the versatility of the MDS to adapt to any geometry at various angles and bending moments. In terms of material behaviour and robotic deposition, the research will explore the different states of the polymer during the extrusion process, from heating to cooling and hardening, and its relation to speed, motion toolpaths, material feed rates, angle cantilever and span distance.

7. Conclusion

The paper discusses the development of a novel design to fabrication process by linking architectural design, engineering, material science and digital fabrication, to produce a novel, dual formwork and reinforcement system for free-form concrete in the context of shell structures. The findings discussed is part of a project, which is progressively developing a novel formwork system that investigates in-depth material processes for robotic fabrication and construction of lightweight geometries. The deployment of a novel building system intends to solve the disadvantages associated using traditional formwork techniques for customised complex concrete forms in terms of efficiency and cost.

Acknowledgements

The authors of this paper would like to acknowledge Ahmed Abbas, a graduate engineer, for his insight and assistance on research conducted in plastic formwork systems.

References

Agrawal, R.: 2018, *Built: The Hidden Stories Behind our Structures*, Bloomsbury Publishing PLC, London.

Asprone, D., Menna, C., Bos, F.P., Salet, T.A.M., Mata-Falcón, J. and Kaufmann, W.: 2018, Rethinking reinforcement for digital fabrication with concrete, *Cement and concrete research*, **112**, 111-121.

Calladine, C.R.: 1983, *Theory of Shell Structures*, Cambridge university press, Cambridge.

Daas, M. and Wit, A.J.: 2018, *Towards a Robotic Architecture*, ORO Editions, San Francisco.

Houda, M.: 2018, 3D PRINTING TOWARDS MASS-CUSTOMISATION, *T. Fukuda, W. Huang, P. Janssen, K. Crolla, S. Alhadidi (eds.), Learning, Adapting and Prototyping – Short Paper Proceedings of the 23rd CAADRIA Conference*, Beijing, China, 71-76.

Houda, M. and Reinhardt, D.: 2018, Structural Optimisation for 3D Printing Bespoke Geometries, *In T. Fukuda, W. Huang, P. Janssen, K. Crolla, S. Alhadidi (eds.), Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference- Volume 1*, Beijing, China, 235-244.

Huijben, F.A.A., van Herwijnen, F. and Nijsse, R.: 2011, Concrete shell structures revisited: introducing a new "Low-Tech" construction method using vacuumatics formwork, *In E. Oñate, B. Kröplin, & K-U. Bletzinger (Eds.), Structural membranes 2011 : V International Conference on Textile Composites and Inflatable Structures*, Barcelona, Spain, 409-420.

McMillen, G.G. and McClendon, J.H.: 1979, Leaf Angle: An Adaptive Feature of Sun and Shade Leaves, *Botanical Gazette*, **140**(4), 437-442.

Meyer, C. and Sheer, M.H.: 2005, Do Concrete Shells Deserve Another Look? Industry professional give mixed opinions, *In Concrete International 2005*, 43-50.

Rian, I.M., Sassone, M. and Asayama, S.: 2018, From fractal geometry to architecture: Designing a grid-shell-like structure using the Takagi–Landsberg surface, *Computer-Aided Design*, **98 (May)**, 40–53.

Robert, H.: 2007, Think formwork – reduce cost, *Structure magazine*, **April**, 12-14.

Slack, J.: 2013, *Essential Developmental Biology*, John Wiley & Sons, West Sussex.

A BLOCKCHAIN APPROACH TO SUPPLY CHAIN MANAGEMENT IN A BIM-ENABLED ENVIRONMENT

ADAM FITRIAWIJAYA[1], TSAI HSIN-HSUAN[2] and JENG TAYSHENG[3]
[1,2,3]*Department of Architecture, National Cheng Kung University*
[1]*adam@unsri.ac.id* [2]*tsaimax1992@gmail.com*
[3]*tsjeng@mail.ncku.edu.tw*

Abstract. The blockchain is a distributed ledger managed by a peer to peer network that stores all transaction records. The distributed ledger technology offers new possibilities, promising to ensure that data is secure, decentralized and incomparable. In the Architecture, Engineering, Construction (AEC) industry, Building Information Modeling (BIM) has quickly become a standard platform where all parties work together on a single and shared model for collaboration. The issues of Supply Chain Management (SCM) within BIM can be identified in BIM maturity level, based on PAS1193 that developed through Common Data Environment (CDE). The research strategy is to make model and simulation of SCM using BIM and create CDE to become decentralized and integrate the blockchain technology. The smart contract system validates every material and configuration of components within the model from the design stage until the operation stage. Traceability and auditability through an immutable historic eventually be more visible and allow real-time tracking of a material to a construction site providing a history from the origin.

Keywords. Blockchain; BIM; Supply Chain.

1. INTRODUCTION

In more recent times, blockchain applications have appeared to go far beyond their first application domains in virtual currencies, for instance, they are now important in fields such as domain registration, crowdfunding, prediction markets, and even gambling. (Peters & Panayi, 2016) In order to truly appreciate the complex technology known as blockchain and the impact it will have, one requires some understanding of various topics such as decentralization, consensus mechanisms, incentives, encryption, peer-to-peer systems, network effects, and economics, all of which this report covers. (Kinnaird & Geipel, 2017). The development of blockchain is currently a promising concern in future technological developments. The Blockchain continues to develop after being discovered by Satoshi Nakamoto in 2008 to serve as a public transaction ledger from bitcoin cryptocurrency. The blockchain is currently entering a wave of massive research, providing several high-profile proofs-of-concept (PoCs)

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 411-420. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

and applied programs in various industries. Identification and valid analysis of blockchain ecosystems and application scenarios impose a prevailing issue for practitioners and researchers. (Glaser, 2017) The scope of research and development is strengthened and the extent of the industry that explores expanded blockchain. According to Ashley Lannquist from WEF Blockchain team at Berkeley, the financial sector has historically led research and development on blockchain investment, with implementation projects starting in 2015 or earlier, 2017 seeing more activities from retail, shipping, telecommunications, aviation, automobiles, and several other industries. In this paper, the author explains how blockchain can be applied to Supply Chain Management (SCM) by adopting Building Information Modeling (BIM) in supporting the activities of architecture, Engineering, Construction (AEC) industries. There are 3 things that are briefly presented, namely : (1). Blockchain (Smart Contract, Decentralised Application); (2).BIM (BIMmodel, BIM Level2); (3) Supply Chain Management (Input-Output, Actor, Delivery Product). The role of the blockchain in SCM-BIM activity leads to the development and improvement of coordination, integration, and products in the activities of AEC industries.

2. BACKGROUND

2.1. BLOCKCHAIN TECHNOLOGY IMPROVING THE SUPPLY CHAIN MANAGEMENT IN AEC

A supply chain encompasses all of the activities that go into the delivery of goods or services, beginning at the earliest stage of creation and ending at the final stage of destruction or extinction. They can also vary significantly in terms of length (i.e. the number of tiers across the supply chain) and depth (i.e. the number of suppliers or customers within each tier), depending on the good or service in question. The complexity of a generic supply chain network is illustrated in Figure 1.

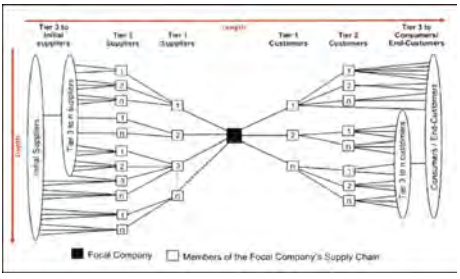


Figure 1. The Complexity of Generic Supply Chain Network (Law, 2017).

Again, recently the construction industry has been specifically challenged to reduce construction costs for government contracts by 15-20% by 2015, from the baseline of 2012(CabinetOffice, 2011). Globalization, diverse regulatory policies, and varied cultural and human behavior in supply chain networks make it almost impossible to evaluate information and manage risk in this intricate network (Sarpong 2014; Ivanov, Dolgui, and Sokolov 2018).

According to ARUP's book series, Blockchain technology could solve these issues in a number of ways: (1.) Increasing the speed and scale of decision making and procurement processes. (2.) Providing consistent reporting for subcontractors, contractors, and owners. (3.) Providing objective data on the best people for a job. Some of the methods explain the blockchain that supports Supply Chain is able to build a certainty in perfecting digital contracts safely and surely with supporting features (digital signature, timestamp).

2.2. HOW WILL SMART CONTRACT SUPPORT SUPPLY CHAIN

Blockchain enables the creation of smart contracts, with terms and conditions both sides can specify and that assure trust in the enforceability of the contract and the identity of the counterparty. Contracts must be written to ensure fairness even when counterparties may attempt to cheat in arbitrary ways that maximize their economic gains. (Delmolino et al. 2016) Smart contract execution can be compared to atomic transactions, i.e., the transition from the current database state to the next database state by changing data. (Glaser, 2017)

This system of distributed trust allows for lower transaction costs in the short term, but this is just the beginning. In the long run, it will enable more agile value chains, closer cooperation with business partners and faster integration with the Internet of Things (IoT), among other things. Also present in the system are numerous IoT devices (e.g., sensors and actuators), which are connected to the P2P network via the IoT gateways (Zhang et al., 2018). By using smart contracts to handle the multiple exchanges between parties, blockchain technology can reduce complexity and allow for greater transparency and trustless verification across the supply chain. This will help to speed up the supply chain, make it more agile, and foster stronger relationships among partners. Smart contracts can improve SCM in three key ways: transparency, traceability, and efficiency.

The most recent and innovative approach in that regard is Etherum platform, which includes a Turing-complete programming framework aiming to realize smart contracts. (English, Auer, & Domingue, 2016) Smart contracts are written and executed as computer code linked to a digital currency such as bitcoin or ether (the Ethereum blockchain's native currency) as the payment or the representation of an asset. (Kinnaird & Geipel, 2017). Smart contracts as special protocols can contribute to verifying or implementing negotiations or contract performance. In the context of blockchain and cryptocurrency, smart contracts are pre-written logic that is stored and replicated on a distributed storage platform such as a blockchain run by computer networks and can also produce ledger updates. Therefore, if blockchains provide reliable, distributed storage, it is very possible that smart contracts give us reliable, distributed calculations.

2.3. BIM AND SUPPLY CHAIN MANAGEMENT (SCM)

Building Information Modeling (BIM) is a technology-driven approach that offers benefits to both products and processes of AEC, by collecting and representing building project information and hence supporting information sharing. (Papadonikolaki et al., 2015). Inter-disciplinary collaborations within

the AEC industry have revolved around the exchange of 2D-drawings and documents for a long time (Thomassen, 2011). Nowadays, BIM adoption and SCM are only conceptually combined. Although there are reports on changing dynamics in the roles of the stakeholders induced by BIM (Arayici et al, 2011; Sebastian, 2011), only a few include organizational aspects of integration through SCM in AEC (Vrijhoef, 2011). The combination of BIM-based technologies and SCM practices have been studied as an opportunity for the remaining and persistent AEC challenges pertinent to inefficiencies, poor coordination, information redundancies, and waste. (Papadonikolaki et al., 2016)

More broadly, Supply Chain Management activities integrated with BIM are a form of collaboration from digital information exchange management within the scope of AEC industries, prior to the development phase. This is specifically indicated in the PAS1192 document. PAS 1192, which provides specific information management requirements associated with projects delivered using BIM. Furthermore, and for the avoidance of doubt, all project information, whether in conventional data formats or single collaborative data environments (CDE).(PAS, 2013) . PAS 1192 specifies the requirements for achieving building information modeling (BIM) Level 2 during the capital/delivery phase of projects. It builds on the existing code of practice for the collaborative production of architectural, engineering and construction information, defined by BS 1192:2007.

The Common Data Environment (CDE) is defined as a common digital project space, which provides well-defined access areas for the project stakeholders combined with clear status definitions and a robust workflow description for sharing and approval processes. (Preidel, Borrmann, Oberender, & Tretheway, 2017) Furthermore, the CDE leads to a higher rate of reusability of information, simplifies the aggregation of model information and simultaneously serves as a central archive for documentation. (Preidel et al., 2017) This setup of a CDE can depend on a variety of ways affected by the application, project volume and participated parties. Nevertheless, a more detailed implementation of such a CDE shall be presented exemplarily. In general, the architecture of a CDE can be described as a layered structure. (Preidel et al., 2017) (see Figure 2)

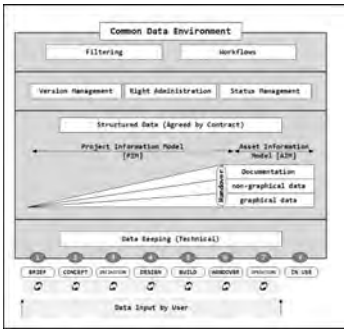


Figure 2. Layer model of a Common Data Environment, inspired by British Standard Institution (Preidel et al., 2017).

3. METHODS

The methodology used in representing Supply Chain Management in BIM activities, with the Blockchain approach, is to build models and simulations. The model that is built is a form or concept of the relationship of the system in SCM, with various scenario concepts. Then the results of the concept are simulated in the implementation chapter.

3.1. BUILD CONCEPT FOR SUPPLYING BIM MODEL TO CDE

The BIM supply chain contains important information from all data supply processes in the form of digital information represented in graphical, non-graphic and documentation data. In this chapter, the authors build a simulation, how to bring the BIM3D model (Supply properties, Material of elements information, and Material Properties) as digital data into CDE. Information for each of these components has a list of milestones and time slots scheduled by planners to ensure that the materials needed for operations will be on site before the start of operations. (see Figure 3)

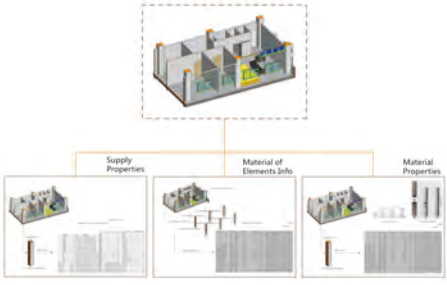


Figure 3. The example of BIM product's type (Author, 2018).

At Figure 4(a), it is shown that the BIM product to be delivered to CDE starts from BIM3D, where data information is taken in the form of 3D models, Material Properties, Cost Properties, Material Properties, and CoBIe Data. The development of BIM data is related to the SCM system built in CDE, which is divided into 3 main platforms, namely: (1). BIM's Platform, (2). Opera's Platform and (3). Information Exchange's Platform.**BIM's Platform** is a space for storing databases from BIM products that have developed decentralized storage systems through Blockchain Technology. Data stored in the BIM Platform is digital data related to PIM, AIM in the form of graphical, non-graphical and documentary data (see explanation in chapter 2.3.) **Operation's Platform** is part of CDE to support integrated BIM Data with products that have been realized post - procurement in the real world with IoT system support, using sensors, RFID and GPS. As an example in Figure 3, how can RFID inform the supply of material according to the material properties in the model that has been distributed in the CDE? **Information Exchange Platform** is a system built on CDE that is supported by the Application Programming Interface (API), as a gateway for information and

transaction exchange by clients or customers registered on CDE.

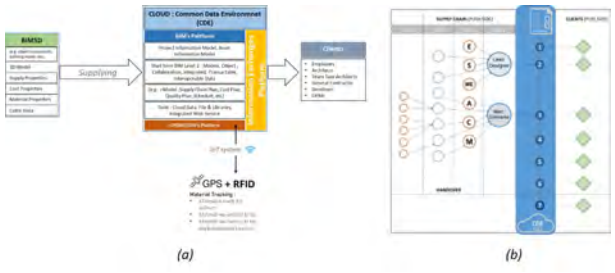


Figure 4. (a) Proposed Concept for Supplying BIM Product into CDE (b) Organisational Model BIM-SCM within CDE (Author, 2018).

The author provides an alternative organizational model in the BIM product distribution process in CDE. This concept is a development of the Supply Chain Organization in the PAS1192-2: 2013 document, in explaining how the implementation of product delivery and information exchange on BIM products in CDE. This model (Figure 4(b)) describes the process of assessment and validation in supply delivery through Tier 1, Tier 2, Tier 3, and Tier n. Tier as a gateway, where Tier 1 parties are the controllers and decision makers of CDE, to validate and assess that BIM products are eligible to be on a CDE system. The number of layers affects the number of suppliers involved in the supply chain process here. And the number of suppliers affects the number of members from each Tier.

3.2. CONCEPT BLOCKCHAIN TO BIM-SCM

3.2.1. Building Smart Contract for Supply Chain Management (SCM) of BIM

Angwei Law stated that there are 3 challenges to using Smart contracts in supply chain management activities, namely determining the provenance of goods, tracking the progress of goods to the supply chain, and building trust through an open database of supply chains partners, including their reputation. (Law, 2017) These three things form the basis for developing smart contracts to support supply chain management at BIM.**Smart Contract for Provenance**: Each supply chain runs on a blockchain, where each SCM actor is connected to access certain functions, especially in the case of provenance validation. From Figure 5(a), it is explained that suppliers of BIM products or can be called producers, manage records of their properties and are distributed through the Blockchain. This system builds trust that is effective and efficient in verifying the products it produces.

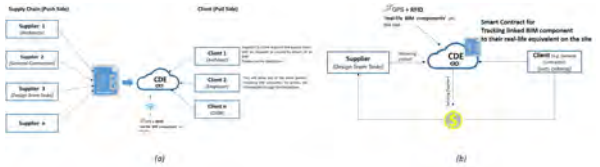


Figure 5. (a) Concept of Smart Contract for Provenance (b) Concept of In the Tracking phase the BIM-Product to the real-life product on site (author, 2018).

In the Tracking phase the BIM-Product to the real-life product on site: All transactions in the supply chain are recorded by the parties involved in the transaction, which will then be verified if the delivery has been successful. Products related to data components when in the field integrated with IoT systems, will be verified by sensors. For example, RFID tracking at this time allows for this and can be directly controlled by related companies, whereas, with a blockchain based approach, data is available and publicly distributed. As the tracking concept, can be seen in Figure 5(b), explained that there is a sending of product BIM by Supplier (e.g. Design Team Task) to the client (e.g. General Contractor). Before arriving at the client, Smart Contract verifies the product and ensures that the product is on the site, through IoT systems (sensors, RFID). Then a verified payment is made in CDE, that the payment matches the criteria. **Smart Contract for supply chain reputation**: There is a reputation score when the transaction in the SCM process is successful or unsuccessful. Some product shipments that are successful in the form of goods, quantity, location, and correct time, as a percentage of the total shipments made. Reputation scores can be done by calling a contract and can be repeated or renewed. The CDE database is open publicly, which can be accessed by all parties involved in transactions in a good reputation. (Figure 6)

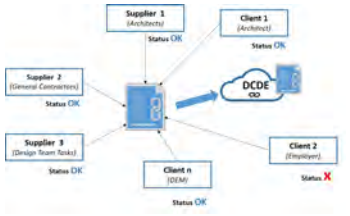


Figure 6. Concept of Supply Chain Reputation (author, 2018).

4. IMPLEMENTATION

Smart Contract implementation in SCM is by demonstrating Proof-of-Concept by using Ethereum which is a Blockchain-based platform with Decentralized Application support. The Smart Contract implementation is written using Solidity IDE, a contract-oriented programming language for implementing smart contracting that runs on Ethereum Virtual Machine (EVM). According to Angwei Law(2017), proof-of-concept demonstrations refer to 3 types of smart contracts,

namely: provenancetracking products and supply chain reputation. Furthermore, this study developed from several resources regarding the use of Remix - Ethereum and then the Functions will be adjusted to the activities of Supply chain management at BIM. (see Figure 7) Building Provenance of BIM Product: In this process use an Oracle-based contract that provides a way to get outside data from any web API onto the blockchain. Then make a simulation to validate Provenance. Starting with input data, namely addBIMProducer, for example, XYZ Consultant and then addBIMproduct, example: door001. In Figure 7, what needs to be known is success information in applying Smart Contract to Provenance, and also displays the hash value of contract address. In this simulation, partner models are built in the SCM process. There are 5 suppliers or producers involved in the transaction.

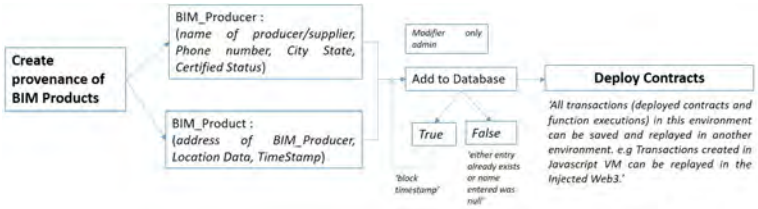


Figure 7. Simulation Create Contract of BIM Product.

In the data input stage, the success of the transaction is executed and the status is informed. This shows that the CDE admin has validated the Producer / Supplier BIM product to enter in the part of the Supply Chain. Furthermore, the data that has been entered will be validated in EVM, as shown in Figure 8, an important point that can be taken from these results is, each transaction always produces a hash value, as a validation hill. And every transaction and function execution has a cost value. (see Figure 8)



Figure 8. Result of Simulation Smart Contract for Provenance.

Tracking BIM product: These functions will be deployed to represent Smart Contract for tracking product. The Tracking smart Contract allows parties in the supply chain to track the shipment of goods and automatically execute a payment in the form of tokens once every leg of shipment is completed, provided that certain predetermined criteria are met (Law, 2017). To show the validation of the smart contract tracking is done by simulating the shipment from BIMProducer

(as a supplier) to the client. For instance, XYZ Consultants send BIM products (window001). When the product sends out, it is automatically validated by the Blockchain and recorded (see Figure 12). Then proceed with the validation of product shipments arriving at the site, (see Figure 13) and validate payments by including information tokens, payment status, and value of the transaction hashes (see Figure 14).

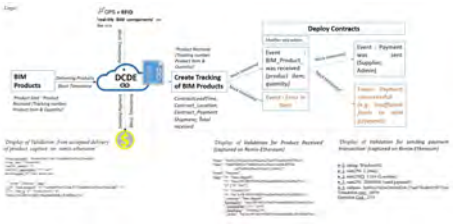


Figure 9. Smart Contract of Tracking BIM-Product (Author 2018).

Building trust of Supply Chain Reputation: After the validation stage on the smart contract tracking, and the payment process, then an assessment of each supplier / BIMproducer is then carried out. This process provides an assessment of suppliers/producers. (see Figure 15) The suitability of items and quantity and predetermined criteria is a determinant in supply chain reputation value.

Name of Producer		XYZ Consultant	ABC Architect	UVW Coorp.	DEH Developer	KLM Consultant
Address		0xca35b7d915 458ef340a6e6d 68d5fe2f44e8fa 783c	0x14723a09acff6d2 a60dcdf7aa4aff308 6dc160c	0x14721a09acff 6d2a60dcdf7aa 4aff308fddc160 c	0x14723a03accff 6d2a60dcdf7aa4 aff308fddc160c	0x14723a09acff6 d2a60dcdf7aa4a ff308fddc160c
Transaction Cost (gas)		113574	113702	113382	113830	113843
Execution Cost (gas)		88654	88654	88654	88654	88654
Decoded Output	string	XYZ Consultant	ABC Architect	UVW Coorp.	DEH Developer	KLM Consultant
	uint256	89822334456	217234566	98768894	341563157	1234567
	string	Taipei	Jakarta	New Delhi	Singapore	Palembang
	string	Taiwan	Indonesia	India	Singapore	Indonesia
	bool	FALSE	TRUE	TRUE	TRUE	TRUE
Name of Product		BIM Component (Window)	BIM Component (Door)	Building BIM Model (House)	Wall Partition	BIM Component (Window)
Decoded Output	string	XYZ Consultant	ABC Architect	UVW Coorp	DEH Developer	KLM Consultant
	uint256	89822334456	217234566	98768894	341563157	1234567
	string	Taipei	Jakarta	New Delhi	Singapore	Palembang
	string	Taiwan	Indonesia	India	Singapore	Indonesia
	bool	FALSE	TRUE	TRUE	TRUE	TRUE
uint 256 (Reputation Score)		67	80	65	76	80

Figure 10. Results of Reputation Smart Contract.

5. CONCLUSION

According to PAS 1193 and BSI 2013, supply chain management able to run on the BIM level 2 corridor. This is indicated by supply chain organizations that are configured in layers (Tier-1, Tier-2, Tier -n) to the process of filtering and validating the Supply Chain actors (supplier, clients) in determining the reputation of producers and their products. However, SCM-BIM can be elaborated to BIM level 3, 4, and level-n. The improvements can be conducted by optimizing BIM-products within The asset management of life cycles that supported by collaborative capabilities and interoperable data. In reach organizational of SCM-BIM configuration, the role of the blockchain is quite significant for entire the BIM product supply activity and transaction processes. The Smart

Contract with a proof-of-concept mechanism is able to support the effectiveness of transaction validation without involving a third party. Furthermore, smart contracts are able to provide an assessment for representing the reputation of suppliers/producers and product transactions as well. At the simulation stage, Remix-Ethereum and its environment could exposure the SCM process, quite clearly. EVM that runs on the blockchain platform of SCM-BIM, could represent CDE as Storage. That platform capable be a model for the development of CDE as a cloud of data in the exchange of digital information related to BIM and the environment, which is mutually integrated and must be accessible to all projects supporting for a BIM-based collaboration process.

References

"Running Smart Contract" : 2018. Available from <https://remix.ethereum.org/> (accessed 1st December 2018).

CabinetOffice, C. O.: 2011, *Government Construction Strategy*, www.e-government.cabinetoffice.gov.uk.

Delmolino, K., Arnett, K., Kosba, M. and Miller, A.: 2016, Step by step towards creating a safe smart contract: Lessons and insights from a cryptocurrency lab, *the International Conference on Financial Cryptography and Data Security.*.

English, M., Auer, S. and Dominique, J.: 2016, Block chain technologies & the semantic web: a framework for symbiotic development, *the Computer Science Conference for University of Bonn Students J. Lehmann, H. Thakkar, L. Halilaj, and R. Asmat, Eds.*.

Glaser, F.: 2017, Pervasive Decentralisation of Digital Infrastructures : A Framework for Blockchain enabled System and Use Case Analysis, *Proceedings of the 50th Hawaii International Conference on System Sciences*, Hawai.

The British Standard Institution, B.S.I. 2013, Spesification of information management for the capital/delivery phase of construction projects using building information modeling, *in* B.S.I. The British Standard Institution (ed.), *PAS 1192-2:2013 Incorporating Corrigendum No.1*, BSI Standards Limited 2013.

Kinnaird, C. and Geipel, M. 2017, Blockchain Technology : How the Inventions Behind Bitcoin are Enabling a Network of Trust for the Built Environment, *in* S. Cousins (ed.), *Blockchain technology*, ARUP, 13 Fitzroy Street, London WIT 4BQ.

Law, A.: 2017, *Smart Contract and their Application in Supply Chain Management*, Master's Thesis, Massachusetts Institute of Technology.

Papadonikolaki, E., Vrijhoef, R. and Wamelink, H.: 2015, Supply chain integration with BIM: a graph-based model, *Structural Survey*, **33(3)**(doi:10.1108/ss-01-2015-0001), 257-277.

Papadonikolaki, E., Wamelink, H. and Vrijhoef, R.: 2016, inteGration in desiGn and ConstruCtion: tHe Case oF bim-enabled sCm, *4th International Workshop WHEN SOCIAL SCIENCE MEETS LEAN AND BIM*.

Peters, G. W. and Panayi, E.: 2016, *Understanding modern banking ledgers through blockchain technologies: Future of transaction processing and smart contracts on the internet of money. In Banking Beyond Banks and Money*, Springer.

Preidel, C., Borrmann, A., Oberenderr, C. and Tretheway, M.: 2017, Seamless integration of common data environment access into BIM authoring applications: The BIM integration framework, *Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016)*, Cyprus.

Thomassen, M.: 2011, *BIM & Collaboration in the AEC Industry*, Master's Thesis, Aalborg University.

Zhang, Y., Kasahara, S., S, S.h.e.n., Jiang, X. and Wan, J. J.: 2018, Smart Contract-Based Access Control for the Internet of Things., *arXiv preprint*, **arXiv:1802.04410**, https://arxiv.org/abs/1802.04410.

MACHINIC DESIGN INFERENCE: FROM POKÉMON TO ARCHITECTURE

A Probabilistic Machine Learning Model for Generative Design using Game Levels Abstractions

IMMANUEL KOH[1], PEDRO AMORIM[2] and JEFFREY HUANG[3]
[1,2,3]*École polytechnique fédérale de Lausanne (EPFL)*
[1,2,3]*{immanuel.koh|pedro.caldeira|jeffrey.huang}@epfl.ch*

Abstract. In this paper, we use a probabilistic machine learning model, trained with a corpus of existing game levels tile-maps, to study the potential of an inference design system for architectural design. Our system is able to extract implicit spatial patterns and generate new spatial configurations with similar semantics of perception and navigation.

Keywords. Machine Learning; Artificial Intelligence; Generative Design.

1. Introduction

As early as in the 1970s, urbanist and geographer Michael Batty, building on the general system theory approach of architect Christopher Alexander (Alexander, 1964), has suggested using Markov process as a plausible decision-making design machine for urban planning (Batty, 1974), albeit mainly an analogical and theoretical one. Unlike Alexander's hierarchical design methods, he appropriated the sequential nature of the Markov chain to argue that design activity is akin to a process of sequential averaging in the weights of conflicting factors to arrive at a design solution. In this paper, we will investigate the potential of the Markov process and extend its probabilistic mechanism to architecture's computational design domain. Similarly, we will appropriate Batty's style of theory building in using abstract models, such as those tile-based or cell-based models found in his early works, for both simulating our process and interpreting our results. More specifically, we will appropriate the same underlying spatial order of grid systems found in architectural plans and game levels in our proposed inference design system based on machine learning. Unlike Batty's rule-based system of cellular automata implemented with *NetLogo* (Batty 2005), we use a stochastic model trained with a corpus of existing *Pokemon* game levels tile-maps to extract implicit spatial patterns of the game level inputs and probabilistically generate new ones with similar semantics of perception and navigation. We used data from the game *Pokemon Red* (1996) and *Pokemon FireRed* (2004) to train our models. The former has a total of 125 unique tiles, while the latter has a higher visual complexity with 1207 unique tiles. The motivation for using game maps as our training

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 421-430. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

dataset is its greater availability and discrete form of semantic representations. These factors directly contribute to the ease of implementation of our proposed stochastic Markov process and interpretation of our results. As evident in our results, we argue that the semantic categories used in virtual game levels has a direct reference or mapping to those used in physical architectural design planning. Our binary (black-white) tile maps can be understood as the typical figure-ground representation of spaces, while our multi-coloured tile maps can be understood as the typical programmatic representation of zones during the planning design stage. Likewise, the navigability of our game space configuration is also a plausible approximation of those found in real physical spaces. The contribution of the work lies in its demonstration that new spatial configuration can be inferred from a given dataset to produce formally and semantically coherent designs without the need for any explicit rule-making. It is a fundamental departure from the current, as well as, dominant practice of generative design in architecture. The paper concludes with the evaluation that our proposed machine learning model, despite its generative capacity, would not readily scale up given a high number of unique tiles and low number of datasets.

2. Background

In the context of the game industry, Shaker et al. (2012) use generative grammars combined with an evolutionary algorithm to create *Super Mario Bros* game levels that adapt themselves to the player's experience. In another paper, Sorenson and Pasquier (2010) also use an evolutionary algorithm to create a generic framework for level creation. Their approach allows the level designer to enforce multiple constraints on the generated levels making it adaptable to multiple genres of games. Rather than being evolutionary, our method draws from machine learning techniques. The designers do not have to explicitly articulate rules about their designs but simply need to provide the system with examples of what they want to create. Papers using machine learning methods to generate game levels are still a minority, but the trend seems to be on the rise. Likewise, architectural design research demonstrating the innovative use of probabilistic machine learning models for generative design is also limited. More recently, the *Infinite Series* by Immanuel Koh (2018) convincingly demonstrates the use of generative deep learning models to encode and learn formal features of urban configurations (Barcelona) and then sampling from their probability distribution to infer new ones. Our architectural inference approach is inspired by his work (Figure 1), while our use of Markov chains is inspired by the game design research work of Snodgrass and Ontañón (2013) and Dahlskog, Togelius, and Nelson (2014). They both use Markov chains to create *Mario* levels with very convincing results. The difference with our approach lies in the fact that *Mario* levels have a linear nature. The maps we focus on are non-linear; the player can move through both dimensions and not in a left-to-right manner. Additionally, we use maps with a much higher number of tiles: *Pokemon Red* (1996) has a total number of 125 unique tiles, *Pokemon FireRed* (2004) has 1207 unique tiles; in contrast, the maps used by Snodgrass and Ontañón (2013) have only 11 unique tiles. Apart from these technical differences, we are concerned with the understanding and interpretation of the generated maps'

spatial semantics, in order to evaluate and extrapolate the gained knowledge for architectural design purposes.

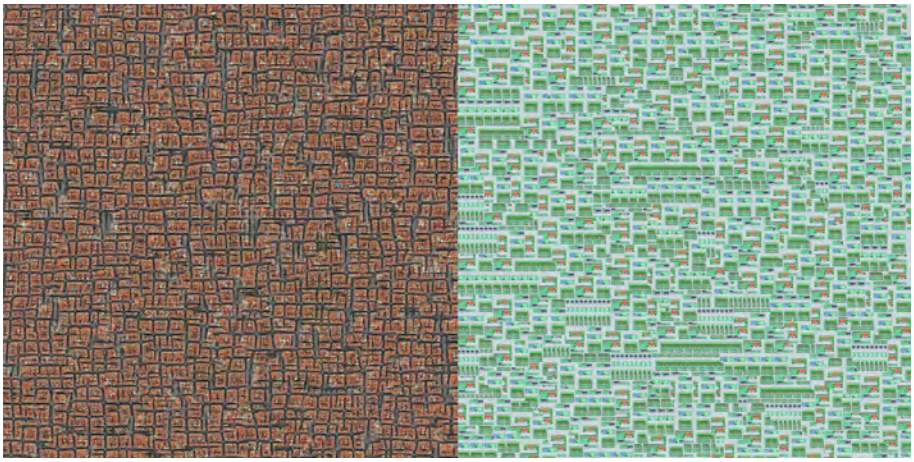


Figure 1. (Left) 'Infinite Series - Barcelona' (with permission of the author) as inspiration for (Right) our generated pokemon game level.

3. Methods

Tile-maps are a staple of many genres of games and they are formed by individual tiles of predefined size assembled into a grid. As explained in the introduction we decided to use tile-maps as our tool of choice to represent space for their computational advantages: they can be represented discretely and they are formed by atomic elements whose meaning can be abstracted at the architectural level. In generating the tile-maps from a set of representative examples, our process is as follows:

- Choose the set of maps whose spatial style we want to reproduce.
- Represent maps as matrices where each entry contains a tile type identifier. This will be our input dataset (Figure 2).
- Generate a Markov chain whose probability distributions reflect those of the original dataset. This is the learning phase of the model.
- Sample this Markov chain to generate a map of any given dimension.

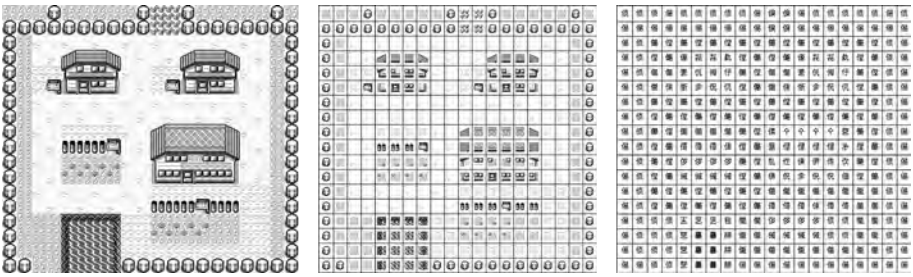


Figure 2. Conversion(from left to right) of a tile-map from Pokemon Red into matrix form. We use Chinese characters for the tile identifiers since the games possesses a total of 125 unique tiles, a number too large to be contained by the Latin alphabet.

This is comparable to the case where Markov chains are used for automatic essay writing (Murphy 2012). These automatically written essays use similar idioms and vocabulary to the ones present in the learning dataset; in a certain sense they emulate the style of a given text. For the same reasons we expect our Markov chains to reproduce the spatial style of its learning examples.Markov chains are a mathematical formalism that allows us to model state transitions of a stochastic process. The particularity of Markov chains is that they only take the current state of the system into account to compute the next state. In our use case we represent a tile-map as a matrix where each entry corresponds to a specific tile. The Markov chain generating the map will have one state per tile type and will fill the matrix of the tile-map sequentially by sampling the next state at each entry. The chains are trained on the example data with a frequency computation. Rather than just depending on the current state, Markov chains can depend on any number of previous states. We can even assume that the predecessors are not only linear but that they are taken in multiple dimensions (Figure 3).

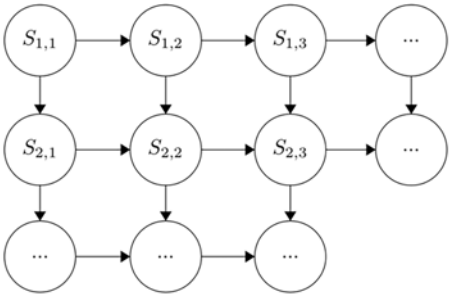


Figure 3. The dependencies in a 2d Markov chain.

The number and position of previous tiles that are taken into account are explicitly defined by the predecessors matrix. For example, the following are 3 possible predecessors matrices (where *T* represents the focal tile) implemented in our study:

- P1 which only considers the nearest left neighbour.

- P2 which only considers the nearest upper neighbour.
- P3 which considers all neighbours that are at a distance of 3 or less of the current tile.

$$P1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & T \end{bmatrix} P2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & T \end{bmatrix} P3 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & T \end{bmatrix} \quad (1)$$

4. Results

Let us start with a few examples of the maps generated with our method. We used data from the game *Pokemon Red* (1996) and *Pokemon FireRed* (2004) to train 2d Markov chains. The *FireRed* version is a remake of the *Red* version meaning that it is mainly a visual upgrade of the first game; the locations and the spatial distribution of both games are very similar. The *FireRed* game however, has a higher visual complexity which is reflected by its higher number of unique tiles. As such *Pokemon Red* has only a total of 125 unique tiles versus 1207 in *Pokemon FireRed*. In the generated *Red* version (Figure 4) the overall result looks plausible. Most of the navigable spaces in both maps are reachable. Aesthetically the maps are comparable to what we can find in the original *Pokemon Red* game with a similar distribution of tiles. The maps however, are not perfect and we can find a few inconsistencies in them. Some houses and buildings for example either overlap or have missing tiles. In the generated *FireRed* version (Figure 5) there is a marked increase in the number of visual glitches. While the maps look believable in a local scale the transitions between environments prove to be more problematic. These differences suggest that our method works better at a higher level of abstraction. The relative lack of variety in *Pokemon Red* implies that each individual tile can be considered as having more semantic meaning than their equivalents in *Pokemon FireRed*. In *FireRed* for example we can find many types of houses and buildings when compared to those in *Red*. As a result the model will have a harder time generalizing the placement of buildings. The end result being that our method is probably better suited for datasets with a relatively low number of tiles.

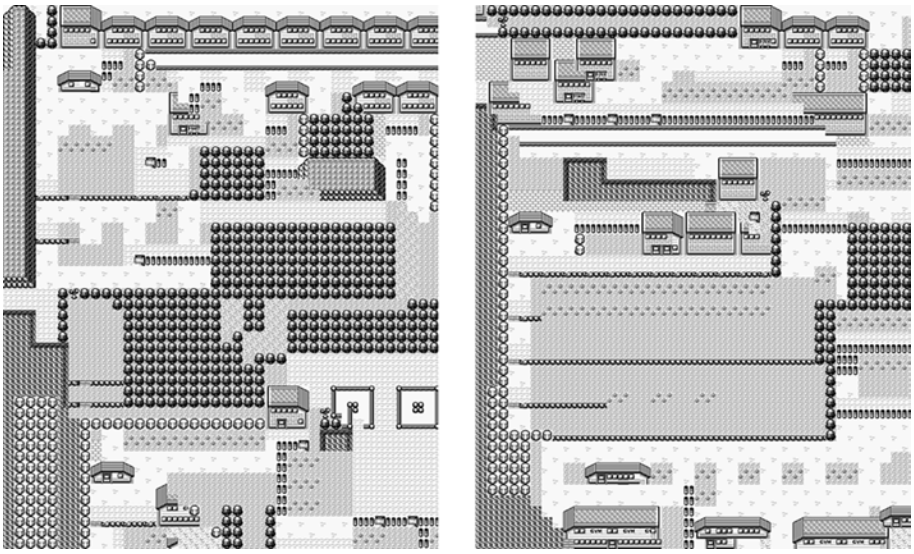


Figure 4. Two generated maps based on Pokemon Red.



Figure 5. Two generated maps based on Pokemon FireRed.

Let us now observe how the generated maps are influenced by the choice of the predecessors matrix, in other words, the number and placement of previous tiles that are taken into account. To this end we generated a set of maps with two different predecessors matrices. In Figure 6 each tile takes only its immediate left neighbour into account, the chain is linear and we can see that there are no relations between each rows; they are formed independently of each other. In

Figure 7 we use a predecessors matrix that is two-dimensional and as a result the generated maps produced much more complex spatial structures such as houses and buildings.

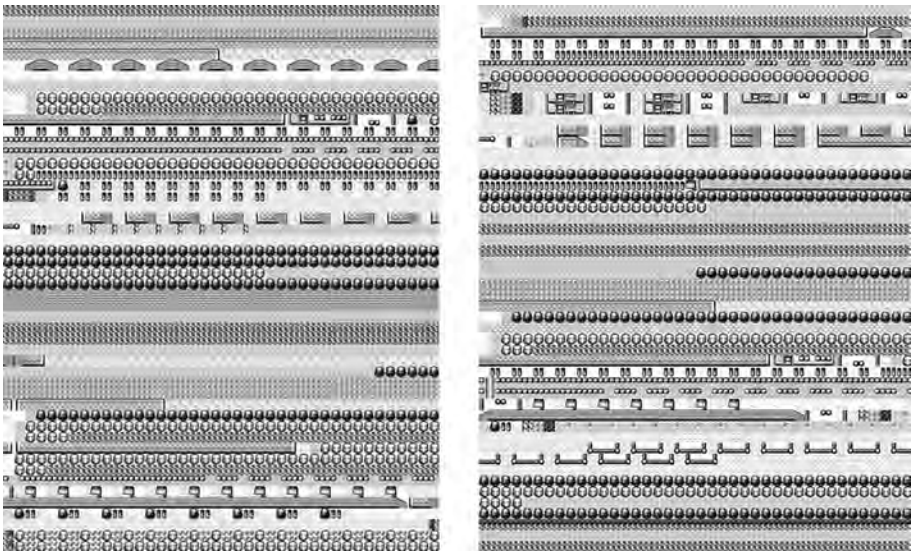


Figure 6. Two maps generated with predecessors matrix P1.

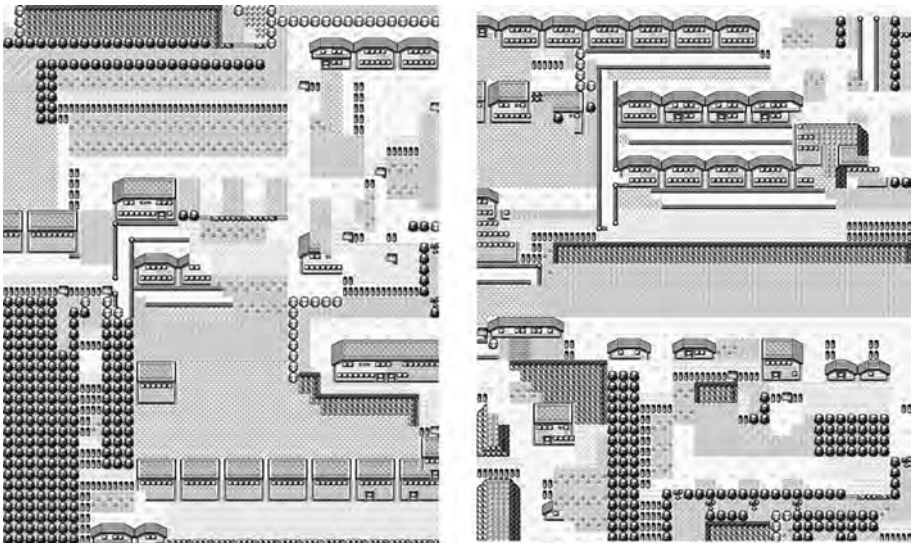


Figure 7. Two maps generated with predecessors matrix P3.

In general, larger predecessor matrices allow the expression of more complex structures, their use however is limited by the fact that they require more data to

train. Imagine we take a predecessor matrix of the size of the training maps, then the trained Markov chain would only be able to generate copies of its training data since it has not learned anything else. We thus lose the potential for variability in the maps generated with larger predecessors matrices. Like we alluded to earlier in the Background section, tiles are a useful concept for game developers because they allow a clear distinction between space that is navigable or not. Some tiles can be traversed while others not. Based on this information we can represent maps in a binary fashion. The middle maps of Figure 8 and Figure 9 are depicted in this fashion with black tiles signifying non-passable space and white tiles representing passable space. This binary distinction based on space is not the only one we can make, at a higher level we can regroup tiles based on what their space means inside the game; that is their semantics. The rightmost images of Figure 8 and Figure 9 are generated with this in mind. Each colour has a particular semantic:

- Orange refers to buildings or houses.
- Yellow refers to doors, such as entry points to other zones or houses.
- Red refers to artificial obstacles, such as signposts or fences.
- Pink refers to artificial walkable space, such as roads or pavements.
- Blue refers to water bodies.
- Green refers to natural walkable space, such as grass.
- Brown refers to natural obstacles, such as mountain ranges or rocky formations.

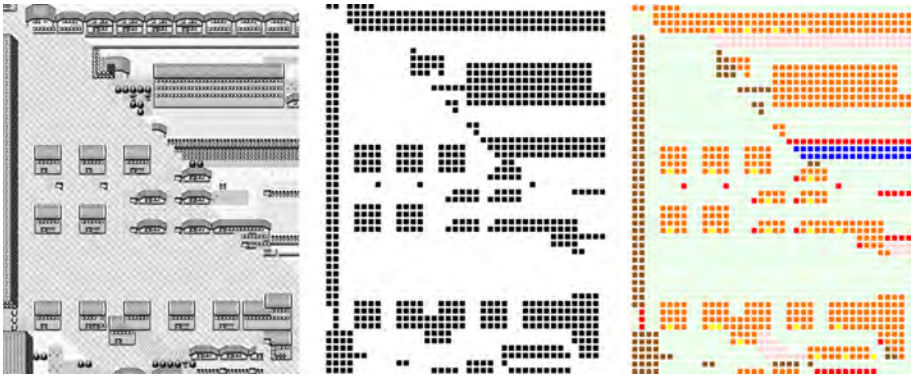


Figure 8. A generated map and its binary and semantic counterparts.

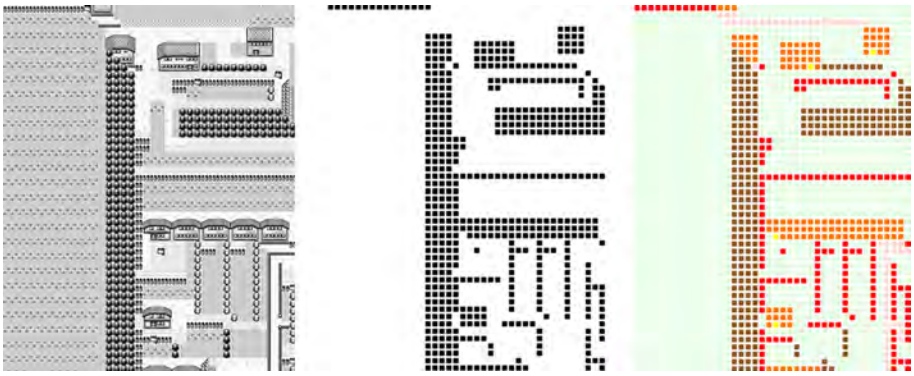


Figure 9. Another generated map and its binary and semantic counterparts.

5. Discussion

As evident in our results, we argue that the semantic categories used in virtual game levels has a direct reference to those used in physical architectural design planning. Even at the most basic semantic level, our binary (black-white) tile maps can be understood as the typical figure-ground representation of spaces used by architects or planners, where the navigability of a game space configuration is akin to the circulation of a real space design. With our higher-level semantic representation, here annotated with specific colors, we could further uncover and generate a coherent distribution of both functional and formal architectural elements or regions in space. For example, orange regions inscribe the extent of building footprints or enclosures; yellow tiles suggest main front entrances of buildings; red tiles are urban objects that signify differing political or social territories; pink regions are the city's infrastructures and lastly the blue-green-brown regions are the hard and soft landscapes with different levels of perceptual and physical accessibilities. Thus, we can now use the same types of architectural design criteria to evaluate our resulting game maps- themselves an architectural referent.

We shall now identify specific aspects of the generated maps shown in Figure 8 and 9 to illuminate our hypothesis of a viable data-driven design approach, by looking at the colored semantic maps alone. There are moments where different building footprints (orange) become merged, yet almost always ensuring the presence of a front entrance (yellow). At other times, such mega-block demarcates semi-permeable thresholds (red) within their immediate vicinity to choreograph public/private usage of the spaces. The prevailing presence of natural landscape (blue/brown) also suggests a reliable distribution of both natural and artificial land use within the city, based on those of the training set. In fact, the overall results suggest the potential of training a dataset of urban plans with their corresponding semantics abstractly embedded. For instance, one could imagine using a limited set of color-coded categories-keys available on *OpenStreetMap* and learn their spatial probability distribution. In doing so, one could potentially infer useful urban properties of different existing cities and generate new cities that retain the desired distributions.

6. Conclusion

Our proposed inference design system has demonstrated, through game levels abstraction, its potential for generating semantically and spatially meaningful configurations that can be appropriated for architectural design planning. Few of its current notable limitations include the assumed availability of a pre-labelled tile-map dataset with a relatively small number of unique tiles and the inaccessibility for designers to spontaneously interrupt the sequential Markov process to guide or constrain the trajectory of the design evolution at a granular level. Nonetheless, we believe this initial demonstration will pave the way towards the incorporation of probabilistic machine learning models for a data-inference-based approach in the generative design process of the architect.

References

Alexander, C.: 1964, *Notes on the Synthesis of Form*, Harvard University Press, Cambridge.

Batty, M.: 1974, A Theory of Markovian Design Machines, *Environment and Planning B: Planning and Design*, **1**(2), 125–146.

Batty, M.: 2005, *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*, MIT Press, Cambridge.

Dahlskog, S., Togelius, J. and Nelson, M.J.: 2014, Linear Levels through N-Grams, *Proceedings of the 18th International Academic MindTrek Conference on Media Business, Management, Content & Services*, Tampere, 200-206.

Koh, I. 2018, Inference Design Machine & "Infinite" & "Recombinant" Series, *in* N. Leach and P.F. Yuan (eds.), *Computational Design*, Tongji University Press Co., Ltd, Shanghai, 291-296.

Murphy, K.P.: 2012, *Machine Learning: A Probabilistic Perspective.*, MIT press, Cambridge.

Shaker, N., Nicolau, M., Yannakakis, G.H., Togelius, J. and O'Neill, M.: 2012, Evolving Levels for Super Mario Bros Using Grammatical Evolution, *IEEE Conference on Computational Intelligence and Games*, Granada, 304-311.

Snodgrass, S. and Ontanón, S.: 2013, Generating maps using Markov chains, *Proceedings of the 2013 AIIDE Workshop on Artificial Intelligence and Game Aesthetics*, Palo Alto, 25-28.

Sorenson, N. and Pasquier, P.: 2010, Towards a Generic Framework for Automated Video Game Level Creation Applications of Evolutionary Computation, *European Conference on the Applications of Evolutionary Computation*, Heidelberg, 131-140.

Summerville, A.J., Snodgrass, S., Mateas, M. and Ontañón, S.: 2016, The VGLC: The Video Game Level Corpus, *Proceedings of the 7th Workshop on Procedural Content Generation*.

SPACE SEMANTICS

An investigation into the numerical codification of space

SARAH YAP[1], GLORIA HA[2] and RIZAL MUSLIMIN[3]
[1,2,3]*The University of Sydney, Sydney, Australia*
[1,2]*{syap3858|glha9393}@uni.sydney.edu.au*
[3]*rizal.muslimin@sydney.edu.au*

Abstract. "Space-Semantics" is a computational design proposition that interrogates how architectural spaces can be interpreted and codified within an adaptable semantic framework. The investigation seeks to view space through an alternate lens, abstracting architectural spaces into a set of numerical descriptions that can either be used to interpret the qualities of an existing space, or as a seed to generate a coherent network of spaces based on identified spatial patterns within a chosen site. The article comprises of two parts: a theoretical investigation into representing spaces through numerically expressed semantic descriptions and a case study in the form of a proposal for an underground metro station within an urban context.

Keywords. Space; semantics; grammar; code; generative.

1. Introduction

Space is fundamentally difficult to describe because it is intangible, and thus analysing space is often conducted through an examination of the surfaces that enclose it rather than the actual space itself (Hillier and Hanson 1984). Methods of articulating formal or spatial relations such as 'space syntax' (Hillier and Hanson 1984) and 'descriptive functions' (Stiny 1981) are effective in describing physical adjacencies and patterns, allowing the underlying logic of a spatial system to reveal itself. Whilst Hillier and Hanson (1984) contained their spatial analysis to two dimensions, extrapolating this logic to three dimensions can yield a more holistic understanding of spatial systems, particularly within the complexities of an urban context (Ratti 2003). Schroder et al. (2007) explores urban visibility by extending the principles of 'axial mapping' (Hillier and Hanson 1984) into a three-dimensional space syntax. Substituting shapes for volumetric extrusions, an algorithm constructs a subset of three-dimensional axial lines around these massing buildings, and their points of intersection give form to a 'visibility surface' which articulates the varying level of visual range around a given site. Whilst Schroder et al. (2007) focuses on the representation of topography and the connective space around discrete buildings, *Space Semantics* is concerned with the qualitative and quantitative description of the spaces themselves. It is apparent

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 431-440. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

that there is scope to integrate spatial characteristic data into an artificial language whilst maintaining its capacity to describe a host of varying spatial conditions. Adopting the methodology of another syntactical model - 'justified gamma maps' (Hillier and Hanson 1984), *Space Semantics* proposes how these principles can be applied in three-dimensions through a 'discursive grammar' (Duarte 2005) that incorporates shape, language descriptions and heuristics. Using numbers as a medium, *Space Semantics* allows information about a particular space such as permeability, accessibility and circulation to be condensed into an ordered string of digits. These codes are then fed into McNeel's Grasshopper and processed through recursive functions to produce a logical spatial network that is site-specific.

2. Background

Designing a spatial grammar requires an understanding of three important aspects: human spatial perception, forms of grammatical notation and methods of computational manipulation. An artificial language is of limited use if it is purely representational, rather it should have an embedded generative potential to reveal new ways of viewing or creating spatial systems. Description grammars contain both programming and design rules (Duarte 2005). In other words, their formulation necessitates a consideration of how data can be symbolically integrated into a specific input component and how that can then be manipulated through simple rules in order to generate new compositions. It is critical that these grammars are constructed from interchangeable semantic variables so as to maintain its applicability to a wide variety of architectural situations and scales. The following theoretical exploration traces how descriptive grammars have been developed, identifying potential areas where *Space Semantics* can further evolve these approaches.

2.1. UNDERSTANDING SPATIAL RELATIONSHIPS

Social structures are intrinsic to the organisation of space (Hillier and Hanson 1984). Thus, an understanding of spatial relationships necessitates a consideration of how people perceive themselves in regards to others and their environment. Fundamentally, people understand space as either interior or exterior - seeing themselves as the occupant or the outsider (Hillier and Hanson 1984). It is this simple and innate dichotomy that dictates how space is demarcated and organised into logical systems. Space syntax (Hillier and Hanson 1984) relies on establishing binary relations in order to analyse and reveal the morphology of social-spatial networks. In particular, 'justified gamma maps' examine spatial relationships by determining whether one space is simply accessible from another. In turn, the 'depth' of a space can be deduced by counting the number of spaces one must pass through in order to access that space. Whilst this method of mapping a spatial system is effective in understanding its distribution, there is the potential to extend this thinking to account for more detailed information, for instance - the extent of the opening or its visual transparency. Understanding space through dichotomies - internal or external, public or private, connected or disconnected - is inherently reductive. Rather, these polarities should be perceived as two ends of a defined spectrum and a space is posited within that domain.

2.2. NOTATING SPACE

There are two critical aspects to defining a shape grammar: the rules dictating how spatial elements are composed and the rules that describe these designs in terms of form, type, function and purpose (Stiny 1981). Whilst these considerations refer to the language of design, they are also applicable to the inverse - the design of language. The grammar of an artificial language is critical in determining its analytical and generative capacity. 'Justified gamma maps' denote spaces and their connections through a diagram of linked strings and beads which clearly depict the spatial distribution of the system (Hillier and Hanson 1984). Stiny (1981) uses a series of letters and subscripts to define a particular shape grammar- #a1#a2#a3#a4#a5#a6#a7#a8, where # is used to separate distinct elements and ai represents a specific component in the form of an integer, co-ordinate pair, list or matrix (Stiny 1981). Since each element is described discreetly, a single description can contain very disparate pieces of information - from the number of enclosed rooms, to a list of windows or the configuration of architectural elements. Furthermore, mathematical functions can be applied to specific parts of the description in order to only modify the desired components of the output. Architectural configurations can also be described through a 'JPG grammar'- a schema based on shapes, nodes and links notated as X_i , node(X_i), link (X_i,Y_i) respectively and where *i* denotes a particular characteristic of the shape X (Lee et al. 2015). The spaces, their adjacencies and their formal language are described independently, allowing individual elements to be changed without necessarily impacting the rest of the output.

2.3. HEURISTICS

Heuristics are essential in refining a pool of spatial system outputs because it allows the generation of formally and semantically correct designs (Duarte 2005). Whilst spatial 'correctness' is inarguably subjective, there is an inherent logic in the way that spaces are planned architecturally. As such, this raises the problem of how we define spaces that are logical or illogical and more importantly, how this may be translated into a function that can be integrated into a discursive grammar.

Duarte (2005) implements a set of rules in order to generate customised iterations of Alvaro Siza's houses at Malagueira. These functions involve the manipulation of rectangular blocks - subdividing, connecting and scaling them in order to generate housing that is formally varied. Other rules specify the programmatic functions of particular rooms, denoted by an abbreviated subscript, which can then be overrode by subsequent functions until a specified termination point has been reached. The resulting descriptions are articulated as a string of letters and numbers, separated by commas, periods and brackets. This allows the 'fitness' of description to be tested by inputting this data into an equation which weights spatiality and topology against each other, the values of which are derived from the lengths of walls, the distance between rooms and the area of spaces. The ability to evaluate a given design output computationally is significant, as it will allow the process of generating and discarding descriptions to become fully automated, resulting in higher quality architectural solutions.

Similarly, Lee et al. (2015) uses a series of chronological steps and rules to construct a 'JPG grammar' which describes variations of Glenn Murcutt's Marie Short House both spatially and stylistically. Whilst some of these functions simply define particular components or characteristics, others are designed to check a grammatical description using conditional statements. As such, particular functions are only applied if certain criteria are not satisfactory. Furthermore, these functions can also override and modify the outputs of previous rules. For example, where a solid and transparent wall are specified in the same location, the overlap will result in a solid wall. This schema allows heuristics to be designed into the discursive grammar and as such the descriptions undergo a process of refinement and optimisation before they are finally output.

3. Semantic Framework

3.1. OBJECTIVES

The proposed discursive grammar, *Space semantics* was developed in response to the limitations and potential of *space syntax* (Hillier and Hanson 1984). The diagramming of 'justified gamma maps' (Hillier and Hanson 1984) abstracted space and spatial relationships into a system of connected points and lines. Whilst this method of representing spatial relations revealed patterns of distribution within these systems, it neglected to capture other non-visual characteristics of space. Furthermore, *Space syntax* relies on the input of an existing architecture in order to derive a diagram of spatial relationships. As a function, the rules only operate in one direction, limiting its capacity to generate new spatial propositions. The proposed *space semantics* code is a framework to interpret and articulate space both quantitatively and qualitatively, embedding symbolic meaning into a new artificial language. It posits an alternate method of describing space without geometric constraints by focusing on spatial utilisation and permeability. It democratises our perception of space and allows individual spaces to be considered through a different lens within a broader system. As a framework that functions in both directions - it is a tool for analysing and interpreting existing sites, but also a device that can produce multiple schematic iterations of spatial systems. This translation from a diagram of numerical codes to a physical form can manifest in a multitude of ways; the proposed method is just one of infinite interpretations.

3.2. NUMERICAL CODE

Space semantics is premised on the assumption that spaces can be described through a range of characteristics and therefore are codifiable. Each space is represented by a string of n digits, where each digit is a rating of a particular spatial quality. In order to lessen the computational load, we have limited the case study to seven digits or characteristics, however, these codes could theoretically contain an infinite amount of numbers.

For each digit, there is a maximum domain of 0-9. These integers can have a smaller domain depending on the nature of the characteristic. For the purposes of this study, we have allocated three characteristics to measure the utilisation of a space, and four for assessing the permeability of the space. See Table 1 and 2;

Table 1. Space Semantic Code Breakdown.

	permeability					utilisation		
integer domain:	0-9	0-9	0-9	0-9		0-1	0-3	0-6
	2	1	1	3	.	1	1	4
	visual permeability	environmental permeability	physical accessibility	centroid isovist area		non-void or void	traversability	public accessibility

Table 2. Numerical Digits and Corresponding Spatial Characteristics.

	Spatial Characteristic						
Digit	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	Visual Permeability	**Environmental Permeability**	**Physical Permeability**	**Centroid Isovist Area**	**Non-Void or Void**	**Traversability**	**Public Accessibility**
0	0-9.9%	0-9.9%	0-9.9%	0-9.9%	Void	Egress	Egress
1	10-19.9%	10-19.9%	10-19.9%	10-19.9%	Non-Void	Horizontally	Services/Plant
2	20-29.9%	20-29.9%	20-29.9%	20-29.9%		Vertically	Back of House
3	30-39.9%	30-39.9%	30-39.9%	30-39.9%		Diagonally	Privately Owned, Publicly Accessible
4	40-49.9%	40-49.9%	40-49.9%	40-49.9%			Privately Owned, Publicly Welcomed
5	50-59.9%	50-59.9%	50-59.9%	50-59.9%			Public
6	60-69.9%	60-69.9%	60-69.9%	60-69.9%			
7	70-79.9%	70-79.9%	70-79.9%	70-79.9%			
8	80-89.9%	80-89.9%	80-89.9%	80-89.9%			
9	90-100%	90-100%	90-100%	90-100%			

This set of criteria can then be used to evaluate the quality of spaces on an existing site, producing strings of numerical codes that can then analysed for trends. In this sense, deriving spatial patterns becomes a task of recognising number patterns, a computational exercise that can be handled through digital means. The proposed case study is situated in two disparate locations of Sydney's Central Business District, and hence the trends for each site vary, reflective of their programming and location. Each of these number patterns can then be translated into a function that will be used to refine the new generated codes for each specific area.

3.3. MATRIX

Hillier and Hanson (1984) depict their *space syntax* models two-dimensionally in plan, however this has obvious limitations in capturing more complex, multi-storey spatial systems. *Space semantics* arranges points in a three-dimensional gridded matrix, allowing spatial relationships to be read in both plan and section simultaneously. The dimensions in the X, Y and Z axis are controlled in McNeel's Grasshopper and can begin to reflect the physical parameters of the project. This case study utilises an $8 \times 8 \times 8$ matrix to model a potential 8 storey underground train station.

Each point in the matrix is first assigned a code by randomly selecting an integer from the given domain for each digit of the code. For example, the first digit is always an integer from 0-9, whilst the fifth digit is either 0 or 1. The ratio of integers can then be skewed in favour of particular spatial characteristics. For example, a train station typically has a higher proportion of public space, and hence

the probability of choosing a larger integer for the seventh digit is higher. This is scripted in McNeel's Grasshopper by duplicating data for each of the integers to a variable ratio, generating a pool of numbers to randomly select from. The script to generate a single code is looped recursively (Zwierzycki 2015), where the number of recursions is set to the number of points in the matrix. The result is an ordered, discrete list of codes which describe a potential spatial system.

3.4. CODE TO DIAGRAM

Spatial relationships are diagrammatically represented with a polyline that carves a path within the matrix. It is composed of smaller line segments that connect points (representing spaces) within the matrix, be it vertically or horizontally. The path begins with selecting the start point in the matrix. The first line segment is generated by randomly selecting one of the closest points to the start (previous) point and joining them together. The script is programmed such that the previous point cannot be re-selected, in other words, the polyline cannot travel back onto itself. Non - naked points will have six points of choice, whilst naked points in the matrix can have three or four. Looping this process through the Anemone plugin in Grasshopper generates a string of consecutive segments of the polyline, the length of which is determined by the number of recursions. See Figure 1;



Figure 1. Space Semantics Diagram - Proposed Martin Place Station, Sydney, Australia.

3.5. TROUBLESHOOTING

Inherent code patterns were discovered through *Spatial semantic* mappings undertaken at Martin Place and World Square, Sydney. These deduced number

patterns were reincorporated back into the script as a means of not only creating a sequence of spaces that have rational relationships to each other, but to create spaces with logical characteristics. This was achieved by systematically checking each code and adjusting the number patterns through an override in the Grasshopper script. Generally:

- If the fifth digit is 0, then the space is a void, hence it is also an egress and therefore the sixth and seventh digit in the code is also 0. For example,

6 1 2 8 . **0** 1 4 → 6 1 2 8 . 0 **0 0**

- If a space is represented by an endpoint of a vertical line, it is vertically or diagonally traversable. Hence the sixth digit in the code must be a 2 or 3. For example,

6 1 2 8 . 1 **1** 4 → 6 1 2 8 . 1 **2** 4 or 6 1 2 8 . 1 **3** 4

- The 7th digit of adjacent spaces must have consecutive or equal numbers. This reflects the gradual transition between public and private space. For example, in a sequence of three codes:

6 1 2 8 . 1 1 **4** → 6 1 2 8 . 1 1 **4**
8 3 1 5 . 1 1 **6** → 8 3 1 5 . 1 1 **5**
9 4 7 3 . 1 1 **2** → 9 4 7 3 . 1 1 **6**

3.6. DIAGRAM TO FORM

Space Semantics provides a schematic spatial diagram from which a form can be generated from. The following architectural manifestation of this case study is just one of infinite methods of interpreting the code in a formal sense.

3.6.1. FLOOR PLATES

The floor plate of each space is determined by the seventh digit of its corresponding code. This digit represents a rating of public accessibility - the higher the number, the more public a space is. Therefore, in order to create spaces that are more generous towards the public domain its size must be proportional to its seventh digit. The line between two adjacent spaces is divided by the sum of the seventh digits of the codes representing its end points.

For example, a line between 2 3 5 6 . 1 1 **4** and 7 8 1 2 . 1 1 **5** would be divided into $4 + 5 = 9$ segments. The edge of the rectangular footprint is determined by the ratio of the two numbers on that line. See Figure 2;

3.6.2. THRESHOLDS

The size of the threshold openings between two adjacent spaces is calculated using the second and third digit of these two codes. The height of a threshold is determined by the second digit (environmental permeability) and the width is controlled by the third digit (physical permeability). Therefore, the higher the numbers are, the larger the threshold opening, and thus the more permeable it becomes. Since a space can be connected to multiple thresholds, each interface

also takes into account the values given to spaces that are not immediately adjacent. The numbers are weighted differently depending on how close each space is to the threshold being calculated.

Our perception of space extends beyond the space we immediately occupy, and thus if one digit in a particular code is modified, the localised change triggers a global reaction in the system. Digits of spaces closer to the threshold in consideration are given a higher weighting. The resulting numbers from the calculations are rounded to the nearest integer and used to determine the width and height of the opening, as illustrated in Figure 2.

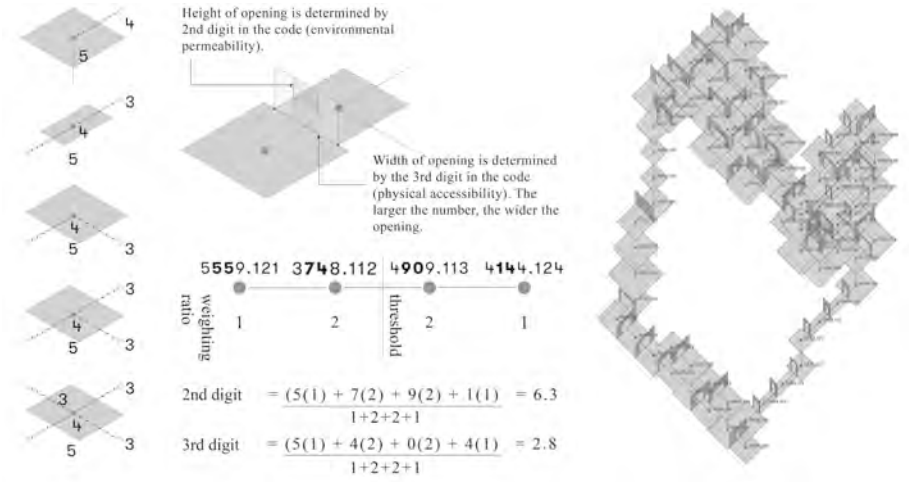


Figure 2. Generating form from codes - Proposed Martin Place Station, Sydney, Australia.

3.7. ARCHITECTURAL OUTPUTS

Through the generation of multiple iterations, it was apparent that new building typologies began to emerge. These were largely determined by the initial seed value that dictated the polyline starting point within the matrix. Through a visual comparison between a group of iterations it is clear that there are similarities between some and others which are complete outliers. In a sample of 24 iterations, iterations 06, 13, 15 were outliers. More interestingly, iterations 11, 19, 20, 21, 22, 23 closely resemble each other with only subtle variations. Iterations 07, 08, 10 are also comparatively similar. It is interesting to note that often two iterations shared a similar formal typology despite not having consecutive seed numbers, such as 00 and 16, or, 05 and 09. The emerging similarities between iterations yields the potential to identify a particularly successful typology and filter iterations based on certain geometric criteria. This could potentially be achieved through machine learning to seek out better iterations based on previously evaluated forms. See Figure 3;

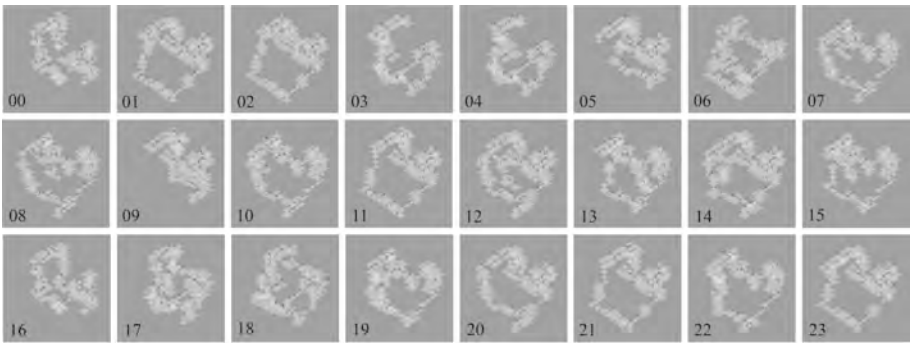


Figure 3. New spatial typologies - Proposed Martin Place Station, Sydney, Australia.

3.8. DISCUSSION

Digitally generated design has naturally evolved to become synonymous with a particular aesthetic, whereby style and form are prioritised over non-visual characteristics of architectural design, such as spatial qualities, relationships and organisation. *Space semantics* shifts the way in which we not only view computer-generated design, but also how spaces and their relationships are described. This case study of the seven digit code reveals the analytical and generative potential of *Space semantics* as the chosen architectural characteristics can be substituted depending on the architectural typology and the code can be extended indefinitely. How codes are linked can also be entirely restructured to output different formal permutations.

3.8.1. DESIRABLE CONFIGURATIONS

With such variation in the *Spatial semantic* outputs, a set of design criteria was necessary for assessing the functional appropriateness of a specific configuration. The following list outlines the design criteria used for this case study to recognise the architectural traits that constitute a functional configuration:

1. Forms with strong horizontal linear configurations at the top of the matrix are ideal because they can be integrated into the existing circulation axis at ground level.
2. Forms with 1 or 2 horizontal linear configurations at the base of the matrix are preferred as they can be translated into station platforms. The best outcome occurs when these forms connect directly to street level.
3. Forms with a strong vertical linear articulations are ideal as they can be converted into lift cores.
4. Forms with a tight cluster of points at the top or the middle of matrix are ideal because they can be translated into retail hubs or food courts.
5. Forms with two separate clusters at the top of the matrix are preferred as they can be translated or interpreted as openings at street level.

Iteration 01 for World Square Station, Sydney, consists of compact linear forms stacked on top of one another. This dominant axis is easily integrated into the existing main thoroughfare in World Square's ground plane. Openings

periodically cut out along the main access provide multiple entry points into the station without disturbing the existing retail spaces. See Figure 4;

Iteration 02 for World Square Station, Sydney, is a dispersed branching form. The existing staggered axis in World Square matches this iteration, offering the potential to integrate the station access points at the most critical node of World Square's ground plane. See Figure 4;

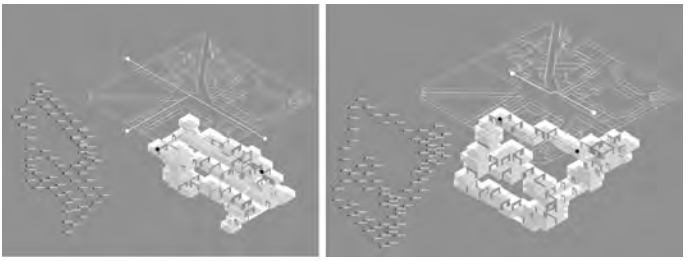


Figure 4. Iterations 01 & 02 World Square Station, Sydney, Australia.

4. Future Applications

Whilst this initial case study explores the carving out of functional space for an underground train station, the same logic could be used for other buildings, particularly where strict structural grids must be observed or when intervening into a complex existing site. *Space semantics* has the potential to be incorporated into the feasibility studies of adaptive reuse sites, carving out new spatial systems for various programmatic functions. Buildings such as towers and carparks are prime candidates for such projects, whereby re-programming part or all of these buildings can inject a second life into these sites, re-connecting them with the cities they occupy. Through the selection of desirable outputs, machine learning can be integrated into *Space Semantics*, allowing this system to learn the unique spatial logic that architects and urban planners design with.

References

Duarte, J.P.: 2005, A discursive grammar for customizing mass housing: the case of Siza's Houses at Malagueira, *Automation in Construction*, **14**, 265-275.

Hillier, B. and Hanson, J.: 1984, *The Social Logic of Space*, Cambridge University Press, Cambridge.

Lee, J.H., Ostwald, M.J. and Gu, N.: 2015, A syntactical and grammatical approach to architectural configuration, analysis and generation, *Architectural Science Review*, **58**, 189-204.

Ratti, C.: 2004, Space syntax: some inconsistencies, *Environment and Planning B: Planning and Design*, **31**, 487-499.

Schroder, C.: 2007, *Quantifying Urban Visibility Using 3D Space Syntax*, Master's Thesis, The University of Edinburgh.

Stiny, G.: 1981, A note on the descriptions of design, *Environment and Planning B: Urban Analytics and City Science*, **8**, 257-267.

Zwierzycki, M.: 2015, "Anemone for Rhino & Grasshopper" . Available from <https://www.food4rhino.com/app/anemone> (accessed March 2018).

PROTOTYPING OF CHITOSAN-BASED SHAPE-CHANGING STRUCTURES

SACHIN SEAN GUPTA[1], DHILEEP KUMAR JAYASHANKAR[2], NARESH D SANANDIYA[3], JAVIER G. FERNANDEZ[4] and KENNETH TRACY[5]
[1,2]*Research Assistant, Singapore University of Technology and Design*
[1,2]*{sachin_gupta|jayashankar}@sutd.edu.sg*
[3]*Research Fellow, Singapore University of Technology and Design*
[3]*naresh_sanandiya@sutd.edu.sg*
[4,5]*Assistant Professor, Singapore University of Technology and Design*
[4,5]*{javier.fernandez|kenneth_tracy}@sutd.edu.sg*

Abstract. In the built environment, the typical means of achieving responsive changes in the physical features of a structure is through energy-intensive actuation mechanisms that contradict the intended goal of energy-efficient performance. Nature offers several alternative energy-free examples of achieving large-scale shape change through passive actuation mechanisms, such as the intrinsic response of water-absorbing (hygroscopic) materials to humidity fluctuations. We utilize this principle of passive actuation in the context of chitosan biopolymer, a material demonstrating a combination of mechanical strength and hygroscopic potential that enables it to serve for both load-bearing and actuation purposes. By inserting biocomposite films of chitosan as dynamic tensile members into a space truss, a structural system is constructed whose variable structural performance is manipulated and expressed as a large-scale, programmable, and fast-acting shape change. We present a method for rationalizing this responsive structural system as an assembly using a combination of materials engineering and digital design and fabrication. As a proof-of-concept, a two-meter-long fiber-reinforced cantilevering truss prototype was designed and fabricated. The truss transforms in minutes from one shape that shelters the interior from rain to another shape that acts as an air foil to increase ventilation.

Keywords. Passive Actuation; Chitosan; Structural Assembly; Digital Fabrication.

1. Introduction

1.1. PASSIVELY-ACTUATED STRUCTURES

Responsive structures, buildings, and infrastructure maintain high performance levels in fluctuating environmental conditions through programmed changes in their physical properties, surface features, or form (Loonen, Trčka, Cóstola,

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 441-450. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

& Hensen, 2013). Transformation of shape through controlled motion is a contemporary challenge seen across many disciplines such as robotics (Laschi, Mazzolai, & Cianchetti, 2016), manufacturing (Raviv et al., 2015), materials science (Oliver & Seddon, 2016), interface devices (Yao et al., 2018), and biomedicine (Gao et al., 2016). Currently, the means of enabling shape-changing motion in architecture operates within an electromechanical paradigm, relying on energy-intensive active mechanisms that are complicated and also costly in terms of design, construction, operation and maintenance (Correa et al., 2015). In contrast, biological systems offer alternative examples of water-responsive kinematic structures relying on material properties (Reyssat & Mahadevan, 2009). Material-based passive actuated systems reduce the need for electrical systems, while cutting down points of failure; such material systems are also sustainable and have the potential to simplify the design of the assembly (Correa et al., 2015). The application of water-based actuation for architectural systems is a physical materialization challenge with significant energy-saving benefits that several notable research projects (Correa et al., 2015) (Reflexive Architecture Machines), (Reichert, Menges, & Correa, 2015), (Rüggeberg & Burgert, 2015) have already undertaken. While they demonstrate the exciting potential of hygroscopic-based passively actuated systems, it has been noted there are still two primary challenges facing the development, adoption, and deployment of hygroscopic built structures: firstly, the ability of these structures to bear significant load, and secondly, the time required for water absorption and therefore for the actuated shape changes to occur. The hygroscopic systems of these state-of-the-art projects were designed to sustain only their self weight and respond to alterations in humidity, such that their capacity to achieve significant and quick expansion when saturated with moisture was not exploited; as a result, full actuation typically required several hours.

1.2. CHITOSAN BIOPOLYMER

Hygroscopy is not limited to cellulose-based materials like wood. Chitosan is a highly hygroscopic deacetylated form of chitin, which is the second most ubiquitous natural biopolymer on earth after cellulose. Chitin is found in the exoskeleton and internal structure of invertebrates (Dutta et al., 2004) (Goosen, 1997). In addition to fast-acting hygroscopic potential in its derivative form, chitin can have an ultimate strength capacity of up to approximately 60 MPa - a performance that is comparable to the lower bound tensile strength of aluminium alloys (typically 70-700 MPa), and superior to conventional plastic polymer used in standard additive manufacturing (Fernandez & Ingber, 2012). This unique combination of mechanical strength and hygroscopicity is the reason chitosan has been explored in several industrial and engineering applications such as biomedicine, agriculture, pharmaceutical products, and food packaging.

1.3. CHITOSAN-BASED SHAPE-CHANGING STRUCTURES

Considering the limitations mentioned in section 1.1, we opted to use chitosan as an alternative hygroscopic material that possesses both potential for fast actuation and the strength to sustain full-scale load-bearing of shape-changing structures. By inserting biocomposite chitosan films as dynamic tensile members into a space

truss, a structural system was constructed whose variable structural performance was manipulated and expressed as a large-scale, programmable, and fast-acting shape change. The mechanism that this work was based on is the variability of chitosan's mechanical properties with water content. As chitosan films become saturated, their stiffness and strength decrease markedly (Alvarado et al., 2015). Thus, when the chitosan is inserted as a critical structural member in an assembly, the assembly's structural performance depends on the chitosan's water content. This is expressed particularly clearly in the performance of a cantilever. Weak tensile members (i.e. saturated films) cause a cantilever to "fail" and sag, while strong tensile members (i.e. dry films) allow the cantilever to remain aloft. If these deformations happen in a programmed way and the stresses on the films and members do not overtake their strength, the apparent "collapse" and resurgence of the cantilevering structure can be expressed as a high-deformation shape change. We present a method for rationalizing this responsive cantilevering truss structure as an assembly using a combination of materials engineering and digital design and fabrication. As a proof-of-concept of this materialization methodology and the resultant passively-actuated system's capabilities, a two-meter-long truss prototype was designed and fabricated which transformed in minutes from one shape that creates shelter from rain to another that acted as an airfoil to provide increased ventilation.

2. Material Characterization - Water absorption and Pulling force test

Two types of material characterization were conducted: water absorption and pulling force test. The ability of the chitosan films to absorb water results in linear expansion that contributes to the shape change of the assembly. Therefore, it is important to quantify this expansion. Water absorption studies were conducted by following ASTM standard D570 - Standard Test Method for Water Absorption of Plastics. While this test is typically focused on gauging the weight change of hygroscopic samples due to water absorption, we opted to record both the weight and length changes of the film samples. For this experiment, three gauze reinforced films were cut into 6 x 2 cm strips and conditioned in the oven at 60 ºC for 24 hours, then the weights and lengths were measured. Next, the films were immersed in distilled water for two hours to achieve complete saturation. It was noted, however, that the films could achieve saturation in as little as a few minutes due to their minimal thickness with rolls and twist in the film {Figure 1} during the test. The films were removed from the water and wiped using a dry cloth to remove the excess water on the film. Wet weights and lengths of the film were measured and percentage water absorption for each film were calculated using the formula below {see Table 1 for results}. Hygroscopic materials that have the capacity to absorb large amounts of water undergo large internal forces as the materials dries and the water evaporates. In the case of this research, the drying actuation shape change of the assembly was dependent on the films' internal drying forces being sufficient to lift the weight of the truss structure. For this reason, it was important to quantify this internal drying force, which the authors have termed "pulling force". At present, there are no test methods or standards are available to test this parameter so a custom test method for pull force was created. The test

was performed on an Instron 5943 - 1 kN tensile testing machine {Figure 2(a)}.

$$WeightIncrease \quad (1)$$



Table 1 Increase in % weight and % length

	increase in weight, %	increase in length, %
Film 1	127	11.2
Film 2	136	12.6
Film 3	122	10.8

Figure 1. Rolls and twists in the film during water absorption test.

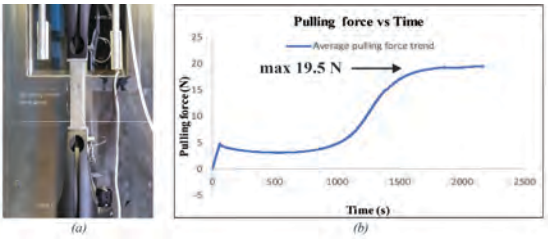


Figure 2. (a) Pulling force test setup; (b) Pulling Force v.s. Time .

The pull force test was initiated by wetting the film until it was saturated and mounting it between grippers (with tabs to avoid slipping) in the tensile testing machine. The initial load of 40 N was applied to the film with 1 mm/min as rate of grip separation in order to pretension the film. Once the ram reached 40 N, the machine held the film at this state. The film would then commence to dry, retracting back to its original size through internal drying forces which were plotted as pulling force vs time. The maximum pulling force observed was 19.5 N {Figure 2(b)}, which is equivalent to the film being able to pull 1.95 kg in truss weight. The truss assembly had to therefore be designed according to these material constraints.

3. Truss Shape Change Simulation

In order to predict the motion of the truss with reference to increasing or decreasing water content of the chitosan, the truss geometry was digitally modeled and a simulation using the Rhinoceros-Kangaroo physics engine was developed. The ties that represented the films were attributed the ability to change their length, reflective of the films' physical ability to expand and contract, while the other struts and ties in the geometric model were given fixed lengths. By feeding the material properties of the film and truss geometry into the iteration-based simulation tool, the shape changes of the assembly over time were visualized and the final expectant geometry output was done. {Figure 3(a),(b),(c)} shows the fully dry curvature profile, initial (partly saturated, zero curvature) profile, and fully wet curvature profile of the cantilevering truss, given the expansion properties of the films.



Figure 3. Different curvature profiles a) Fully dry curvature profile; b) Initial profile (partly saturated, zero curvature); c) Fully wet curvature profile.

In the simulation model, rotations about the truss nodes were assumed to be free, and it was the culmination of the rotations about each node that defined the overall shape change of the assembly. By experimenting with different truss curvature profiles and chitosan expansion properties, the assembly could be intuitively designed and shape change could be programmed. The performance criteria for deciding the final wet and dry state curvature profiles of the prototype were the ability to create shelter from rain in the wet state, and an airfoil-like profile that encourages ventilation in the dry state. Once satisfactory wet and dry shapes were selected, the required nodal rotations and strut and tie configurations of the truss in its noncurved state were then forwarded to the solid modeling process for subsequent parts fabrication.

4. Fabrication of Truss and Film Production

4.1. TRUSS FABRICATION

To simplify the design of the passively actuated structure, the goal was to rationalize the truss as a modular, easy-to-assemble kit of parts in which the films could be inserted. The truss kit consisted of three types of material components: the truss members (the collection of struts and ties), the transversal beams spanning the truss width, and the rotational joints. To ensure that the weight of the truss was within the limits of the chitosan films' pulling force, the truss members were fabricated from hollow carbon fiber composite tubes. Carbon fiber composites feature an excellent strength-to-weight ratio (Bhatt & Goel, 2017), and the tubes were readily available in the required sizes. The transversal beams, and more importantly the joints, were the aspects of the assembly that required customized, irregular details. The simulation results demonstrated that the nodal joints of the truss required increasing rotation around their axis along the length of the truss in order to achieve the desired shape changes. In addition, the angles at which the truss members converged at the joint, as well as the thickness of the members, altered along the length of the truss due to its gradual decrease in depth. Thus, each joint demanded a variable morphology {Figure 4(a), (b)}. Like the joints, the transversal beams required male extrusions in order to fit the tubes, and so these parts also featured custom geometry. For this reason, 3D printing technologies were implemented for the fabrication of these parts. Traditional fused deposition method (FDM) printing on the Fortus 450mc with ASA material was suitable for the transversal beams, considering that they were predicted to take very little load.



Figure 4. Parts designed with bespoke geometries a) Transversal beam design; b) Joint design between two trusses; c) Design of internal fiber arrangements in joint using Eiger software.

FDM and ink jetting printing processes were explored for the joints, with the conclusion that carbon fiber-reinforced FDM printing on the Mark II Markforged printer was required for the large-scale prototype to increase the structural capacity of the joints. After being modeled in Solidworks, the joint designs were imported into the Markforged software Eiger and the internal fiber arrangements were designed to provide the best compromise between structural performance, weight, and material usage {Figure 4(c)}. After printing and finishing, ball bearings were inserted with glue into the joints to reduce rotational friction.

4.2. FILM PRODUCTION

Production of chitosan film {Figure 5(a),(b),(c),(d)} comprised of four steps: i) solution preparation, ii) casting, iii) neutralization, and iv) drying.

i. To prepare the chitosan solution, 3 wt.% 85%-deacetylated chitosan powder of medium molecular weight, 1 wt.% diluted acetic acid, and 96 wt.% distilled water were mixed in a beaker and stirred until no more solid particles were visible. The solution was then covered with aluminium foil and kept for 3 days to completely dissolve. The solution was then centrifuged at 2000 rpm for 5 mins and degassed at 2000 rpm at 20 psi for 12 mins to remove impurities and air bubbles.

ii. A rectangular mould of size 350 x 350 mm was designed and laser cut from acrylic stock material. To prepare the fiber reinforcement, the cotton gauze was pre-stretched, placed at the bottom of the mould, and oriented. The solution was carefully poured to avoid air bubble formation. The mould was then placed in an oven at 60°C for 24 hours.

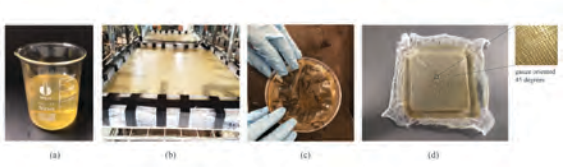


Figure 5. Film production process a) Preparing the chitosan solution; b) Pouring chitosan solution in mold; c) Neutralizing the film: d) Securement of film during final drying and gauze orientation.

iii. The film was then removed from the mould and neutralized with sodium hydroxide (NaOH) for 15 minutes. The purpose of neutralization was to align

the chitin chains at molecular level, facilitating improved strength (Fernandez & Ingber, 2012). The film was then washed with water.

iv. The film then required a second round of drying. A stepwise scheme of three acrylic frames around which the film was wrapped. This allowed the films to pull inwards while being held, with the film shrinkage being translated to sliding of the bottom frames upwards until they all laid on the same plane. This method resulted in the successful creation of flat films.

5. Assembly and Experimental Setup

The assembly was first tested in a series of small-scale models that provided feedback on the film behaviour, joint performance, tolerance for fitting of the tubes, fastening details, and design aesthetics {Figure 6(a),(b)}.

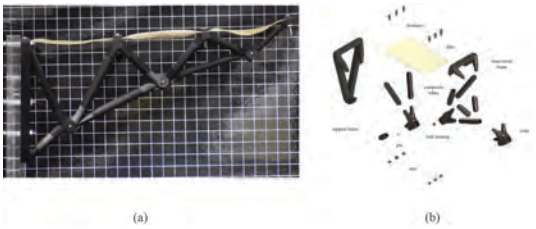


Figure 6. Assembly a) Fully assembled small scale model b) Exploded view of all assembly components.

The final two-meter-long cantilever prototype {Figure 7} was an assemblage of thirteen triangular trusses, joints, and films. The overall assembly weighed just 1.2 kg, which was within the limits of the chitosan films' pulling force (1.95 kg). A support scaffold was constructed using aluminium profiles with an attached acrylic plate for mounting the truss. For testing, the structure was subject to alternating periods of wetting until full saturation of the films and drying until complete dehydration. Means of wetting were tested in different ways, from manual spraying to dousing using low-pressure shower heads to simulate rain. Drying occurred through air drying with different test conditions such as the presence of natural breezes, sunlight, and/or fans. States of fully wet and completely dry were determined based on an absence of noticeable changes in truss curvature over extended periods of time. The data that were being sought from these tests consisted of: 1) the actuation time for both wetting and drying shape changes; 2) the semblance of the shape changes to the simulated profiles; and 3) confirmation of the structural integrity of all the material components.

6. Results & Discussion

6.1. ACTUATION TIME

The average actuation time for the response from the initial truss shape to the programmed wet shape was found to range predictably based on the manner of wetting the films.

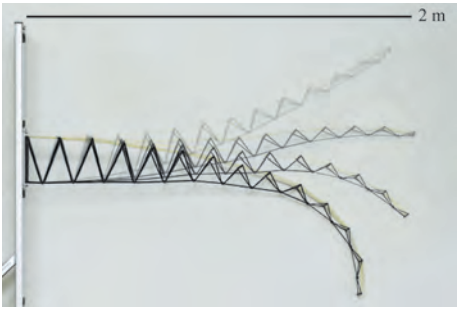


Figure 7. Full scale demonstrator of chitosan based passively actuated structural assembly.

For manual spraying of the films at intermittent intervals, this actuation required 32 minutes, but was shortened to as little as 4.5 minutes when simulating rain by using the low-pressure shower head. For both conditions, the actuation time was drastically lower than previous research projects investigating hygroscopically-actuated structures and pushes the boundary of how responsive a passively-actuated structure can be. Actuation time to reach the programmed dry shape from the wet shape similarly varied, with air drying in little daylight and minimal air flow lasting for 74 minutes and cutting down to a record of 35 minutes in the presence of sunlight and breeze. The large difference in actuation time between drying and wetting was expected given chitosan's hydrophilic nature.

6.2. SHAPE CHANGE COMPARISON

Comparison between the predicted and actual truss profiles was based on the simulations and physical tests, respectively {Figure 8(a),(b),(c),(d)}.

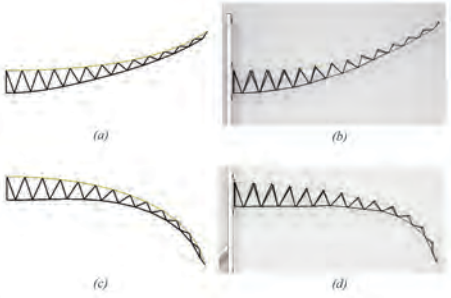


Figure 8. Shape change comparison a) Simulated truss profile in wet state; b) Simulated truss profile in dry state; c)Actual truss profile in wet state; d) Actual truss profile in dry state.

Generally, the simulation predicted the overall conformation of the assembly in both the wet and dry states reasonably well. There were, however, slight differences between the expected and actual results. The simulation is currently purely geometric and does not take into account any loads such as self-weight, which can contribute a degree of mechanical strain to the films located at the beginning of the truss in addition to their hygroscopic strain.

6.3. STRUCTURAL PERFORMANCE

In terms of the structural performance, there was no evident signs of breakage or failure for any of the films, truss members, or truss joints. As demonstrated in the material tests, the films' capacity to pull was sufficient to lift the 1.2-kg lightweight structure into the programmed dry state from the wet state. By involving the hygroscopic material as a key load-bearing component of the assembly, large-scale, fundamental shape changes of the entire structure were achieved. The light weight of the truss had one major downside in that the structure did not feature optimal lateral stiffness, tending to experience torsion due to wind as a result of the minimized size of the joints and beams. In the next prototype, mechanical joints and films have to be strengthened in response to the expected wind loads. In the digital realm, the simulation could be augmented to include analysis steps considering mechanical properties of the assembly components, testing to see if the film's pull strength is adequate to lift the fortified truss at different points of saturation. In addition to improving the structural rigidity of the trusses and pulling capacity of the chitosan films, the durability of the bio-based films to fend off predatory microbial organisms must be increased before implementation in outdoor environments for extended periods of time can commence.

7. Conclusion

In summary, we have developed materials engineering, digital design and fabrication methods for rationalizing a water-actuated, chitosan-based responsive structural assembly as a kit-of-parts. To validate these methods, a large scale prototype was created as a proof-of-concept. The assembly featured large-scale shape change into programmed conformations, and in doing so, proved the ability of a fiber-reinforced hygroscopic material to bear the weight of the entire structure while simultaneously actuating it. This feat was particularly impressive when considering that the truss came in at a total weight of 1.2 kg, while the films themselves only weighed about 3.6 g each, an over 300-fold difference. In addition, the timescale of the dry-to-wet-state actuation was minimized to only 4.5 minutes, which far exceeds the speed of any hygroscopically-actuated architectural assembly to date, to the authors' knowledge. The particularity that went into producing and controlling the responsive biopolymer, which requires more involved forming processes than other traditional polymers or construction materials, was rewarded with enhanced capabilities and new opportunities. This work hopes to push the research field a few steps closer to overcoming the material and fabrication boundaries that currently pervade the widespread adoption of low-to-no-energy passively actuated systems.

Acknowledgements

The authors would like to thank many institutions affiliated with the Singapore University of Technology & Design, including the Fermat Lab, Digital Manufacturing & Design Research Center (DManD), the SUTD-MIT International Design Center (IDC), Architecture & Sustainable Design Pillar

(ASD), and the Fabrication Laboratory. In addition, the authors would like to thank Pablo Valdivia y Alvarado and Oindrila Ghosh.

References

Alvarado, S., Sandoval, G., Palos, I., Tellez, S., Aguirre-Loredo, Y. and Velazquez, G.: 2015, The effect of relative humidity on tensile strength and water vapor permeability in chitosan, fish gelatin and transglutaminase edible films, *Food Science and Technology*, **35**(4), 690-695.

Bhatt, P. and Goel, A.: 2017, Carbon Fibres : Production , Properties and Potential Use, *Material Science Research India*, **14**(1), 52-57.

Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Reichert, S., Menges, A. and Tibbits, S.: 2015, 3D-Printed Wood: Programming Hygroscopic Material Transformations, *3D Printing and Additive Manufacturing*, **2**(3), 106-116.

Dutta, P.K., Duta, J. and Tripathi, V.S.: 2004, Chitin and Chitosan: Chemistry, properties and applications, *Journal of Scientific and Industrial Research*, **63**(1), 20-31.

Fernandez, J.G. and Ingber, D.E.: 2012, Unexpected Strength and Toughness in Chitosan-Fibroin Laminates Inspired by Insect Cuticle, *Advanced Materials*, **24**(4), 480-484.

Gao, B., Yang, Q., Zhao, X., Jin, G., Ma, Y. and Xu, F.: 2016, 4D Bioprinting for Biomedical Applications, *Trends in Biotechnology*, **34**(9), 746-756.

Khan, O.m.a.r., Brucz, J.a.m.e.s., Bruscia, N.i.c.k. and Hume, M.a.t.t.: 2010, "Reflexive Architecture Machines |" . Available from <http://cast.b-ap.net/reflexivearchitecturemachines/warped/>.

Laschi, C., Mazzolai, B. and Cianchetti, M.: 2016, Soft robotics : Technologies and systems pushing the boundaries of robot abilities, *Science Robotics*, **3690**(December), 1-12.

Loonen, R.C., Trčka, M., Cóstola, D. and Hensen, J.L.: 2013, Climate adaptive building shells: State-of-the-art and future challenges, *Renewable and Sustainable Energy Reviews*, **25**, 483-493.

Oliver, K. and Seddon, A.: 2016, Morphing in nature and beyond : a review of natural and synthetic shape-changing materials and mechanisms, *Journal of Materials Science*, **51**(24), 10663-10689.

Raviv, D., Zhao, W., McKnelly, C., Papadopoulou, A., Kadambi, A., Shi, B., Hirsch, S., Dikovsky, D., Zyracki, M., Olguin, C., Raskar, R. and Tibbits, S.: 2015, Active Printed Materials for Complex Self-Evolving Deformations, *Scientific Reports*, **4**(1), 7422.

Reichert, S., Menges, A. and Correa, D.: 2015, Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness, *Computer-Aided Design*, **60**, 50-69.

Reyssat, E. and Mahadevan, L.: 2009, Hygromorphs: from pine cones to biomimetic bilayers., *Journal of the Royal Society, Interface*, **6**(39), 951-7.

Rüggeberg, M. and Burgert, I.: 2015, Bio-Inspired wooden actuators for large scale applications, *PLoS ONE*, **10**(4), 1-16.

Sanandiya, N.D., Vijay, Y., Dimopoulou, M., Dritsas, S. and Fernandez, J.G.: 2018, Large-scale additive manufacturing with bioinspired cellulosic materials, *Scientific Reports*, **8**(1), 1-8.

Yao, L., Niiyama, R., Ou, J., Follmer, S., Della, C., Link, C., Yao, L., Niiyama, R., Ou, J., Follmer, S., Silva, C.D. and Ishii, H.: 2018, PneUI : Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces Accessed PneUI : Pneumatically Actuated Soft Composite Material s for Shape Changing Interfaces, *UIST '13 Proceedings of the 26th annual ACM symposium on User interface software and technology*, **26**, 13-22.

INNOVATIVE DESIGN APPROACH TO OPTIMIZED PERFORMANCE ON LARGE-SCALE ROBOTIC 3D-PRINTED SPATIAL STRUCTURE

ZHEWEN CHEN[1], LIMING ZHANG[2] and PHILIP F. YUAN[3]
[1,2,3] *Tongji University*
[1,2,3] *{zhewench|1810140|philipyuan007}@tongji.edu.cn*

Abstract. This paper presents an innovative approach on designing large-scale spatial structure with automated robotic 3D-printing. The incipient design approach mainly focused on optimizing structural efficiency at an early design stage by transform the object into a discrete system, and the elements in this system contains unique structural parameters that corresponding to its topology results of stiffness distribution. Back in 2017, the design team already implemented this concept into an experimental project of Cloud Pavilion in Shanghai, China, and the 3D-printed spatial structure was partitioned into five zones represent different level of structure stiffness and filled with five kinds of unit toolpath accordingly. Through further research, an upgrade version, the project of Cloud Pavilion 2.0 is underway and will be completed in January 2019. A detailed description on innovative printing toolpath design in this project is conducted in this paper and explains how the toolpath shape effects its overall structural stiffness. This paper contributes knowledge on integrated design in the field of robotic 3D-printing and provides an alternative approach on robotic toolpath design combines with the optimized topological results.

Keywords. 3D-Printing; Robotic Fabrication; Structural Optimization; Discrete System; Toolpath Design.

1. Introduction

With the rapid development and extension application in additive manufacturing, architects have proposed various design methods in robotic fabrication for large-scale spatial structure to meet the requirements in light weight, high productivity, and flexible customization. A method used to create lattice structure by robotic 3D-printing technique has been widely adopted in many projects, for example, Mesh Mould by ETH Zurich (Hack et al 2015), Daedalus Pavilion in Amsterdam by Ai Build (Simondetti et al 2017), Flotsam & Jetsam in Miami by Oak Ridge National Laboratory (ORNL), SHoP Architects, and Branch Technology (Archdaily, 2018). Different printing toolpath logic in the design phase results a unique appearance texture, and this kind of uniform spatial lattice structure formed by robotic extrusion usually plays a role of space filling. However, varying degrees of structural inefficiency exist in those

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 451-460. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

projects due to lack of structural optimization process involved in an early design stage. Researchers start to integrate robotic extrusion with structural optimization methods. One City Pavilion is Branch Technology's newest project aims to create a compressed form by eliminating the parts with low structural efficiency (Branch Technology, 2018). Massachusetts Institute of Technology (MIT) also starts a research on topology optimization framework allows robotic extrusion follows a toolpath to materialize a 3D topology-optimized truss (Huang et al 2018), but up to date this framework can only apply for small physical scale work. The project of Cloud Pavilion by Fab-Union has a similar purpose of combine structure topological solution with robotic 3D printed spatial structure, the different toolpath indicates a specific stiffness level (Yuan et al 2018). Through extensive research, the design team from Fab-Union has started to reconstruct the pavilion using an upgrade design method for robotic toolpath. In contrast with the previous version (Figure 1), the new version Cloud Pavilion 2.0 analyzes the structural behavior of a specific space frame form that meets the constrains of toolpath design in a discrete system, and provides an effective approach to combine topology-optimized results with large-scale 3D printed structure.



Figure 1. Cloud Pavilion 1.0.

2. Methodology

In general, the robotic spatial printing techniques focus more on the application in shell structures or the structures that can be described as a mass of curved surfaces. Application of 3D-printing in building industry requires more efforts on 3D-printed object's structural performance, especially if the design target is a large-scale structure. The conventional design method follows three main steps: (1) define the mesh form for the design object, including parameters like thickness, mesh density and UV ratio; (2) design a toolpath to create cellular or other kinds of supporting structures for space-filling; (3) apply the load constrains and analyze the overall structural performance to check if any loaded element excess the material strength, and the structural failure from simulation results readjustment on mesh parameters in first step. This readjustment processes should repeat until no damages occur and normally cost large amount of design time. To solve this problem, it needs to take considerations of structural optimization in the first step and avoid causing structural problems by improper designed sizes. A new and faster approach to reduce the time of readjustment and achieve a more effective robotic toolpath design process has been introduced and used in the project of Cloud Pavilion 2.0.

2.1. UNIT TOOLPATH PROTOTYPE

Refer to the design process of the Cloud Pavilion, the printed structure is considered as a discrete system, a combination of finite individual elements. In contrast with other robotic spatial printing projects, the robotic end-effector completes an individual toolpath and moves to the next one in the printing direction. It allows the end-effector has an independent toolpath within every mesh box and brings design flexibility for a discrete toolpath. Figure 1 gives an example of a designed mesh with U=10 and V=10, and the printed structure is filled with a single type of toolpath element uniformly.

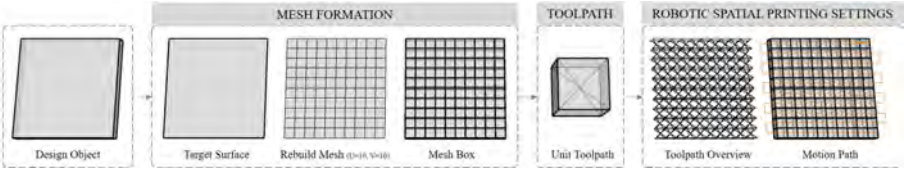
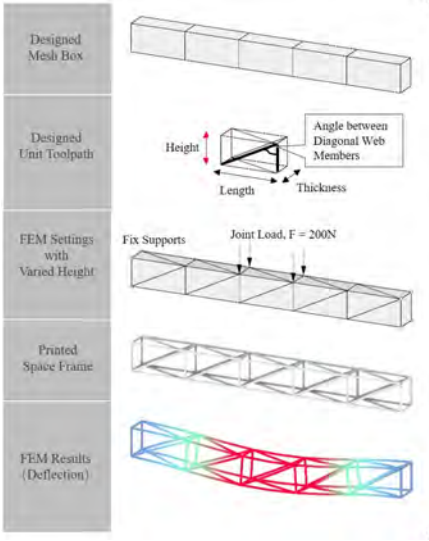


Figure 2. Design Process of Robotic Spatial Printing.

As shown in Figure 1, the unit toolpath design is an independent step for the entire workflow. The unit toolpath design is a critical step since the overall structural behavior is strongly depends on individual elements. A robotic spatial structure is similar to space frame structure system, both constructed from numbers of structs in a geometric pattern and connected with rigid joints. A simple space frame element (Table 1) is selected as the unit toolpath prototype for Cloud Pavilion 2.0 in considerations of collision-free end-effector movement and inherent rigidity of geometry shape.

Table 1. Structural Performance of Printable Beam Struct with Different Heights.



NO.	Thickness	Length	Height	Angle (°)	Max Disp. (m)	Structural Stiffness (F/Max Disp.), (N/m)
1			0.04	78.69	0.01140	17543.9
2			0.06	73.30	0.00560	35714.3
3			0.08	68.20	0.00343	58377.1
4			0.10	63.43	0.00240	83333.3
5			0.12	59.04	0.00184	108577.6
6			0.14	55.01	0.00151	132538.1
7			0.16	51.34	0.00130	154083.2
8			0.18	48.01	0.00116	172562.6
9			0.20	45.00	0.00107	187793.4
10			0.22	42.27	0.00100	200000.0
11			0.24	39.81	0.00096	208986.4
12			0.26	37.57	0.00093	215285.3
13			0.28	35.54	0.00091	219298.2
14			0.30	33.69	0.00091	220507.2
15			0.32	32.01	0.00091	219539.0
16			0.34	30.47	0.00092	217391.3
17	0.08	0.2	0.36	29.05	0.00093	214362.3
18			0.38	27.76	0.00095	210748.2
19			0.40	26.57	0.00097	206611.6
20			0.42	25.46	0.00099	202224.5
21			0.44	24.44	0.00101	197628.5
22			0.46	23.50	0.00104	193050.2
23			0.48	22.62	0.00106	188501.4
24			0.50	21.80	0.00109	183823.5
25			0.52	21.04	0.00112	179211.5
26			0.54	20.32	0.00115	174672.5
27			0.56	19.65	0.00117	170357.8
28			0.58	19.03	0.00120	166113.0
29			0.60	18.43	0.00124	161943.3
30			0.62	17.88	0.00127	157977.9
31			0.64	17.35	0.00130	154083.2
32			0.66	16.86	0.00133	150375.9
33			0.68	16.39	0.00136	146735.1
34			0.70	15.95	0.00140	143266.5

The design team of Cloud Pavilion 2.0 conducts research on structural stiffness of a printable beam struct, which joined by five space frame elements. The value of mesh box's thickness and length remain same while height changes within a domain of 0.04˜0.7m. Given that the beam is under a boundary condition of 50N point loads at 4 joints in the middle and 8 fixed supports at the ends, the maximum displacement can be calculated through finite-element methods. The stiffness of each specimen is collected and analyzed in Figure 2. It shows that the strut reaches its maximum stiffness at height of 0.3m which created an angle between diagonal webs of 33.7 degrees. The results indicate the overall structural stiffness remain relatively stable only within an included angle range between 20 and 55 degrees. The included angle below 20 degrees may result changes in the overall structure behavior, above 55 degrees will contribute insignificant stiffness and may cause unpredictable consequences.

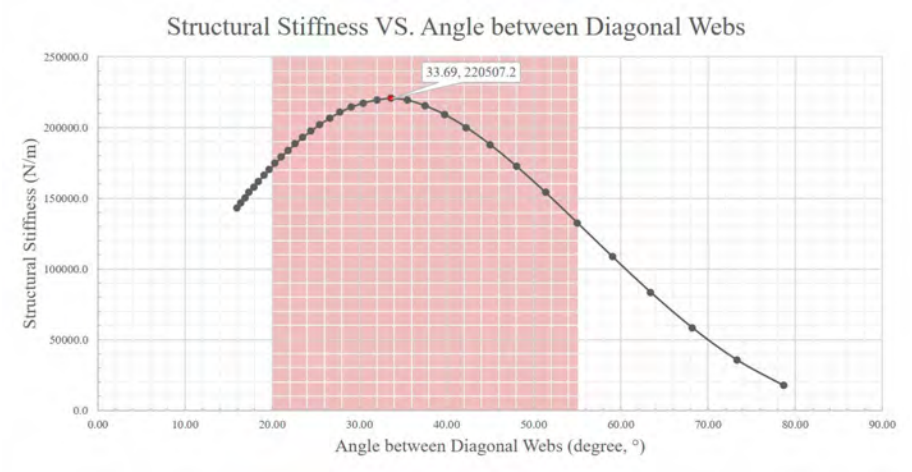
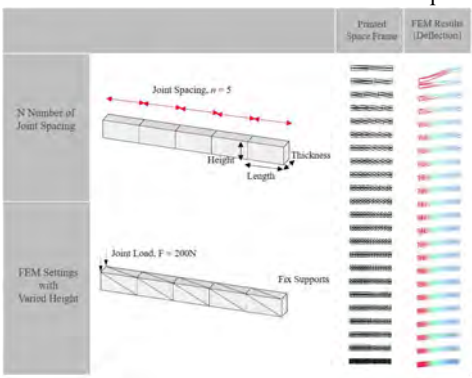


Figure 3. Structural Stiffness of a Printable Beam Struct with Different Heights.

To verify this hypothesis, another approach is given to test the structural stiffness for a cantilever strut with total length of 1m and a combination of n number of space frame elements (Table 2). Given a boundary condition of 100N point loads at 2 joints on the left end and 4 fixed supports on the right end.

As the number of joint spacing changes, its corresponding stiffness is collected and analyzed in Figure 3. The maximum stiffness exists in a combination of 13 space frame elements with an angle between diagonal webs of 52 degrees. If setting 98% efficiency of the maximum value as an evaluation criterion, the number of joint spacing should roughly within a range of 7˜25 and the angle between diagonal webs in each combination have a corresponding range of 22˜55 degrees, which close enough to the first simulated test.

Table 2. Structural Performance of Printable Cantilever Struct with Different No. of Joint Spacing.



NO.	Total Length	No. of Spacing	Length	Height	Thickness	Angle (°)	Max Disp. (m)	Structural Stiffness (F/Max Disp.), (N/m)
1		1	1.000			84.29	0.21977	910.0
2		2	0.500			78.69	0.10810	1850.1
3		3	0.333			73.30	0.08827	2265.8
4		4	0.250			68.20	0.08035	2489.1
5		5	0.200			63.43	0.07709	2594.4
6		6	0.167			59.04	0.07534	2654.6
7		7	0.143			55.01	0.07432	2691.1
8		8	0.125			51.34	0.07370	2713.7
9		9	0.111			48.01	0.07331	2728.1
10		10	0.100			45.00	0.07308	2736.7
11		11	0.091			42.27	0.07295	2741.6
12	1.0	12	0.083	0.1	0.08	39.81	0.07289	2743.9
13		13	0.077			37.57	0.07289	2744.0
14		14	0.071			35.54	0.07292	2742.7
15		15	0.067			33.69	0.07299	2740.3
16		16	0.063			32.01	0.07307	2737.1
17		17	0.059			30.47	0.07318	2733.2
18		18	0.056			29.05	0.07329	2728.8
19		19	0.053			27.76	0.07342	2724.0
20		20	0.050			26.57	0.07356	2718.9
21		21	0.048			25.46	0.07370	2713.6
22		22	0.045			24.44	0.07385	2708.1
23		50	0.020			11.31	0.07780	2570.5

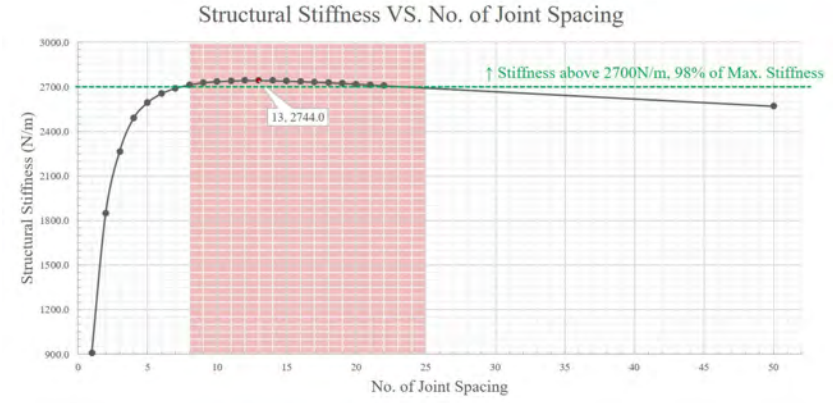


Figure 4. Structural Stiffness of a Printable Cantilever Struct with Different No. of Joint Spacing.

These two studies suggest a unit toolpath design should avoid having an angle below 20 degrees or above 55 degrees between diagonal webs. It also presents a graphic description on the relationship between the mesh box thickness and joint spacing number. For an optimum structural performance, the unit mesh box should have a minimum height-length ratio of 0.7 and not exceeds 2.7. Using the measuring data from mesh box with height of 0.14m as the reference standard, the specimen with 2 times 0.14m (0.28m) has a stiffness value accounts for 165% of the stiffness value for the standard. Similar with joint spacing number, a combination of increased number of unit elements could produce dramatic rising in its stiffness level if within a reasonable range of 7~25 spacings per meter. Base on summarizing the collected data, the first prototype, Type A and two other transformed geometries, Type B and Type C are selected as three kinds of prototypes to represent a clear distinction between its stiffness level (Table 3).

Table 3. Structural Analysis on Three Kinds of Toolpath Prototypes.

		Type A	Type B		Type C
	Standard Toolpath Prototype				
	Combination Length (m)	1	1		1
	No. of Spacing (X Direction)	7	14		14
	No. of Spacing (Z Direction)	1	1		2
	Unit Length (m)	0.143	0.071		0.071
	Unit Height (m)	0.1	0.1	0.2	0.2
	Unit Thickness (m)	0.08	0.08	0.08	0.08
	Angle between Diagonal Webs (°)	55.0	35.5	19.7	35.5
Boundary Condition 1 (Fixed Supports at Ends, 200N Point Load at Middle Part)	FEM Results (Deflection)				
	Max Disp. (m)	0.002038	0.001853	0.001531	0.000795
	Structural Stiffness (F/Max Disp.), (N/m)	98159.5	107918.5	130594.3	251470.6
	% of Type A Stiffness	100%	110%	133%	256%
Boundary Condition 2 (Fixed Supports at one End, 200N Point Load at one End)	FEM Results (Deflection)				
	Max Disp. (m)	0.074343	0.072977	0.023798	0.020118
	Structural Stiffness (F/Max Disp.), (N/m)	2690.2	2740.6	8404.1	9941.3
	% of Type A Stiffness	100%	102%	312%	370%

2.2. STIFFNESS DISTRIBUTION MAPPING OF DESIGNED OBJECT

For the maximum structural efficiency, a two-dimensional topology optimization was applied on the given shell surface. The mesh is divided based on appropriate dimensions on unit element found in previous study, which computes 380 intervals in U direction and 42 intervals in V direction. Run a simulation of topologic-optimization on the re-build mesh surface by using Millipede in Rhino-Grasshopper, given boundary conditions of 4 fixed supports, 3D printing material properties, and under a load condition of gravity. The optimized result is iteratively calculated and shows the corresponding stiffness distribution under the influence of self-weight. According to the analysis results, the demand for the strength of the curved surface was not uniform under the self-weight load. The lighter the color, the stronger its structural demand. The topologic-optimized mesh is separated into 3 zones based on its stiffness level from weakest to strongest, since it is practically impossible to have enough elements with stiffness factor of exactly 1.0, the number of 0.78 is set as the minimum value for zone 3 (Figure 4).

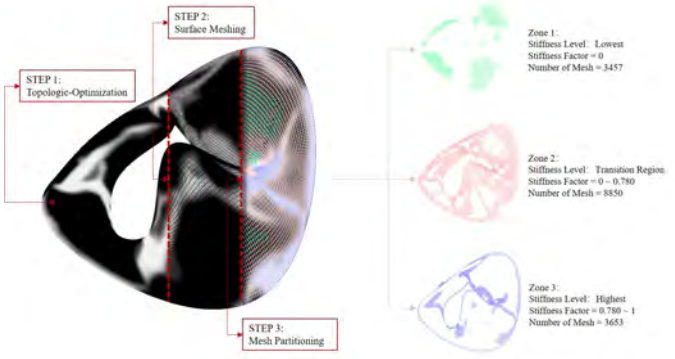


Figure 5. Topologic-Optimized Meshing Process.

As the generation process involves finite element method, the number of stiffness values directly link to the number of discrete elements in the mesh surface. In this project, the mesh (U=380, V=42) has total 15960 discrete mesh units with 16340 mesh vertices. The local stiffness value of every mesh vertices is exacted from a gray-scale value on the topologic-optimized mesh with stiffness distribution. However, the default order of mesh vertices often not sorted at the beginning, a sequence need to be set manually follows a correct robotic printing plane. The overall shell structure thickness varies from 10cm to 20cm, as shown in Table 3, Type A toolpath is set a thickness of 10cm and fills the region of Zone 1 with stiffness factor of 0 (Figure 4), Type B toolpath is for transition use between weakest and strongest region in Zone 2 and Type C toolpath used for region with highest stiffness level, both Type B and C toolpath have a varied thickness from 10cm to 20cm according to its corresponding proportion of stiffness value. The mesh vertices on inner surface is now repositioning by the structural strength needs.

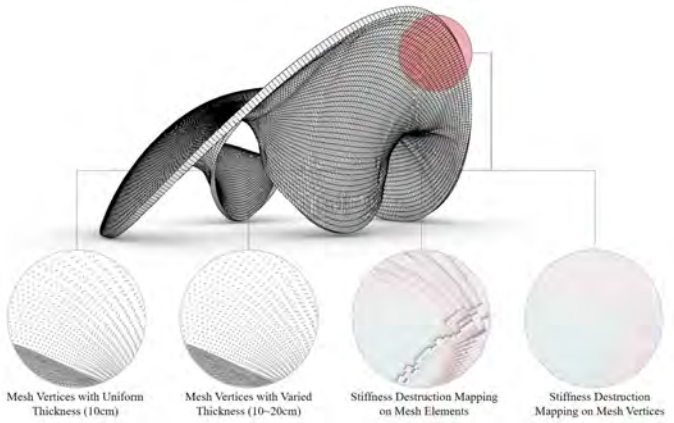


Figure 6. Mesh Vertices Repositioning Process.

A combination of mesh vertices in outer and inner surface is used to form a twisted mesh box, a target box for corresponding toolpath to fill with. Figure 6 shows an overview of the integrated toolpath for Cloud Pavilion 2.0.

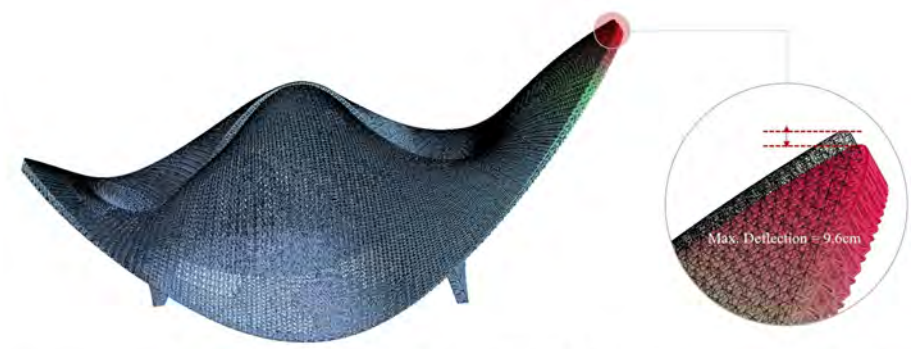


Figure 7. Overview of Robotic Spatial Printing Toolpath.

2.3. STRUCTURAL PERFORMANCE: CLOUD PAVILION 1.0 VS. CLOUD PAVILION 2.0

For large-scaled robotic spatial printing project, it is always important to analysis the overall structural performance to check any potential failure. If the FEA (Finite Element Analysis) results indicate major structural issues exist, the robotic toolpath design process needs repeat until meets its structural requirements. The robotic toolpath design explained above greatly lower the chance on readjustment process since the geometry of unit toolpath is created to maximum its ability of bearing loads. In contrast with Cloud Pavilion 1.0, this project increases the complexity on varying thickness and edge-sealing toolpath in order to achieve a reinforcement purpose. The comparison of the FEA results on the two versions is shown in Table 4.

Table 4. Overall Structural Performance on Cloud Pavilion.



	Max. Compression Stress (Mpa)	Max. Tension Stress (Mpa)	Max. Bearing Tension (kN)	Max. Displacement (m)
Cloud Pavilion 1.0	177.8	8.9	0.57	0.510
Cloud Pavilion 2.0	30.8	5.1	0.3	0.096

For the Cloud Pavilion 2.0, the maximum deflection occurs at the large cantilever with a dropping of 0.096m, which is about a decrease of 82% of the deflection in Cloud Pavilion 1.0. Table 4 also shows that, for Cloud Pavilion 2.0, both compressive and tensile load exist in printed bars are reduced a large amount, the overall structure behavior is more uniform and stable. Massive experiments are conducted on random joints and bars selected from the robotic extruded struct (Figure 6). Results show a failure normally occur at the joints with a tensile load over 0.6kN, which meets the maximum bearing tension of 0.3kN.

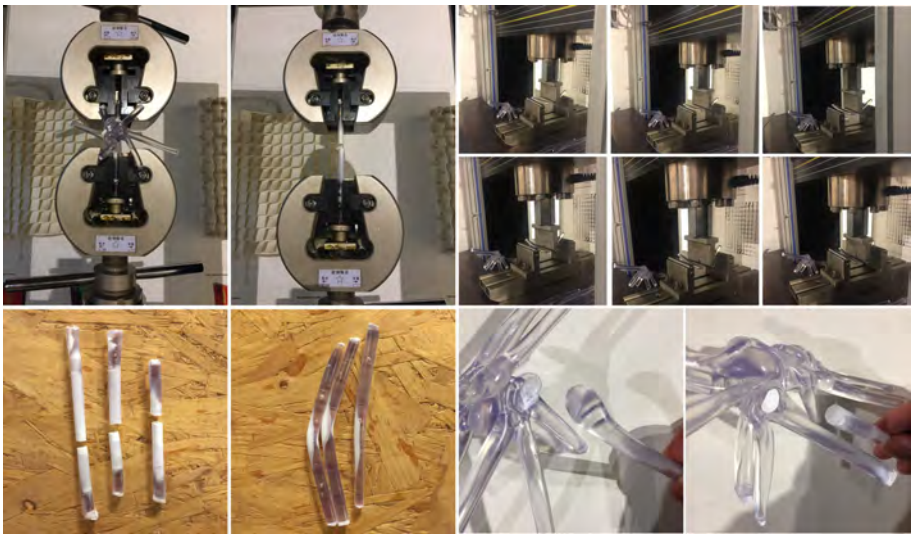


Figure 8. Tensile and Compressive Tests on Extruded Joints and Bars.

3. Limitations

This design process neglects the influence caused by the designed geometry, in this case, a curved surface could bring deformation on the unit mesh box at high curvature region. A deformed mesh box directly impacts the measuring angle between diagonal webs, because a portion of toolpaths have the angle value either below 20 degrees or exceed 55 degrees are not taken in consideration during design process.

The project optimized aiming at maximizing structural stiffness, but the project is in fact a multi-objective optimization problem that involves not only stiffness but also material usage, printing time, and other structural targets. Therefore, the actual complexity of robotic spatial printing projects is higher than expected.

4. Conclusion and Further Research Goal

The discrete system methodology applied in this project of Cloud Pavilion 2.0 improves the efficiency in design process for robotic spatial printed structure by using topologic-optimized toolpath design. There is a huge potential market for the robotic spatial printing applied in the field of building industry, especially in large-span structure, if structural behavior is optimized. But the overall structural performance for a robotic spatial printed structure highly relies on its joint strength. Unlike the traditional injection molding technique, the process of robotic extrusion greatly reduces the joint strength due to temperature difference and less effective contact area between joint elements. More research is needed on new 3D-printing materials and robotic end-effector improvements. This innovative design process for robotic toolpath only provides one type of combination of prototypes, for the aesthetic needs, more studies on different toolpath prototypes should also be

completed.

Acknowledgements

This research is funded by the National Natural Science Foundation of China (Grant No.51578378), the Special Funds for State Key R&D Program during the 13th Five-year Plan Period of China (Grant No.2016YFC0702104), the Sino-German Center Research Program (Grant No.GZ1162), and Science and Technology Commission of Shanghai Municipality (Grant No.16dz1206502, Grant No.16dz2250500, Grant No.17dz1203405, Grant No.18dz1205604).

References

"Flo & Jet / SHoP Architects" : 2018. Available from <https://www.archdaily.com> (accessed 16th December 2018).

"ONE CITY PAVILION" : 2018. Available from <https://www.branch.technology> (accessed 16th December 2018).

Hack, N., Lauer, W., Gramazio, F. and Kohler, M.: 2015, Mesh Mould: robotically fabricated metal meshes as concrete formwork and reinforcement, *Ferro-11 and 3rd ICTRC*.

Huang, Y., Carstensen, J. and Mueller, C.: 2018, 3D truss topology optimization for automated robotic spatial extrusion., *Proceedings of IASS 2018*.

Simondetti, A., Luebkeman, C. and Uerz, G.: 2017, *2060: An Autonomously Crafted Built Environment*, Architectural Design.

Yuan, P. F., Chen, Z. and Zhang, L.: 2018, Application of discrete system design in robotic 3-D printed shell structure, *Proceedings of IASS 2018*.

Theory, Philosophy & Methodology

DIGITAL FABRICATION - FROM TOOL TO A WAY OF THINKING

Toward redefining architectural design methodology

DANIELA SILVA
[1]*ISCTE-IUL*
[1]*danielamoreirasilva@gmail.com*

Abstract. The digital design appears as an integrated process from conceptualization to materialization and fabrication. The main question is: How the new medium changed the workflow in architecture from a linear model to a cyclic model and the role of new materialization as a form of design thinking? This paper is part of a study that investigates the architectural design process and starts from the premise that we should expand the study of design methods to include other approaches. It considers digital fabrication not as a tool, but as an integrated strategy in collaborative digital processes that can allow a better communication along the design process. It presents the development of design methodologies in order to contribute to a greater understanding of the methodology for design projects with caution to the fact that each one reflects the period in which it was developed.

Keywords. Digital Fabrication; Computational design; Architectural design.

1. INTRODUCTION

"(...) What can this medium do? (...) What do I wish to do with this medium?" [McCullough, 1998].

The rapid development of computational design methods has a huge impact on contemporary architectural design practice. Design methods have always changed, considering that design thinking is bound to the representational medium [Leach & Yaun, 2017] [Menges & Ahlquist, 2011]. Thus, its scope can be expanded by the enlarged possibilities offered by the new media and techniques [Carpo, 2017] [Kieran & Timberlake, 2004].

Today, most of the buildings are both designed and fabricated with computational methods. The use of digital tools and manufacturing processes and their synthesis through the use of novel technologies is significantly changing the future of architecture and construction [Kolarevic, 2003]. With the introduction of in-house rapid prototyping machines, the architectural design process within the practice has changed [Peters, 2008]. Currently, computational techniques have enabled new design methods, casting a revaluation of theories related to design

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 463-470. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

[Ostwald, 2012] [Booth, 2009]. Digital design emerges as a holistic integrated process from conceptualization to materialization to fabrication [Oxman, 2014].

In this context, is necessary to offer an informed overview of the development of design methodologies in architectural practice, from computerization to computing and the role of advanced digital fabrication in the design process [Burry & Burry, 2016]. The main question is: How the new medium changed the workflow in architecture from a linear model to a cyclic model (Figure 1 and 3) and the role of new materialization as a form of design thinking?

The thesis of this article is that the assimilation and synthesis of digital communications among architects, engineers, fabricators and builders is dramatically altering how we work and our relationship to the tools we use. New digital capacities are restructuring the organization and hierarchy of design from autonomous processes to collective workflows. The historical role of the designer as an author, a sole creator, is being replaced with semi-autonomous, algorithmically driven design workflows deeply embedded in a collective digital communication infrastructure [Picon, 2010]. This is creating a number of pressures on the discipline of architecture to reorganize around the opportunities, and risks, of these changes. One of these changes is the role that design itself might play.

The logics of digital fabrication in architecture have begun to structure the way that architects design, the way that builders build, and the way that industry is reorganizing.

2. BACKGROUND

Starting in the 1950's, the study of design methods evoked the perception of the increased complexity in industrial products. The first models presented in a linear paradigm, evolved to more integral representations of the design process in a way that affects the entire system.

During the end of the 1950s and beginning of the 1960s, researchers were trying to describe the creative problem-solving process at work in design by way of the logical structure of apparent activities that appeared to take place. In this context design was seen as a series of stages defined by dominant forms of activity, such as analysis, synthesis, evaluation and so on.

Bruce Archer (an industrial designer from Hochschule fur Gesttaltung at Ulm and the Royal College of Art in London) proposed a more "operational" model of design. In a simple way, Archer's model is schematically showed in Figure 1. The design process model that he proposed predicts the necessity for different approaches in different moments of the process: systematic observation and inductive reasoning in the analytical phase, and subjective and deductive reasoning in the creative phase. Design is then seen as a sequence of activities defined by their orientation and by the type of task involved, and the lineage of tasks can be easily recognized. Additionally, the process can be described in a general form, regardless of specific circumstances. Feedback loops of relationships between activities are clearer in this case than in previous models, resulting in an organization of activities less quietly set. With the reference to

three interrelated domains for the process, particularly the external representation, process of activities, and the problem solver, a distinction begins to be made between overt behavior and the cognitive realm - a departure from the behaviorist position [Rauterberg, 2008] [Pallasmaa, 2009]. The focus is still on the sequence of activities and on the behavioral domain.

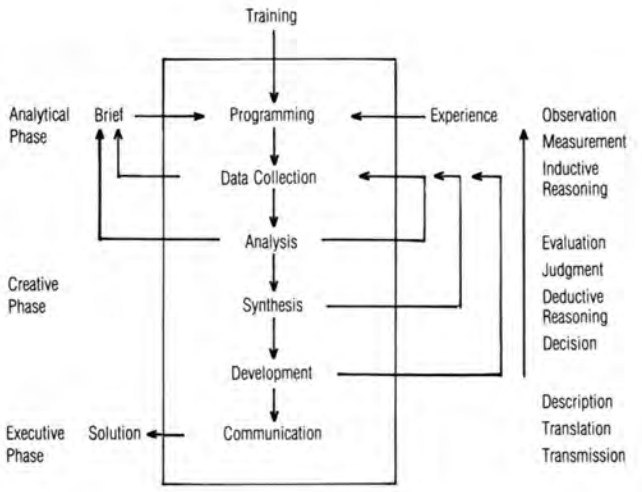


Figure 1. Bruce Archer's model of the design process [Rowe, 1987].

Looking at the first representations, linearity was a common characteristic. Many authors considered the existence of loops and feedbacks in their research, but it was seen as a problem or an opportunity to correct errors and not as part of the design activity and its nature of uncertainty. The process was no longer linear because successive iterations are needed to define both problem and solution. To this concept of parallel evolution between problem and solution is given the name co-evolution. This concept is deeply analyzed by Nigel Cross [2008].

March's [1984] (Figure 2) broke with the linear representation of design process, based on the assumption that the problem is dependent on the solution and that the inductive-deductive thinking is inadequate for the production of synthesis in the design process. March defends the idea of abductive thinking, which is linked to the production (synthesis), while induction and deduction are related to research (analysis). In other words, "deduction proves that something must be; induction shows that something actually is operative; abduction suggests that something may be" [Cross, 2008]. March's representation for design process (Figure 2) is a cyclic model that starts with production (preliminary requirements and assumptions about solution types to describe a design concept), followed by deduction (to predict solutions performance) and goes through a moment of induction (indicating changes and refinements in the concept).

The IDEO's design process introduces us to a nonlinearity, described by Brown [Brown, 2008, pp. 88] as "a system of spaces rather than a predefined series of orderly steps". Figure 3 demonstrate a system that goes beyond the classic models.

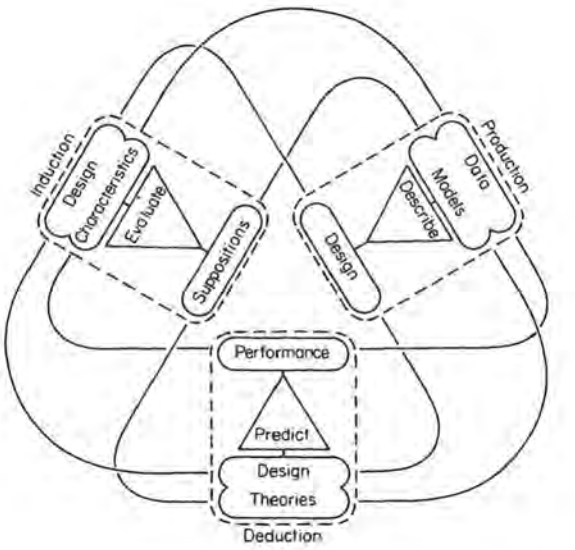


Figure 2. March's diagram [Cross, 2008].

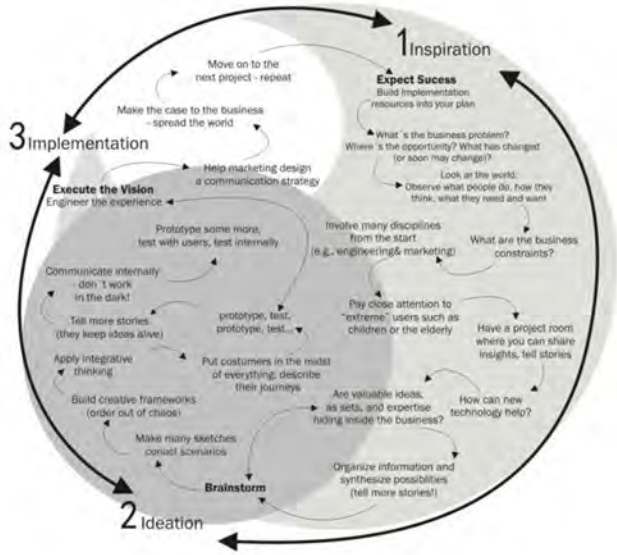


Figure 3. The IDEO process [Cross, 1984].

The process works around three areas: inspiration, ideation and implementation. Inspiration is linked with the motivation behind the search for a solution (a problem, an observation or both). Ideation associates generation, development and testing of an idea that could drive to a solution. Implementation in the other hand is directly related with the product launch. While developing a project, all three

phases can be explored, in particular inspiration and ideation, in order to clarify ideas and enroll in new paths. It's important to refer that the design in IDEO has a competent group of multidisciplinary professionals with different backgrounds. This allows that different activities can be done simultaneously, saving time in comparison with linear processes.

Professionally divided design processes are being redefined as integrated design systems. Vast amounts of information, both descriptive and analytical, are now instantaneously available to help define and assess design options. Much, if not all, of this information is filtered through software that, by extension, structures the digital environment in which architects design. Architectural design has become a complex workflow in which geometric, spatial and technical information is filtered through simulation, analysis and optimization processes, with the aim to form integrated, parametric building information models that can generate an array of output ranging from energy usage to manufacturing instructions. With the introduction of parametric and algorithmic design processes, the reliance on the visual as the primary source of design production and evaluation gets supplemented by rules, numbers and other forms of quantitative logic. This logic is placed between creative thinking and foregrounds the way in which architects are engaging with the broader cultural and technological debate between the open nature of scripting and the closed nature of applications as they begin to define the design space in which they work.

3. METHODOLOGICAL PROCEDURES

Based on the understanding of design methodologies taxonomies, a framework for design thinking has been generated, by observing the models as a manifestation of the design discourse. Clearly, there is a gap between the complexity of practice and the simplicity of a theoretical model [Schön, 1983]. However, the models cannot be neglected due to its main function as an element able to structure a complex activity to allow the detachment of the professional, which enables him to examine critically the process.

This article presents a brief overview of design models in order to contribute to a greater understanding of the methodology for design projects with caution to the fact that each one reflects the period in which it was developed.

The three diagrams presented in this paper (Figure 1, 2 and 3) attempt to summarize the workflow changes in architecture from a linear to a cyclic model. The identification of these tree moments in the design methodology practice helps us to understand the evolution of the methodologies of thinking along the design process.

4. RESULTS

This paper presents the preliminary research results that attempt to understand the role of digital fabrication on design process in architectural practice along with a discussion of their capacity to question the basis of education and the conceptualization of architecture.

The emergence of complex technological and environmental problems, challenge the professionals to seek novel practices of collaboration and exchange

that deliberately overcome and dissolve traditional disciplinary boundaries. This collective approach to working with technology is not only revolutionizing how things are designed and made, but is fundamentally transforming the culture, politics and economics of the creative industries as a whole.

If the first robotic age - the age of industrial automation - vastly improved our physical productivity, the second robotic age will surely come to distinguish itself as a driver of creative capacity.

The present moment is ripe for connecting technology with imagination and materialization, inspiring new fundamental discoveries and opening new scientific frontiers.

Looking at the presented models as a reflection of the design methodology and development, it's clear that during the half century occurred a notable evolution between the linear model of Bruce Archer and the cyclic model of IDEO. When comparing these models, we must consider the context as well: they arise from different eras and the evolution of technology during this period certainly has an important role in their characteristics. We move from the era of mass production to the era of mass customization and clearly the second has become the reference. There is a gap between the complexity of practice and the simplicity of a theoretical model that the studies around methods for design can't ignore. Nonetheless, the models cannot be ignored due to its essential function as a component that has the ability to structure a complex activity but with a detachment of the professional, which facilitates the critical analyses of the process. Also one important function of these models is to standardize the language adopted by a team of product development, allowing communication between different teams.

Considering the current state of architecture practice, it is clear that the IDEO model (Figure 3) is still relevant to the current context of practice. Depending on each studio practice, other denominations could be applied, but the workflow has as a common ground the one presented in Figure 3. New digital capacities have restructured the organization and hierarchy of design from autonomous processes to collective workflows, making a new dialogue between design and making. In this sense, digital fabrication has reinforced the idea of a flexible and permeable system for design thinking process. The multidisciplinary nature of integrating digital processes remains a key challenge to establishing a digital building culture. Traditionally separated disciplines such as: architecture, structural design, computer science, materials science, control systems engineering, and robotics now need to form strong research connections.

5. DISCUSSION

This paper is part of a study that investigates the architectural design process and starts from the premise that we should expand the study of design methods to include other approaches. It considers digital fabrication not as a tool, but as an integrated strategy in collaborative digital processes that can allow a better communication along the design process. It presents the development of design methodologies in order to contribute to a greater understanding of the methodology for design projects with caution to the fact that each one reflects the period in which it was developed.

The Architecture, Engineering and Construction industry is in a state of flux fueled by transformative shifts in technology and design. Financial incentives around new economics of production, increased efficiencies afforded by streamlined communication and the automation of labour-intensive processes are already underway. The suggestion of this article is that there is a momentary opportunity to give a direction to this shift that will set the foundation for the next generation of architects.

Technology research should not be bound by constricting disciplinary standards, constrains or ideologies lest we limit its potential. Yet to explore this unprecedented potential requires not only a technical grasp of digital fabrications' capabilities and limitations but also an in-depth understanding of the disciplinary consequences of technology research.

There is no doubt that the profession is expanding traditions of making towards new techniques that integrate manual craft, computational design, digital fabrication and advanced robotic technologies, often in hybrid relationships.

The identity of the architect is largely built upon the ability to author design solutions that satisfy pragmatic concerns while also capturing the imagination by producing unique visual and spatial experiences. Pragmatic concerns are usually well defined and therefore can be solved with a high degree of certainty - the respective design space is relatively narrow, more quantitative, and possible to define algorithmically. The creation of unique experiences, by contrast, is ambiguous, it relies on inference and an indirect connection between an architect's knowledge and own lived experiences and how well they can anticipate responses from users. The result is never fully known of predictable. In this case, the design space is difficult, if not impossible to define algorithmically; it is highly qualitative and therefore better suited to human judgment.

While this portrayal of design space as either quantitative or qualitative is perhaps oversimplified, as these two threads are more typically intertwined, it serves to highlight the challenge of capturing the full range of architectural design intent within digital workflows. With more and more steps in these workflows being driven by design, analysis and performance algorithms authored by anonymous programmers, the identity and authorship of the architect come into question. If the architect has been increasingly displaced by technologically mediated processes over a long time, the expanded realm of digital workflows transforms this in historically new ways.

6. CONCLUSION

Digital technologies have handed architecture a very powerful tool, which has led to an explosion of experimentation in the last two decades. This technology has shaped an entire generation of architects. Current research on digital fabrication in architecture indicates that the development and integration of innovative digital technologies within architectural and construction processes are transforming the building industry.

Questioning the importance and impact of design thinking methodologies in the architectural design studios is a backbone of architectural education in the twenty-first century. 3D printing and digital manufacturing are disruptive

technologies that are changing architects and designers daily lives. These trends require new skills, based on a deep understanding of digital continuum from design to production, from generation to fabrication. This continuity transcends the merely instrumental contributions of a person-machine relationship to praxis, has begun to evolve as a medium that supports a continuous logic of design thinking and making.

If we may speculate on the future of design thinking and its influence on architecture, we can say that it's becoming a hybrid model of practice with manufacturing.

Design thinking methodologies associated with digital fabrication emerged as a leading technological and design issue of digital research and design. As designers, we are witnessing a no frontier between computational design and digital fabrication.

With digital fabrication, we turn our attention to the physical nature of architecture. We open up new aesthetic and functional perspectives and address the digital in architecture as a radically contemporary building culture. Through not only digital designed but also digitally materialized architectures, it becomes possible to engage with both the fundamental issues of our digital age and the purpose of architecture itself, that is, its concrete physical realization.

ACKNOWLEDGEMENTS

This work is partly supported by the Fundação para a Ciência e Tecnologia (FCT), Portugal project grant UID/Multi/04466/2019.

References

Booth, P.: 2009, Digital materiality: emergent computational fabrication, *Conference: 43rd Annual Conference of the Architectural Science Association, ANZAScA 2009*.

Brown, T.: 2008, Design Thinking, *Harvard Business Review*, **1**, 84-92.

Burry, M. and Burry, J.: 2016, *Prototyping for Architects*, Thames & Hudson.

Carpo, M.: 2017, *The Second Digital Turn: Design Beyond Intelligence*, MIT Press.

Cross, N.: 1984, *Developments in design methodology*, Wiley.

Cross, N.: 2008, *Engineering design methods: strategies for product design*, John Wiley & Sons.

Kieran, S. and Timberlake, J.: 2004, *Refabricating Architecture: How Manufacturing Methodologies Are Poised To Transform Building Construction*, McGraw-Hill.

Kolarevic, B.: 2003, *Architecture in the Digital Age: Design and Manufacturing*, Taylor & Francis.

Leach, N. and Yaun, P. F.: 2017, *Computational Design*, Tongji University Press.

March, L.J. 1984, The Logic of Design, *in* N. Cross (ed.), *Developments in design methodology*, Wiley.

McCullough, M.: 1998, *Abstracting Craft: The Practiced Digital Hand*, The MIT Press .

Menges, A. and Ahlquist, S.: 2011, *Computational Design Thinking*, John Wiley & Sons.

Ostwald, M. 2012, Systems and Enablers: Modeling the Impact of Contemporary Computational Methods and Technologies on Design Process, *in* G. Ning and X. Wang (eds.), *Computational Design Methods and Tecnologies. Aplications in CAD, CAM and CAE Education*, IGI Global.

Oxman, R. and Oxman, R.: 2014, *Theories of the digital in Architecture*, Routledge.

Pallasmaa, J.: 2009, *The thinking hand*, John Wiley & Sons.

Peters, B. and De Kestelier, X.: 2008, Rapid Prototyping and Rapid Manufacturing at Foster + Partners, *Proceedings of the ACADIA 2008*.

Picon, A.: 2010, *Digital Culture in Architecture*, Birkhäuser.

Rauterberg, H.: 2008, *Talking Architecture: Interviews with Architects*, Prestel.

Rowe, P.: 1987, *Design Thinking*, Cambridge MA MIT Press.

Schön, D.: 1983, *The Reflective Practitioner: How professionals think in action*, Temple Smith.

ARCHITECTURAL FORM GENERATION BASED ON THE DNA ALGORITHM

CHUANWEN LUO[1], MINGYU JIN[2] and LU YIN[3]
[1,2]*School of Architecture and Art, North China University of Technology, China*
[1]*witchwen@163.com* [2]*jinmingyu@126.com*
[3]*School of Architecture, Tianjin University, China*
[3]*yinlu1983@126.com*

Abstract. With the development of computer technology, complex patterns in architectural design modeling have become a reality. The core of architectural form generation in the parametric design is the algorithm. The article observes the morphology and structure of DNA and implements the algorithm by the secondary development of Rhinoceros. By comparing the different parameter combinations that generate forms, the affection of each parameter is more intuitively understood. In the end, a prototype design of a landscape bridge has been carried out applied with the Double Helix algorithm.

Keywords. : DNA algorithm; Double helix structure; Architectural Form Generation; Secondary development; parametric design.

After Modernism, architects devoted themselves to the design of diverse building designs. One important way is to learn from nature and biology. It is generally believed that the utilized of biomimicry for form-generation is for efficiency, because biological forms have evolved for higher efficiency and survival over generations.

This paper proposes a novel method for the architecture design, based on the digital diagram of the biological form of DNA double helix structure, analyzing the prototype and form characteristics, using the computer technologies, the algorithm is designed and developed and applied to architectural design.

1. Research background

1.1. THE PRINCIPLE OF FORM GENERATION

As a complex of function, technology and art, architecture has its own characteristics. It is both an opportunity and a challenge to learn from or transform natural biological forms. The current parametric architectural design combines computer technology with graphics, mathematics, biology, and geometry to form a more intelligent and logical architectural design method. New architectural forms are generated based on algorithms, which can help inspire designers. The form that algorithmic logic produces leads to deeper thoughts.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 471-480. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

The integration of parametric into architectural design leads to parametric design. In the parametric design, the core is algorithm, and algorithms can translate geometric rules into different forms. The algorithm contains the logic and functional relation of the form to be generated, and determines the influences of each parameter in the algorithm, and, also, determines the result of the form generation after the calculation. A series of related researches of parametric design carried out by applying algorithm has been studied, such as DNA algorithm, cytoskeleton algorithm, and birds foraging, etc.(Xu Weiguo 2018)According to Xu Weiguo, a professor at the school of architecture, Tsinghua University, parametric design is to quantify parameters changes in design. Each parameter is an analysis of one or more important factors in the design process. Changing the values of the parameters will lead to different design results. (Xu Weiguo 2016)

1.2. APPROACH

As Peter Eisenman said, as a generative device in process of architecture design, the diagram is a form representation. (Eisenman 1999)The pioneer architects combined graphics theory with digital technologies to form a digital graphic design method that integrates the graphics with algorithms in specific operations, which provides a new method and content for architectural design. (Xu Weiguo 2018) At the same time, the development of computer technology also provides a much more powerful technical support for digital graphics. The gradual perfection of the modeling, rendering and human-computer interaction functions in graphics, and the development of computer language all play a crucial role in the architectural prototype design, model analysis and scheme optimization of the parametric design. (Leach 2012)

To borrow biological form for architectural form generation, firstly, the characteristics of biological morphology have to be distinguished and embody these features in the algorithm. Then, the algorithm is written into the program. A series of graphics that share the same biological morphology characteristics can be generated as the embryonic form of architectural design after the computation. The program is not only the simulation of the biological form, but also the generation of plenty of architectural prototypes according to different parameters.

The logic of this research is as below:

(1) Morphological feature analysis of biological archetypes.

(2) Research and design of the algorithm with a flow chart.

(3) Second development based on Rhinoceros, which is programming.

(4) Generating the design prototype by inputting parameters.

(5) Revise and perfect the logic of the algorithm.

1.3. INNOVATIONS

The innovations of this paper are as follows:

(1) The logic of the DNA algorithm has been sorted out and completed.

(2) The realization of algorithm directly using C # language on both Visual Studio and Xamarin platforms, that makes the algorithm able to run on Windows

and OS system.

2. Prototype analysis

Currently, the recognized secondary structure of DNA is the double helix structure, and the establishment of this model is based on two aspects. The first is the quantitative analysis of various DNA bases by E. Chargaff et al in the early 1950s(Edström 1951). Secondly, Wilkins's team used X-ray diffraction to study the crystals of DNA and measured the DNA molecules as spirals(Zubay, Wilkins 1962).

James D. Watson and Francis Harry Compton Crick are based on the study of Maurice Hugh Frederick Wilkins and Rosalind Elsie Franklin in Nature (Watson, Crick 1953), which describes the double helix structure of DNA for the first time, determines the basic morphology of this biological macromolecule and gives the schematic of the double helix structure in Figure 1. The DNA double helix structure they discovered was the B-DNA confirmation, and that is the confirmation of DNA under physiological conditions or under low saline conditions. This confirmation makes the DNA in the lowest energy state, the most stable structure, and it is an ideal state. In addition, there are multiple conformations of DNA such as A-DNA, C-DNA, D-DNA, E-DNA, T-DNA, Z-DNA, etc., but these confirmations are based on a double helix structure.

The morphology of DNA can be divided into two related forms: secondary structure and tertiary structure. The secondary structure of DNA molecules is formed by two long chains of deoxygenated nucleotides coiled in antiparallel, in the form of a double helix. Based on which, the double helix chain is constantly changing, then forming different types of helix space segments. DNA tertiary structure is a super-helix structure formed by continuing winding and rotating on the basis of secondary structure.

The first thing to study DNA morphological algorithm is to study the algorithm of the helix. On the basis of helix algorithm, the chain formed by helix is deformed to form a super-helix structure. A spiral can be formed based on an existing curve. If the curve, which the initial helix formed along, is straight, the resulting form is similar to the secondary structure of DNA. Or the resulting form is similar to the tertiary structure if the origin curve is a spatial curve.

Based on the geometric principle of DNA morphology, this study uses the control point method to construct the algorithm, which is setting control points generates the curve. The control points can be set in various ways and can be selected randomly or one by one. For example, the production curve of control points can be selected randomly from the generated points in the rectangular plane. According to the same geometrical principle, the morphological generation is carried out through different data structures and parameter relations.

3. Implementation of the DNA Algorithm

3.1. PLATFORM

In this paper, according to modeling requirements, Rhinoceros is used as a modeling platform, Xamarin and Visual Studio are program development platforms, and based on Rhinoceros Application Programming Interface (API), the algorithm can be developed in C # language on Xamarin and Visual Studio. Rhinoceros is professional 3D modeling software developed by McNeel in 1988 based on NURBS surface, which runs smoothly on personal computers. It can be widely used in architectural design, 3D animation, industrial manufacturing, scientific research, and mechanical design. Its model is suitable for almost all 3D software.

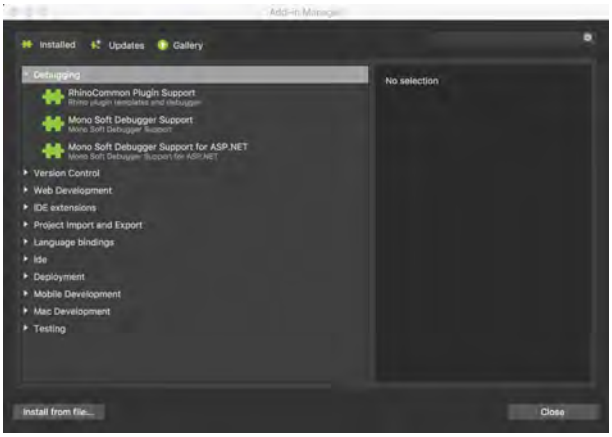


Figure 1. RhinoCommon Plugin Support Library has been loaded in Xamarin Platform.

Under the OS system, the Xamarin software platform can directly call Rhinoceros in time and execute C # program scripts after the RhinoCommon Plugin Support Library, including wizards and the Rhino debugger, (Thompson 1917) has been loaded. Compared to Visual Studio on Windows, Xamarin was acquired in 2016 which lead it contained the same functionalities in Visual Studio in September 2017. To develop an algorithm, it needs to be generated a .dll file and manually invoke the script in Rhino. The steps are complicated and many temporary files are generated. Therefore, Xamarin on the OS system was used for development in this study.

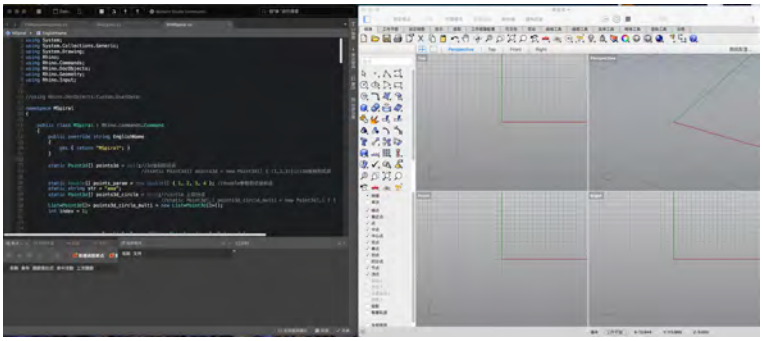


Figure 2. Xamarin Platform and Programming Interface, Xamarin can directly Calling Rhinoceros for modeling using the command newly developed.

The algorithm development in Xamarin creates Rhinoceros' Application object, establishes the root object, realizes Rhino application control and interface rewriting through the access to RhinoCommon, Rhino.UI and other function libraries, and invokes the properties and methods of the root object. The referenced library eventually implements handle the exchange.

3.2. STEPS OF ALGORITHM FUNCTION IMPLEMENTATION

Based on the biological morphology, characteristics, and graphical learning and analysis of secondary and tertiary DNA structures, it can be seen that the DNA morphology algorithm needs to study the helix algorithm at first, and on this basis, the helix is deformed into a super-helix structure. The main implementation features are as below:

(1) Select the curve A to generate a form on (the type curve including the type of line). According to the Rhino API defines, the *RhinoCommon* curve type contains the method *DivideByCount (Int32, Boolean, Point3d [])*, using by which, A can be divided into equal segments by inputting the parameter n, the method will also output the equal points collection *points3d_part* on the curve segment.

Table 1. Divide the curve.

```
private static Result dive_spiral(ObjRef objref, Point3d[] points3d_part,
                                  Double[] points_param_part, RhinoDoc doc, string tmp)
{
        var curve = objref.Curve();
        if (curve == null || curve.IsShort(RhinoMath.ZeroTolerance))
                return Result.Failure;
        RhinoApp.WriteLine("Let's begin the devided part.");
        var segment_count = 2;
        var rc = RhinoGet.GetInteger("How many segments the curve will be divided into?", false,
        ref segment_count);
        if (rc != Result.Success)
                return rc;
        tmp = "Curve divided.";
        points_param_part = curve.DivideByCount(segment_count, true, out points3d_part);
        points_param = points_param_part;
        points3d = points3d_part;
        if (points3d_part == null)
        return Result.Failure;
        foreach (var point in points3d_part)
        doc.Objects.AddPoint(point);
        return Result.Success;
}
```

(2) A vertical plane can be generated at a specified point on the curve object by calling the method *PerpendicularFrameAt (double t, out Plane p)* contained in the curve object shown in the Rhino API.

(3) The algorithm sets two different generation modes T. Mode T=1 means Random mode, in this mode, the user enters the parameter as the circle radius R, each generated circle are with radius Ri which takes a random value between (0-R) at each point in *points3d_part*. Mode T=2 is the normal mode, in this mode, the radius of the section circle is what the parameter user inputted, that is $Ri = R$.

(4) Same as (1), equally divide each generated circles circumstance Ci into m equal segments by inputting the integer m, which will generate m points *points3d_circle* on each Ci. Then input parameter d as the distance between two helix's curve, the method *DivideByCount (Int32, Boolean, Point3d [])* will choose out a set of points Pi from points *3d_circle [i]* as set *point_choice*, and $Pi+d$ will compose set *point_choice2*.

Besides, the mode T will work on the index i of *points3d_circle [i]*. In mode 1, Pi is randomly selected; in mode 2, Pi is selected by gradually with next index i, that is rotating Pi an angle of on the next circumstance.

Table 2. Divide each generated circles.

```
for (int j = 1; j < Num; j++)
{
    ArcCurve circle1 = new ArcCurve(new Circle(Planelist[j], points3d[j],
    radius2[j]));
    circle1.DivideByCount(per, true, out points3d_circle);
    points3d_circle_multi.Add(points3d_circle);
    if (typenum == 1)
    {
        index = num.Next(0, per);
    }
    else
    {   index = j % per;        }
    Point3d point_choice = points3d_circle[index];
    int index2 = (index+ di) % per;
    Point3d point_choice2 = points3d_circle[index2];
    points_end.Add(point_choice);
    points_end2.Add(point_choice2);
}
```

(5) Generating the two curves derived from helix, *curve1* and *curve2*, by using the method of *CreateInterpolatedCurve (IEnumerable (Point3d), Int32)* based on the sets of *point_choice* and *point_choice2*.

Call the method *SweepTwoRail()* in the Geometry library displayed by the Rhinoceros API, that is, call Rhinoceros' own commands *Sweep2*. Using curve1 and curve2 as the sweep paths, connecting the endpoints of the two curves as the cross-section curve, and sweep by *Sweep2* command, and then plough into the surface.

Table 3. Generating the two curves.

```
Line line0 = new Line(points_end[0], points_end2[0]);
Curve line_between = line0.ToNurbsCurve();
var sweep = new SweepTwoRail();
sweep.AngleToleranceRadians = doc.ModelAngleToleranceRadians;
sweep.ClosedSweep = false;
sweep.SweepTolerance = doc.ModelAbsoluteTolerance;
sweep.MaintainHeight = false;
var breps = sweep.PerformSweep(nc, nc2, line_between);
for (int i = 0; i < breps.Length; i++)
{
    doc.Objects.AddBrep(breps[i]);
    doc.Views.Redraw();
}
```

4. Architectural form generation

4.1. PROTOTYPE SIMULATION

The parameters affecting the shape of the DNA algorithm program are as below: the initial input curve *A*, the number of copies of the curve n, generate mode *T*, the section circle equals the fraction *m* (instead of the angle of rotation), two curve intervals *d*, the radius *R* of the circle of the section (distance of the origin curve from the generation line). In the prototype generation simulation, the line and circle are selected as the typical curve types in the Rhino API. Lines, curves, circles represent two-dimensional curves; spirals and spatial curves represent more complex three-dimensional curves. It is a multi-parameter combinatorial experiment of algorithms and scripts.

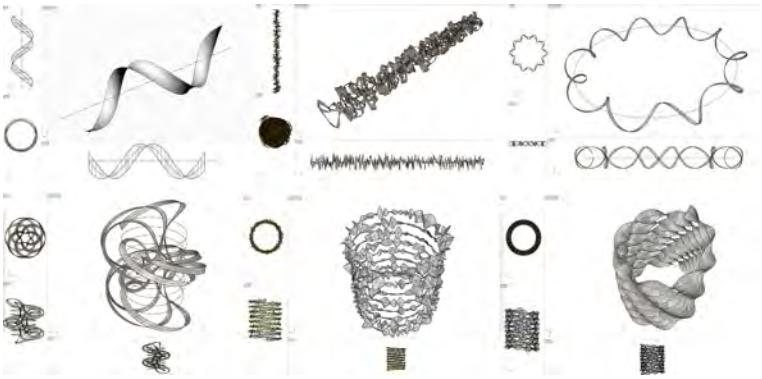


Figure 3. The prototype forms generation based on lines, 2D curves and 3D curves.

By contrast, the input of different parameters generates different shapes, but it also contains a certain rule. The parameter n controls the spiral wrap density of the resulting shape, the parameter T selects the spiral generation mode with free or always equal radius, the parameter R controls the size of the spiral, the parameter m controls the amplitude of the spiral rotation, and the parameter d controls the interval between two spirals, which controls the width of the final swept surface.

4.2. APPLICATIONS OF ARCHITECTURAL FORM GENERATION

This paper takes the design of landscape bridges in a project in Zhengzhou, China, as an example to illustrate the application of DNA algorithms in architectural design. The basis for the suspension of the bridge is generated based on the DNA helix algorithm. The prototype is shown in Figure 4. Based on this prototype, the battery program of the Grasshopper plug-in is used to assist with the detailed design of the landscape bridge. The design of this project is a body generated by algorithms and digital design tools, and it is gradually processed and refined.

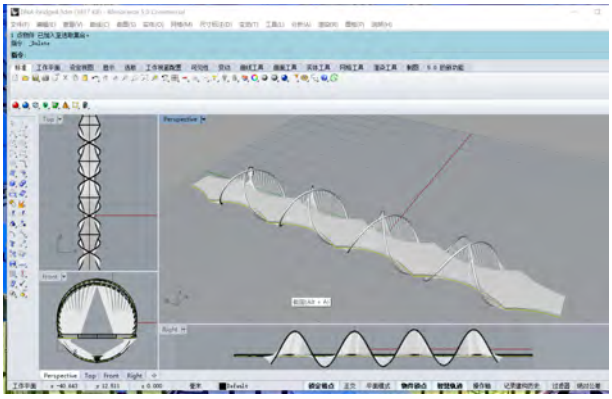


Figure 4. Algorithm Generated Landscape Bridge Prototype.



Figure 5. Facade Rendering of DNA Bridge .

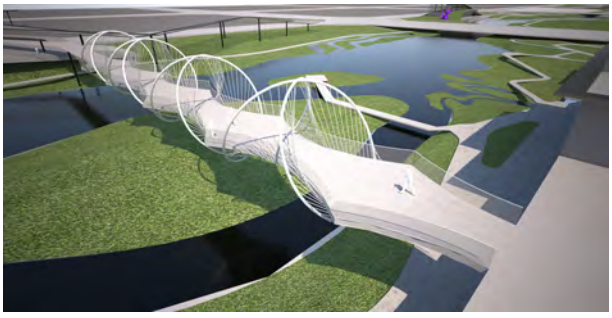


Figure 6. Aerial View of Landscape Bridge.

5. Conclusion

The formation of biological forms often requires a number of relatively simple rules, while the patterns generated based on these rules can be very different. Combined with the computer's powerful computing capabilities, a large number

of architectural forms can be generated. The research method and technology of DNA algorithm has superiorities:

(1) The bionic form, point elements and three-dimensional curves, can be generated based on the DNA algorithm.

(2) The DNA algorithm has the potential to generate and optimize the architectural form, which can produce complex and varied forms, and also provide diversified shapes for two-dimensional plane and three-dimensional surface.

(3) With the help of Xamarin and Visual Studio software, Rhino can provide the technical support for the research algorithm after the secondary development, which is much more efficient and accurate.

This algorithm is applicable to the space form composed of rods, or the generation of the spatial and planar forms constructed by the ribbon and tubular shape elements, which can be adapted to the two-dimensional and three-dimensional shapes design. It can generate architectural forms not only of large scale, but also be applied in design of small scale.

Acknowledgement

The authors were supported financially by the National Natural Science Foundation of China Youth Foud (approval number: 51508003).

References

Ball, P.h.i.l.i.p.: 1999, *The Self-Made Tapestry-Pattern formation in nature*, Oxford University Press, New York.

Chu, K.a.r.l.: 2006, The Metaphysics of Genetic Architecture, *Architectural Design*, **76**, 38-45.

Edström, J. E.: 1951, A Rapid Method for the Determination of Nucleic Acid Components by Paper Partition Chromatography, *Nature*, **168**, 876.

Eissenman, P.e.t.e.r.: 1999, *Diagram diaries*, Universe Publishing, New York.

Leach, N.e.i.l. and Yuan, P.h.i.l.i.p. F.: 2012, *Scripting the Future*, Tongji University Press, Shanghai.

Terzidis, K.o.s.t.a.s.: 2006, *Algorithmic Architecture*, Architectural Press, Burlington.

Thompson, D.'A.r.c.y. W.e.n.t.w.o.r.t.h.: 1917, *On Growth and Dorm*, Cambridge University Press, Cambridge.

Watson, J.D. and Crick, F.H.C.: 1953, Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid, *Nature*, **171**, 737-738.

Xu, W.e.i.g.u.o.: 2016, *Parametric Non-linear Architecture Design*, China Construction Industry Press, Beijing.

Xu, W.e.i.g.u.o. and Li, N.i.n.g.: 2018, *Digital Diagrams from BIO-Form for Architectural Design*, China Construction Industry Press, Beijing.

Zubay, G., Wilkins, M.H.F. and Blout, E.R.: 1962, An X-ray diffraction study of a complex of DNA and a synthetic polypeptide, *Journal of Molecular Biology*, **4**(2), 69-72.

DESIGN PRACTICE COMPLEXITY IN THE POST-DIGITAL AGE

Theoretical discussion and comparative case study of non-standard building façades

SINING WANG[1] and KRISTOF CROLLA[2]
[1,2]*The Chinese University of Hong Kong*
[1]*wangsining@link.cuhk.edu.hk* [2]*kristof.crolla@cuhk.edu.hk*

Abstract. This paper starts by introducing an expression proposed by William J. Mitchell measuring the "complexity" of a designed and constructed architectural project. After reviewing other interpretations of this term, as well as specific peculiarities from the building industry, the article expands this metric from an organisational and technological perspective. This is followed by the case studies of six non-standard façades whose process complexities are driven by their project-specific affordances. By comparing built projects of different architects and implementation environments, the paper suggests specific criteria for non-standard architectural designs. Application of acquired knowledge has the potential to help architects better control their project's design and construction solution space.

Keywords. Project complexity; measurement; non-standard; China.

1. Introduction

Architecture practices are *ill-structured* problems, since the goals and the way of achieving corresponding solutions will be ambiguous at the outset of the task (Hudson, 2010). In order to solve practical design problems, architects, along with other project participants, must iteratively seek proper materialising solutions while constantly changing design descriptions. Rowe (1987) stated that it is impossible to either describe or solve *ill-structured* design problems with specific patterns because: 1) additional design requirements or constraints may emerge any time, 2) design problems and their solutions interact, and 3) there is no ultimate problem-solving method. Modernism's strategies like "form follows function" intend to reduce such uncertainties and standardise the problem-solving approach. In doing so, architectural design is bounded to a safe zone where the financial risks and technological uncertainties are predictable. However, such method may be unfitting for the digital design experimentation frequently found in today's more exploratory practices.

The boundaries of the design space are shaped by various requirements, involved project parties, and their project-specific interests. Lawson (2006) categorised design problems as *internal* and *external constraints*. The *internal*

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 481-490. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

constraints are normally based on the client's task brief, the architect's design intentions and the users' needs, while the *external constraints* describe conditions a design practice needs to accommodate and regulations it must follow. Both types of constraints affect the description of a designed form and its followed problem-solving processes thereby making up the complex nature of architectural practice. Hudson (2010) suggested a heuristic approach for resolving architectural design problems. Steps include describing the space of design problems, fragmenting larger problems to smaller pieces, and then exploring the appropriate options for each sub-problem while reducing the size of an overall design solution space. The mechanism for an architect adopting this approach focuses on his/her strategy of controlling the project complexity.

Such complexity becomes especially visible in today's practice when it is dealing with the realisation of non-standard architecture in challenging building contexts typified by limited engineering, fabrication, or construction capacities. This paper discusses six non-standard façades facing such conditions. Their built forms demonstrate the value of adopted problem-solving strategies and complexity controls. Through studying these non-standard façades, higher-order knowledge is extracted that other architects can use when defining their digital design strategies when being faced with similar contexts.

2. A metric of complexity

Mitchell (2003) defined *state descriptions* as the explicit expressions of design information prior to any construction operation and referred to the steps of transforming a design's state descriptions to its physical form as *process descriptions*. Carpo (2011) defined the Albertian paradigm as a linear *state-to-process* transformation where the designers are responsible for preparing annotation documents and the implementors then materialise whatever has been submitted to them. This paradigm has shifted in recent decades with CAD-CAM integration trying to eliminate the separation between design annotation and construction. Today, architects are increasingly designing and making at the same time (Carpo, 2011). Thus, the *state-to-process* transformation becomes more about using the same digital medium so that information can be explicitly interpreted at both ends. Mitchell (2003) used *design content* to describe the created database in a computer-aided design environment. Designers input strings of commands or use sequences of operations to define the design space. Transforming the digital bits of a design into data that drives the fabrication machines and instructs assemblies is defined as construction operations. The length of these operation sequences and its related built scale are referred to as *construction content*.

2.1. MITCHELL'S MEASUREMENT

Mitchell (2005) suggested a ratio to measure the complexity of a built project:

- **"complexity" = added design content / added construction content**

This expression introduces the relative positions of both design and construction, based on the project-specific conditions. The required quantity for additional

construction content is determined by a project's particular design requirements while limited by the resources the project parties can access within the *construction context* to which they belong. Mitchell (2005) mentioned that this starting point for adding *construction content* relates to the supply chain for construction elements, meaning the minimum fabrication and assembly operations needed to realise the design. The proportion of these two operations may change from project to project

The starting points for adding *design* and *construction content* are up to the capacity and the knowledge of each party involved in the project. Architects create the design problem space based on their past experiences and define it in modelling environments. Newly designed geometries can borrow elements from previous projects, such as a specific script for façade design, or can use component libraries embedded in digital design modellers. The competence of engineers and implementers also adds to the inherited content, including their provided solutions and corresponding industrial capacities.

2.2. OTHER EXPLANATIONS OF COMPLEXITY IN ARCHITECTURE

Lawson's model indicates that for intricate design problems it is difficult to separate the requirements for additional *design* and *construction content*, especially given that the modes of collaboration between the designers and implementors may shift in today's digital era (Lawson, 2006). Baccarini (1996) introduced two characteristics from complexity science when referring to the various interrelated parts in architecture: *differentiation* and *interdependency*. Both characteristics are discussed from the organisational and technological aspect in the architectural practice.

Organisational differentiation concerns the project roles, their correlated tasks, and the composition of the design itself. Baccarini (1996) defined the *horizontal* and *vertical differentiation* of organisational systems. The *horizontal differentiation* refers to the number of different units involved in the system such as the project parties and the component types of a building system, while the *vertical differentiation* means the depth of these differences, such as each party's liability or the variate elements of the same type. The interactions between these *differentiation* are referred to the *organisational interdependency*, which integrates all the members in a system and affects the system as a whole.

Technological differentiation was described as the diversities in a task. This includes the inputs and outputs variations, the number of involved specialists, and the specific design and construction content needed to produce a building entity. Regarding the *technological interdependency*, Baccarini (1996) stated that the *technological differentiation* interacts within a network of practical tasks so that the operations carried out by different project specialists will influence the entire design solution space.

2.3. EXPANDING THE MEASUREMENTS

Mitchell's ratio of added design content to *added construction content* introduced a fundamental idea to understanding the complexity of a built project. Its concepts can be used to evaluate projects accomplished in a lab environment,

where processes are usually *well-structured* and the design solution space clearly defined by the designers/researchers. There, one can assume, design inputs are directly transformed into construction operations. However, when introducing the *organisational* and *technological complexity* in real-world practices, this measurement lacks *differentiation* and must be further expanded. Mitchell's approach appears too abstractive to allow for cross-comparative case studies. Hence, this study imports Baccarini's interpretation of complexity, which Wood (2010) stated is valid to all dimensions in building practice, as the rationale to expand Mitchell's measurement.

In terms of the organisational complexity, architects are commonly not the sole party to add *design content*. Instead, in building-scale practice, initial design information generated by the architects might be recreated by the consultants for contractual purposes; or be further developed by engineers for the sake of production requirements; or even be revised by contractors and fabricators due to a lack of constructability. Since an architect's design contribution is determined by both the *horizontal* and *vertical differentiation* in the added *design content*, the *organisational complexity* concerning an architect's project role can be described as:

- **∑added design content / architect's state description**

Since Mitchell (2005) mentioned construction operations that include fabrication and assembly operations, we can also divide the project complexity using these two aspects. According to Mitchell's concept, the *fabrication complexity* can be addressed as the amount of information inputted to drive the machining or the manual making processes. The assembly complexity, likewise, refers to the ratio of the construction instructions to the on-site assembly actions. These two construction operations are normally carried out by different project parties. Thus, they can be discussed separately. The expression for *technological complexity* can be proposed as:

- **∑ (added fabrication design content/fabrication operations) + ∑ (added assembly design content/assembly operations)**

This expansion of the measurements can be used to cross-compare architects' design strategies and their responsibilities during the *state-to-process* transformations. Such comparisons may form the higher order knowledge that can be used in general to deal with uncertainties of the *ill-structured* architectural design problems.

3. Comparative case studies

Six built non-standard façade projects were studied as part of this research project. All were designed by Chinese designers facing both the opportunities offered by globally available computational tools and the restrictions from unevenly developed building technology in China. The projects include: 1) "Silk Wall" (SW) by Archi-Union, 2) "Yan Ancestral Hall" (YAH) by M.O.D.E.S, 3) "Arachne" by Archi-Solution Workshop, 4) "Art Gallery C1" (AG1) and 5) "Art Gallery C3" (AG3) of the "Foshan Art Village" by Atelier cnS, and 6) "Bird

Watching Tower" (BWT) by Tee-mu Studio (Figure 1). Their design solution spaces are discussed in response to internal and external constraints. To facilitated construction, all six façades were materialised by breaking down overall fluid geometry continuity in discretised elements.

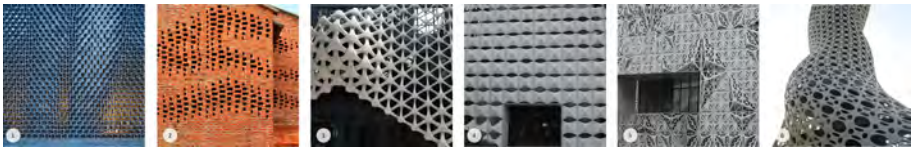


Figure 1. From left to right: 1) "Silk Wall", 2) "Yan Ancestral Hall", 3) "Arachne", 4) "Art Gallery C1", 5) "Art Gallery C3", and 6) "Bird Watching Tower".

3.1. ORGANISATIONAL COMPLEXITY

The *organisational complexity* concerns the architect's authorial role during the design-to-build process. Practicing outside a lab environment may increase the uncertainties in controlling both the input and output information. According to the measurement above, this notion is evaluated by the proportion of data generated by the architects to that used for materialising operations.

The first three cases follow a lab-experiment workflow where the architects' *state descriptions* were directly transformed into construction operations. *Archi-Union* was both the client and the architect of the SW project, as part of the office's renovation work. The advantages of such construction practice include the early confirmation of the material suppliers and implementors, a rational project schedule and the protection of the architect's authority. The SW project was assembled with standard concrete blocks in 12 different horizontal rotations. Architect's *state description* was directly used for the making of 6 brick layering guides and the generation of an assembly schedule. Thus, the ratio of the *organisational complexity* for the architect is close to 1.

Architects of the YAH project also operated at a high authorial position when compared with the SW project. The project is materialised in a rural Chinese village where the construction of homesteads requires less administrative regulations than urban building constructions. Hence, its façade construction proceeded without any conventional construction documents, meaning both the brick fabrication and assembly were carried out on-site by the contractors following the diagrams directly extracted from the architect's digital model.

In the "Arachne" project, *Archi-Solution Workshop* joined the project only in the capacity of the material supplier. However, the firm bypassed administrative regulations and ended up designing the overall form and fabricating the components in-house. The façade system contains around 2800 different parts which were produced with homemade Fused Deposition Modelling (FDM) machines. These FDM platforms operate with *G-code* data streams to define its tooling paths, which the designers could directly translate from the components' geometry definitions. All components adopted standard joint conditions so that the *added design content* for assembly operations was minimised.

The remaining three projects followed a conventional design-bid-build workflow in which the architects submitted traditional tender documents, even though most of this information was redundant from a construction perspective. In the case of AG1 and AG3, the architects of *Atelier cnS* produced façade construction drawings describing the tessellations of all four elevations. Such information, the *state descriptions* provided by the architects, did not contribute to any actual construction operations, except as the visual references. In the case of AG1, the façade component manufacturer recreated the mould geometries with a machine-specific software. Hence, the *added design content* from the manufacturer relates to the total number of mould types and the project's level of non-standardisation affected the organisational complexity. The panel units on the AG3 are made of triangular sub-surfaces which were fabricated with a 2D plasma cutter. Compared with the AG1 project, such operation in the case of AG3 helped to maintain a relatively low-level *organisational complexity*, since the fabrication shop drawings were developed from the architects' *state descriptions* of the unfolded component outlines.

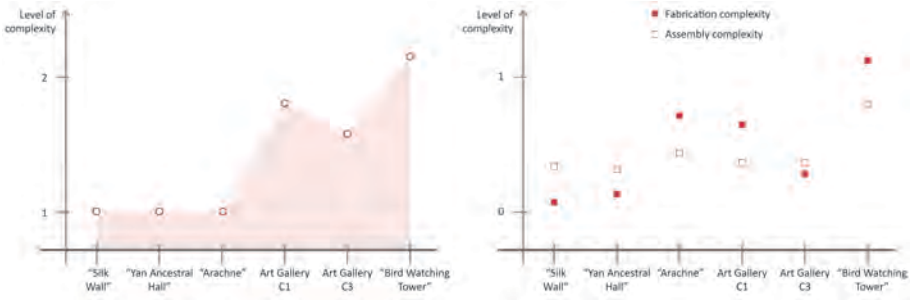


Figure 2. Cross-comparison of organisational (left); Cross-comparison of technological complexity (right).

The materialisation of the BWT project encountered the scenario where the Glass fibre Reinforced Plastic (GRP) manufacturers had to add a large amount of unexpected *design content* in order to materialise the architect's formal requirements. This included the implementor's effort of developing a production flow for the customised façade pieces. Also, due to the lack of 5-axis milling tools, the perforation design could not be precisely transformed from the architect's digital model. Neither the manufacturers nor the on-site contractors were familiar with the designed geometries and some construction-related design decisions were made by them without the involvement of the designer. Hence, the *organisational complicity* is the highest for the architects in the BWT project compared to others.

If we cross-compare the *organisational complexity* for the architects among all six projects, one can notice that the influencing criteria include the project construction context, the administrative regulations, the architect's project tasks, and the capacity of industrial fabrication. Figure 2 left shows a qualitative and relative result based on the measurement of an architect's authorial role mentioned above. The smaller the ratio value gets, the more streamlined a *state-to-process*

transformation it represents. On the contrary, the greater the value becomes, the more *redundant design content* is added to the project. The *organisational complexities* were kept at low levels for the first three cases as the architect's *state descriptions* were directly transformed to construction operations. Meanwhile, the next three cases have varied and relatively high organisational complexities concerning the challenges brought by additional design content and different fabrication environment.

3.2. THE TECHNOLOGICAL COMPLEXITY IN MATERIALISING SOLUTIONS

The contributors to a project's design solution space are determined by the *organisational complexity* it has. These intricate relationships shape the boundaries of a design solution space, which not only responds to the raised design problems but also concerns the interest of each involved project role. The *technological complexity*, on the other hand, describes the interdependent connections between the construction operations carried out by related project roles. In the previous section, the paper defined such intricacy as the summation of *fabrication* and *assembly complexities*. Based on Mitchell's idea, both notions refer to the ratio of inputted design data to the amount of physical operations it drives.

Figure 3 shows the photos of critical construction operations in each studied case. In the SW project (No.1 in Figure 3), the *technological complexity* is measured by the fabrication of customised tools and the assembly of the brick wall. Since the architect has chosen standard concrete blocks as construction materials, there was no specific effort needed for unit fabrication. Meanwhile, because human contractors could not directly use the information extracted from the parametric models, customised tools (the brick layering guides) were needed for the manual assembly. These guides were designed and directly CNC fabricated from metal within the office's workshop. Thus, it added a little *design* and *construction content* to the fabrication operations. By using 6 different brick layering guides the contractors could easily create 12 variations on-site with the same procedure. This made the assembly difficulties in the SW project no higher than building a conventional brick wall. So, the total *technological complexity* stayed at a low-level.

A similar geometric requirement of the YAH project was realised by stacking bricks of different lengths (No.2 in Figure 3). The brick cutting operation was carried out on-site following a computer-generated schedule of unit types and brick amount counts. Therefore, the *fabrication complexity* was kept minimal since the information output was entirely based on a couple of lines of computer code. In order to reduce the *assembly complexity*, the architect adopted the *Flemish bonding* method as the bricks only variate in their long edges. In the façade, all headers are at the same relative positions, making it a reference gird for construction. The only *design content* added for the sake of assembly operations was the legend of the layering sequence of different stretchers. The diagram was generated using procedural modelling software *grasshopper* according to the desired pattern. Because all the fabrication was done manually, the *fabrication complexity* was a little higher than the SW project. Architects of the first two cases controlled

the complexity by referring design innovations to standard constructions - the SW project varied only in the unit rotations while the YAH project only changed the header lengths in certain areas.

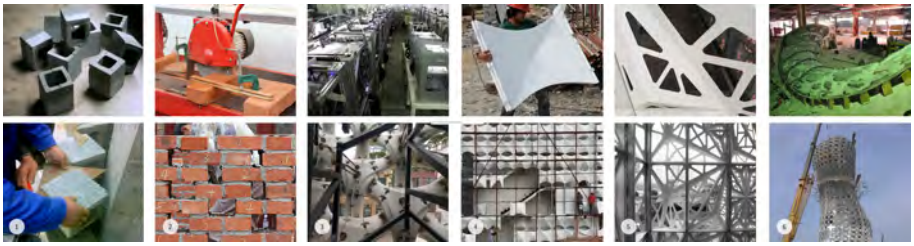


Figure 3. Fabrication and assembly operations in each façade project.

The construction process of "Arachne" (No.3 in Figure 3) combines digital design-to-fabrication methods and labour-centric manual installation. The designer took on a multifaceted role during the project materialisation, including the material (polylactic acid plastic) purchase, the in-house FDM printing, and the post-production management. Therefore, *Archi-Solution Workshop* was the sole party controlling the *fabrication complexity*. Regardless of the incorporation of custom-built FDM printers, the digital design-to-fabrication of 2800 pieces was a streamlined process based on a *grasshopper* script connecting the *Rhino* modeller with a customised CAD/CAM controller. Nevertheless, the total *fabrication complexity* was relatively high because the large amount of post-production management of the 2800 unique elements. This included sorting, coating and shipping according to the different element types. Mass variation increased the difficulty of fabrication management which illustrates the idea that the *fabrication complexity* concerns the entire production life-cycle where the product's non-standard characteristics may impact anytime. On the other hand, all unit assemblies use the same type of joints connecting with each part and with the structural fame behind. Therefore, the *assembly complexity* was maintained at a low level.

Projects AG1 and AG3 (No.4 and 5 in Figure 3) were constructed by one contractor team and adopted the same structural system. In both cases, the façade units were prefabricated off-site so that the entire installation process was possible within one month. There are six different panel types in the AG1 façades and eight types in the AG3 façades. Since both component assemblies were following the same type of instructions created by the architects, their *assembly complexity* is equal. However, the *fabrication complexity* of the AG1 project is higher than that in the AG3. As mentioned in the previous section, the GRP mould production led to extra design and *construction content*, thereby increasing the *fabrication complexity* and the total cost. Comparatively speaking, the materialisation of the AG3 façade was more straightforward. Eight panel types were made of five different planar elements which could be directly produced by plasma cutter, to then be folded and welded manually. The information for such fabrication operations was directly developed from the architect's drawings.

The materialisation of the BWT project (No.6 in Figure 3) illustrates a higher level of *technological complexity* than the other studied cases. The non-Euclidean geometry has led to the uneven subdivisions of the façade units and the non-standard perforations. The architect's *state descriptions* only explained the desired form and the documents fulfilling the requirements asked by the clients and legislators, but these were barely transformed to direct construction operations. Each façade unit is made of two doubly curved GRP surfaces and is enforced with a series of single curved steel ribs inside. These *design contents* were added by the facade consultant from the scratch. The design of waffle scaffoldings for moulding the GRP components and the recreation of façade perforations also increased the total *fabrication complexity*. Due to the fabrication deviations, the related assembly drawings could not be fully transformed into assembly operations. Hence, some on-site adjustments and improvisations had to be carried out by the contractors to ensure the built outcome.

Figure 2 right describes a qualitative comparison on *technological complexities* between the six façade cases based on the above discussion. The value in the chart does not have practical implications and can be scaled up or down proportionally, but its relative relationships indicates some general understandings of materialising non-standard architecture within this context. Comparing with the diagram on the left, we can learn that the *technological complexity* relates to an architect's authorial role, concerns the additional design information. Standardising construction or basing the work on inherited knowledge from the previous projects may help to reduce the risk of invalid solutions since each party is familiar with the design problems.

4. Extracted higher-order knowledge

Li (2008) introduced the design ideology of "make-the-most-of-it," describing an attitude that some Chinese architects adopt to cope with the constraints in the developing construction context while maximising the design problem-solving. Regarding all six façade cases, such expedient notion means the balance between the architect's formal requirements, the façade's materiality and the corresponding implementations. From the previous discussion, we learn that the project complexity raises when redundant information exists in the *state-to-process* transformation. This is determined by the project-specific administrative conditions, the architect's project role, and the design-related construction affordance. A developing construction environment may increase the uncertainty of these factors, which cannot be easily bypassed with a certain problem-solving approach due to the interdependent relationship between the *organisational* and *technological complexity*. Hence, it requires the architects, when pursuing the idea of "making-the-most-of-it", to adjust the design solution space so that its *state-to-process* transformation is controllable.

When architects have a higher level of authority within the project team, i.e., in the first three projects, the generation of design problems can be directly connected to the implementation resources at hand. In such mode, the project's *technological complexity* is at a dominant position, influencing the feasibility of a defined design solution space. The architects are suggested to be aware of the inherited starting

points for adding *design* and *construction content*. By controlling the amount of *added design content*, the projects can be realised with expected outcomes. The uncertainty of the *organisational complexity* matters when the architects must obey the administrative regulations. In the AG1 and AG3 projects, the uneven project complexity occurred due to the different production setups between the cutting of planar steel parts and the moulding of GRP components. In this manner, the key to a guaranteed feasible solution space is to ensure the design is in accordance with the capacity of implementors. Since the workflow requires additional inputs from other project parties, the architects are suggested to increase the reusability of their *state descriptions*.

A top-down problem-solving approach can be risky in the developing construction context. The high level of project complexity in the BWT project was due to the fabricators lacking experience in precisely producing the doubly curved surfaces and locating non-identical openings. Such implementation uncertainties jeopardise the entire *state-to-process* transformation and therefore must be contained. Instead, a bottom-up approach for defining the design solution space ensures more predictable built outcomes.

5. Conclusion

This paper studies six non-standard façade projects built in the China's developing construction contexts and compares them from two perspectives: the *organisational complexity* evaluating an architect's design contribution and the *technological complexity* describing the materialisation difficulties. Applying such measurements to the case evaluation indicates the defined design solution spaces in response to the *ill-structured* architectural design problems. Mitchell's metric to discuss the process complexity of a built solution is expanded. The knowledge gained from the case comparisons can be brought back to the generation of problem-solving strategies. These strategies can be based on the architect's awareness of the upcoming constraints and the project-specific affordance, or they can benefit from his/her enhanced control flexibility by using computational tools.

References

Baccarini, D.: 1996, The concept of project complexity—a review, *International journal of project management*, **14**, 201–204.

Carpo, M.: 2011, *The alphabet and the algorithm*, MIT Press.

Hudson, R.: 2010, *Strategies for parametric design in architecture: an application of practice led research*, Ph.D. Thesis, University of Bath.

Lawson, B.: 2006, *How designers think: the design process demystified*, Elsevier/Architectural.

Li, X.N.: 2008, 'Make the Most of It' architecture, *City*, **12**, 226-236.

Mitchell, W.J.: 2004, Constructing complexity in the digital age, *Science*, **303**, 1472–1474.

Mitchell, W.J. 2005, Constructing Complexity, *in* B. Martens and A. Brown (eds.), *Computer Aided Architectural Design Futures*, Springer, Vienna, 41-50.

Rowe, P.G.: 1987, *Design thinking*, MIT press.

Wood, H.: 2010, *Modelling project complexity at the pre construction stage*, Ph.D. Thesis, University of Brighton.

CAPTURING PARAMETRIC DESIGN EXPLORATION PROCESS

Emperical insights from user activity and design states data

VERINA CRISTIE[1] and SAM CONDRAD JOYCE[2]
[1,2]*Singapore University of Technology and Design*
[1]*verina_cristie@mymail.sutd.edu.sg* [2]*sam_joyce@sutd.edu.sg*

Abstract. Computational design, especially parametric associative modelling tools, have opened a whole new world of possibility in design exploration. However, their now established use poses further questions regarding how they effect design process and ultimately the quality of the outcomes. Answering those questions requires a better understanding of parametric design process through empirical data. In this paper, we extend a method to systematically capture the design process into a structured data of designer's activity and design states. Analysis of design sessions reveal a unique pattern of parametric modelling and exploration strategies produced by each designer. Capability to save design process into structured design states shows potential to improve process.

Keywords. Design exploration; Parametric Design; History Recording; Version control; Conceptual Design.

1. Introduction

Parametric modelling is a common approach used effectively in many modern design practices (De Kestelier and Peters, 2013). When applied at the early exploration stage, it has the ability to increase the impact of a user's design effort (MacLeamy, 2004). Owing to its growing importance, research has been undertaken to understand and improve parametric design workflows. Davis (2013), investigated flexibility issue in parametric design workflow. Whilst (Smith, 2007), explored 'breaking' models problem while creating a major changes.

Data has been used to understand and solve shortcomings in processes and workflows of numerous fields, however design specific examples are relatively few. Meagher et al. (2013) saved user-edited simulation code using software versioning system upon compilation. Changes detected in the code could reflect user's iteration of modifying geometry and running simulations, which eventually could help to understand how users interact with simulation results in a parametric design process. Sakai and Tsunoda (2015) allowed an explicit way of saving design states by giving users the opportunity to choose a design, edit, and save their own versions within *3D WebGL* based platform. These two approaches embodied

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 491-500. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Aish's (2000) and Woodbury (2017) idea of recording changes transaction and design alternatives for concept reuse and design exploration, or more commonly termed as versioning. Revit and similar BIM platforms save states and 'merge' multiple users models together, but the emphasis is on creating singular unified model, and not on capturing or understanding design process.

The concept of versioning is not new. First versioning system was developed to systematically save code of operating system (Rochkind, 1975. Modern versioning systems such as Git (https:git-scm.com) or SVN (https:subversion.apache.org) are ubiquitous in software developments. With a versioning system, overall progress of software development could be tracked and it is easier for programmers to collaborate. Additional feature is developed on a separate branch of the code - a different 'version', before merging the branch back to the main version again. Should code in a certain version fails, programmers would then revert to previous working version. Such availability of code saved at various stages from various projects allows for empirical analysis to improve software design. For example, D'Ambros et. al. (2008) mined software repositories to understand how software evolved, specifically by detecting hotspots (areas of code that frequently change), and measuring impact of code change to the whole system. In this manner, it is possible to predict further defects in the system.

In this paper, we are interested to understand what designers actually do while designing with parametric tools, and what that process looks like by logging designers' activity in a set design task. Designers go through different process of changing parameters 'sliders' and associative logic 'components' and 'wires' to achieve their desired geometry. Potentially, this could offer a new way to understand and improve design support. In particular, we would also like to see if giving the users the capability to capture intermediate design progress impacts design activity. In the next part, the tool developed for this research and the data captured will be explained.

2. A tool to capture parametric design activity

To record parametric design exploration states, the *Grasshopper* Plug-in *GHShot* has been used and extended. *GHShot* is a tool developed by the authors and allows for versioning of parametric model state or 'snapshot' to a cloud repository with a single button action (Cristie and Joyce, 2017, 2018). Each snapshot of parametric design exploration consists of its: (i) *Grasshopper* parametric design definition (as an *XML*), (ii) identified and named input parameters and/or performance values that designers choose to save, (iii) 3D mesh geometric representation, and (iv) designer's notes. Meta-data such as time of saving, and designer name (in case a file is modified by more than one designer) is also saved. Upon saving designers are allowed to specify if the current state is a continuation of previous state, or a branch of previous state (e.g.: making variations of design). The snapshot saved can be viewed online where progress could be observed in a photo album and tree-like visualisation. Performance values of all snapshots sent are also shown in a graph view with filtering mechanism, to allow data exploration.

While *GHShot* saves design states upon designer's command and displaying them in the corresponding custom web interface, in this work an extension plug-in *GHRecorder* is developed. *GHRecorder* periodically sends records of design activity to the server automatically. Design activity is defined as all actions designers do within their *Grasshopper* document. For example: adding components, connecting components, arranging/dragging the components on the canvas, copy paste, etc. Records of these actions and the time they are done are sent to the server.

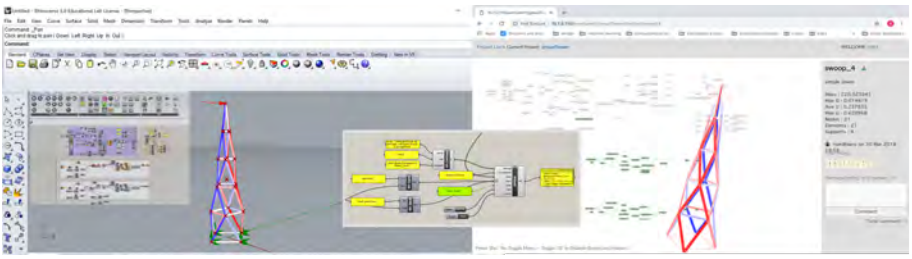


Figure 1. GHShot (center) is used to send parametric design states from designer's Grasshopper file (left) to web (right). State of parametric model (both 3D model and graph connection) is captured and changes (green colour) could be detected.

3. Experiment Design

To understand what designers do during parametric design process and if *GHShot* has effect on this process, experiments with two tasks were designed. In total, eight designers with architectural backgrounds, consisting a mix of undergraduate and postgraduate students were recruited. They have a range of experience in designing from 2 to 15 years, and *Grasshopper* experience from 1.5 years to 10 years. Five designers were to do the first task without *GHShot* and second task with *GHShot*. Three designers were to do both tasks without GHShot as the control group. For all the design tasks, *GHRecorder* logged participants' design activity in the background. In addition, there was screen recording for all the design tasks, and interviews were conducted at the end of the second design case for participants using *GHShot*.

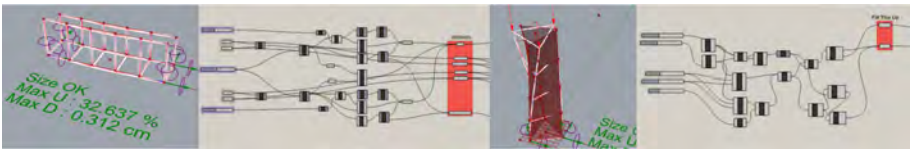


Figure 2. Parametric Bridge Experiment Setup (left): the parametric model consists of 45 components. Parametric Tower Experiment (right): the model consists of 24 components.

A parametric bridge model was used as the first design case, and a parametric tower model as the second. Relatively simple parametric structural design tasks were chosen as they provided flexibility to design aesthetically whilst being

mindful of some performance criteria. For both design cases, designers were to meet requirements on the parametric model's maximum geometric size, maximum utilisation, and maximum deflection. When any of these three requirements were not met, green labels at the side of the 3D model would turn to red (see Fig. 2).

Each participant was given one-hour design time for each of the cases, with a gap of at least three hours before doing the next case. A minimum of 40 minutes of designing was imposed, but participants were allowed to continue over the hour to complete if desired. At the end of the experiment, participants were asked to submit their final design, a design of their liking. To maintain anonymity all users were given a two letter name such as 'HD' or 'MJ'.

Between scale of 1 being non-familiar to 10 being very familiar with structural knowledge, most participants rated themselves with 5 or 6; only one rating themselves 10. Most participants have 0.5 to 1 year of experience with *Karamba*, a *Grasshopper* plugin used for analysing parametric structures, however this was not necessary in this experiment as participants were not allowed to modify the settings on *Karamba* components and the input was basic. They were only to modify the parametric model definition relating to the geometric representation.

4. Results and Discussion

4.1. VISUALISING PARTICIPANT'S ACTIVITY

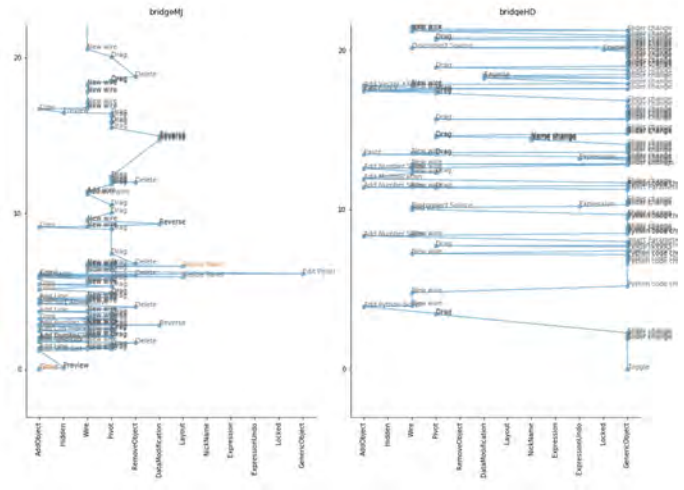


Figure 3. Activity Visualisation for first 20 minutes of bridge design session. User MJ (left) performed less activities than user HD (right). Combination of Add Component – Add Wire is prominent in MJ's while Python Code – Slider Change is prominent in HD's.

Data obtained from designers' activity records was processed and visualised to provide insights into the design process. With activity timeline visualisation, one could observe how rapid designers navigate from one action to another action. For example, in figure 3 we can see on the left a user 'MJ' who immediately changes

the model in the first 10 minutes before slowing down with more careful edits, whilst on the right an initial exploration of sliders was undertaken by user 'HD' before editing was begun.

4.2. POPULAR ACTIVITIES

Eleven unique *Grasshopper Actions* (titled by the software itself) are captured in the activity records; these titles each cover a range of similar actions. They have been grouped into 6 activity types useful for this discussion: Add, Wire, Input, Arrange, View, and Delete (see Table 1).

Table 1. Activity Type Grouping.

Activity Type	Corresponding *Grasshopper* Actions
Add	AddObjectAction (add components, copy and paste component)
Wire	WireAction (connect wire, remove wire, disconnect source/recipient)
	DataModificationAction (list related actions: flatten, simplify, graft, reverse)
Input	GenericObjectAction (slider change, remove parameter, code change, etc),
	ExpressionUndoAction (editing expression)
	PersistentDataAction (set boolean/line/integer, etc)
Arrange	LayoutAction (panel/number slider resize)
	NickNameAction (change of component name)
	PivotAction (component drag, component split, align components)
	ClusterPreviewDocumentAction (clustering related activity)
View	LockedAction (enable/disable a component)
	HiddenAction (preview)
Delete	RemoveObjectAction (delete component, ungroup component, cut component)

On average, designers performed 453 actions until the end of the bridge task, and 360 actions until the end of tower task. Average time spent on bridge task is 57.6 minutes, and 56.4 minutes for tower task. Minimum time spent on the task overall is 39 minutes, and maximum of 67 minutes. Aproximately 7 actions a minute. The highest number of action belongs to bridgeYY, 727 actions in 62 minutes, and lowest belongs to towers, 152 actions in 56 minutes. 'Arrange' activity type is the most popular, accounting for 37.7% of the total activities with 32.76% of this just component dragging alone. Next popular activity type is 'Wiring' at 25.21%, followed by 'Input' at 15.48%. For designers who employ coding strategy such that HD and SH, the use of sliders, which belongs to Input category, are generally higher.

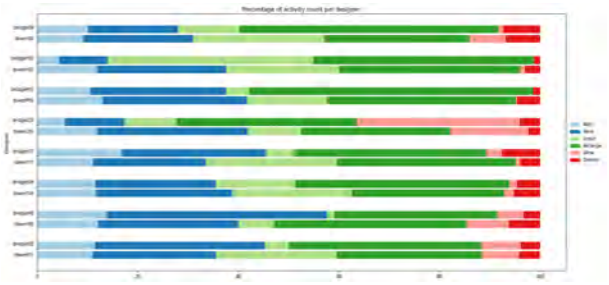


Figure 4. Percentage of Activity Count per Designer for bridge and tower parametric model.

Activity records also showed that although generally designers work similarly in bridge and tower case, designers 'fiddled' with input parameters more in the latter (19.5% as compared to 11.9%). Bridge case has higher 'Arrange' percentage, 42.3% as compared to tower's 33.1%. During interview, this is confirmed:

designers looked at tower structures as a surface system and hence dealing with the input parameters more, while designers looked at bridge structures more as elements of points and lines thus edited the underlying component associations more.

4.3. TYPES OF ACTIVITY : MODEL FIRST, EXPLORE LATER

Overall component addition progress are plotted based on add and delete activity throughout the session (see Fig. 5). Addition has the line to go up, while deletion has the line to go down. A sudden jump on the line usually signified a large delete or copy paste behaviour. For example, an interesting pattern could be detected on the EE's bridge: copying the whole definition at the start as a backup and removing the copied components at the end. Designer YY, on the other hand, on bridgeYY, deleted the whole parametric model definition as the session started, and built a brand new definition. Both of these behaviour exemplifies Woodbury's (2010) observation of two strategies in parametric design: (1) copy and modify, and (2) throw code away. In general, designers added up to about 40 components within the one hour duration.

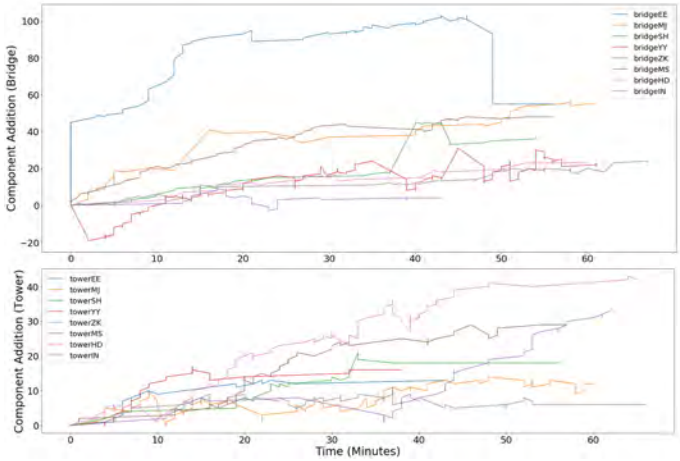


Figure 5. Component Addition Progress throughout design sessions for Bridge parametric model (top) and Tower parametric model (bottom). Addition is typically asymptotic - designers stopped adding components after a while; sliders to explore designs afterwards.

4.4. WHAT COMPONENT ADD ACTIONS FOLLOWS ANOTHER ADD?

'Component Adding Adjacency matrix' (see Fig. 6) shows which components are added after the proceeding one. The add components relationships have been grouped using Louvain Community Detection algorithm (Blondel et al., 2008) and then arranged in the matrix so that those which are used together are close. Most of the adjacent occurrence of add only happen one time, with top occurrence numbered at 6 for Add List Item and Add Number Slider.

Despite the limited data there are five groupings detected from top left diagonal to bottom right: (1) (mostly) basic arithmetic operation (light blue) - add division, add number slider, add list item, etc, (2) vector related addition (dark blue) - unit x, y, z, rotate3D, etc, (3) geometric related (light green) - add line, loft, polyline, merge, flatten tree, etc, (4) algorithm related (dark green) - such as Delaunay and Voronoi and, (5) mesh and surface related (peach)- add mesh brep, mesh surface, etc. Bottom right red colour group only consist of two data points and could not be considered as a group. This shows quite strong grouping of component usage (especially in the first three) and these categories are not the same as the existing grouping by type in the Grasshopper user interface, implying that component section could be possibly streamlined.

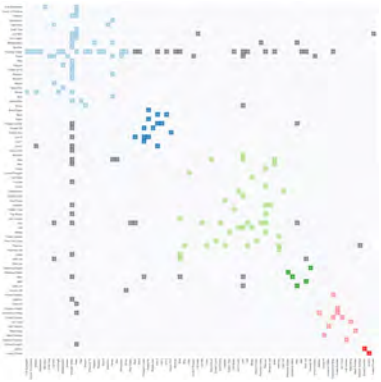


Figure 6. Add Components used in design sessions grouped by their occurences. Component addition on X axis is followed by corresponding component addition on Y axis.

5. An informed comparison: design footprints, design iterations, and GHShot

To have a more detailed look at design activity of each designer in each case, activity is visualized in form of heatmap (see Fig. 7). Types of activity are spread along the Y axis, with timeline in minutes on the X axis. Designers performing more actions have more intense activity footprints. E.g: bridgeYY as compared to towerSH. It is also obvious that Arrange activity has high intensity across all designer (as mentioned in 4.2 earlier), and generally are related to Wire and Add actions. The main strategy of adding component and wiring them at the beginning followed by more intensive use of sliders are adopted by most participants, for example designers EE, YY, and MS. For designer SH and HD, a scripting strategy is employed from the beginning of the session, hence the intensity of Input related activity (Slider Change) higher, spanning from beginning to the end of the session. It is also observable that it is possible to detect similar usage patterns by users between tasks. For example, bridgeSH and towerSH show low footprints and have Input activity spanning through the session intermittently.

Activity footprints further confirmed that all users designed in stages or bursts. Episodes of high activity usually are followed by easily identified gaps of no

modelling activity. During this period of modelling inactivity, designers reassess their design progress by observing the output geometry and further decide what to do next. Designers mentioned that the use of *GHShot* allowed them to look at overall design progress through the snapshots visualisation in the web during this period, as compared to only looking at immediate previous iteration without *GHShot*.



Figure 7. Activtiy Heatmap for each user for bridge case (left) and tower case (right). The vertical lines represent the time where the snapshots were taken.

Further, these episodes were broadly identified by two main action types: *Add-Wire-Arrange* - that is developing associative logic which signifies a creation activity, and *Input* - mainly consisting of slider activity (exploring options). A gap preceding *Add-Wire-Arrange* activity signifies an iteration of exploring a certain design concept (major iteration), while a gap preceding *Input* activity signifies an iteration of parameter exploration within that concept (minor iteration). It is observed that the use of *GHShot* does not modify these two types of iteration, but rather it becomes a clearer indication when these iterations happen. *GHShot* is used periodically in a longer interval to save progress throughout the design session (major iteration), and *GHShot* is also used in a shorter interval, with burst of snapshots (minor iteration). TowerMJ (see Fig. 7), is an exception as she forgot to use *GHShot* and only remember to send snapshots towards the end of session.

In terms of number of iterations and performance outcome, there is no difference observed for designers with or without *GHShot* (see Fig. 8). For both bridge and tower case, generally designers performed three to four iterations within the span one hour, with faster designer reached five and slower designer two. Designers mentioned that they become more aware of the performance of

the design with the graph view available in the web. One gave feedback that the performance graph in the web viewer of *GHShot* challenged them to make the most efficient structure (see Fig. 9).

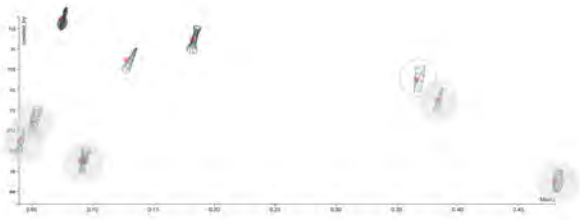


Figure 8. Final tower design from each designers. Towers completed using GHShot are shaded in gray, original design in a white circle. Six designers reduced utilisation value of the original structure.

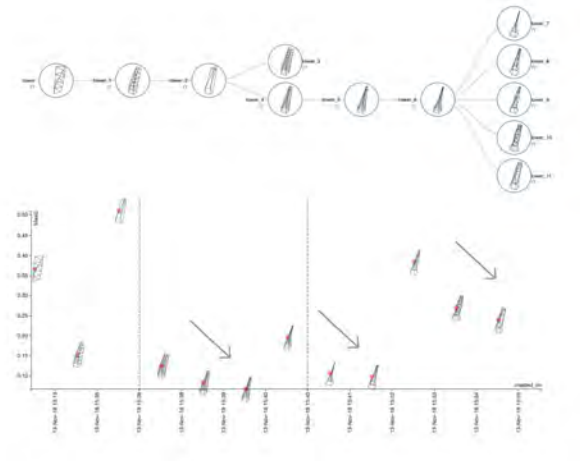


Figure 9. TowerYY design progression. Top: Tree Graph showing different concepts the designer explored at each branching point. Bottom: Continuous effort to improve performance at each iteration.

6. Conclusion and Future Work

In this work, we have demonstrated how capturing designers' actions within *Grasshopper* could reveal user behaviour, including iterations of modelling and exploration action preference during design process. Data captured serves as design footprint unique to a user, but in aggregate telling on how people interact with parametric software. It has shed light on different and shared strategies designers adopt in parametric modelling and design explorations. Grouping consecutive add actions has shown different modelling types performed by designers. Footprint of data collected had shown potentially focus areas of

intervention in improving parametric modelling. For example, if on average 37.7% of designers' time during the session is spent on arranging components this is something that could benefit from better automated tools and/or support.

Capturing design states with *GHShot* exhibits two patterns of recording: periodic snapshots to save design progress and burst snapshots to save outcome by fiddling with input parameters. Designers gave positive feedback on the ease of use of the tool and how the tool gave them capability to look at the overall design progress and design variations and not having to worry of missing previously developed but unsaved parametric model as long as they remember to click to send to server periodically.

Design process can be better understood by capturing user activity and design states empirically. This is the first step before improving the process in the long run. For our further work, we look forward to repeat similar design sessions with different design cases for more participants as it is still inconclusive to say if a certain process would yield a better actual design-result performance due to open-ended design case with limited number of participants in current experiment.

References

Aish, R.: 2000, Collaborative Design using Long Transactions and "Change Merge", *Proceedings of eCAADe 18*.

Blondel, V.D., Guillaume, J.-L., Lambiotte, R. and Lefebvre, E.: 2008, Fast unfolding of communities in large networks, *Journal of statistical mechanics: theory and experiment*, **10**, P10008.

Cristie, V. and Joyce, S.C.: 2017, Capturing And Visualising Parametric Design Flow Through Interactive Web Versioning Snapshots, *Proceedings of International Association for Shell and Spatial Structures Symposium*.

Davis, D.: 2013, *Modelled on software engineering: Flexible parametric models in the practice of architecture.*, Ph.D. Thesis, RMIT.

D'Ambros, M., Gall, H., Lanza, M. and Pinzger, M. 2008, Analysing Software Repositories to Understand Software Evolution, *in* T. Mens and S. Demeyer (eds.), *Software Evolution*, Springer, 37-67.

X. De Kestelier and B. Peters (eds.): 2013, *Computation Works: The Building of Algorithmic Thought*, Wiley.

MacLeamy, P.: 2004, Collaboration, Integrated Information, and the Project Lifecycle in Building Design and Construction and Operation, *The Construction Users Roundtable*, WP-1202.

Meagher, M., Park, A. and Nembrini, J.: 2013, Analysing The Performance-Based Computational Design Process: A Data Study, . *In Rethinking Prototyping: Proceedings of 4th Design Modelling Symposium*, 359-375.

Rochkind, M.J.: 1975, The source code control system, *IEEE transactions on Software Engineering*, **4**, 364-370.

Sakai, Y. and Tsunoda, D.: 2015, Decentralized Version Control and Mass Collective Collaboration in design-A Case Study of a Web Application Utilizing the Diff Algorithm and Automated Design Generation, *Proceedings of eCAADe 33*, 207-214.

Smith, R.: 2007, "Technical Notes from experiences and studies in using Parametric and BIM architectural software" . Available from <http://www.vbtllc.com/images/VBTTechnicalNotes.pdf> (accessed 26 November 2018).

Woodbury, R.: 2010, *Elements of Parametric Design*, Routledge.

Woodbury, R., Mohiuddin, A., Cichy, M. and Mueller, V.: 2017, Interactive design galleries: A general approach to interacting with design alternatives, *Design Studies*, **52**, 40-72.

THREE-DIMENSIONAL MODEL AND NETWORK-BASED REPRESENTATION OF TRADITIONAL JAPANESE WOODEN BUILDING SYSTEM

KEITA KADO[1] and GAKUHITO HIRASAWA[2]
[1,2]*Chiba University*
[1]*kado@chiba-u.jp* [2]*hirasawa@faculty.chiba-u.jp*

Abstract. Traditional Japanese wooden buildings are designed on the basis of a systematised building system. A typical systematised method called "kiwari" sets parametric/algorithmic rules that determine the dimensions and positions of components. These methods, which facilitate traditional wooden architecture, have cultural value. In this work, the authors report a representation method that is aimed at creating a three-dimensional model and a network-based representation of the traditional Japanese wooden building system. A systematised method that enables the construction of a quadruped gate using the traditional Japanese wooden building system is analysed through algorithm creation and visualisation of relations from the variables of the instances by the proposed system.

Keywords. Parametric Design; Japanese Traditional Wooden Building System; Knowledge Representation.

1. Introduction

Traditional Japanese wooden buildings are known to be designed on the basis of a systematised building system. An example of such a system, called "kiwari," sets rules for the determination of the dimensions of parts based on the ratio to a pillar or a "taruki" rafter. These methods have also been applied to calculate the positions of parts.

There have been numerous studies on "kiwarisho", which are traditional Japanese architectural reference documents. Mizoguchi (2006) provided a detailed analysis of how the five-storied pagoda of Horyuji Temple can be interpreted in terms of the building system that systematised column spacing dimensions and rafter distribution. By analysing the kiwari of a two-storied pagoda described in several kiwarisho, Shimizu (2005) conducted a historical investigation of the design system. Systematised construction methods recorded in kiwarisho in this manner play a particularly important part in analysing traditional Japanese wooden architecture. These systematised construction methods, although complex, are known to have a parametric/algorithmic quality. Kado (2011) showed that the traditional design methods used in these forms of architecture can be programmed as an algorithm and used in detailed three-dimensional (3D) modelling. Furthermore, Kado (2017) focused on the cultural value of these

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 501-510. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

methods, which make possible the construction of traditional wooden architecture, and attempted to define them as a form of knowledge representation by visualising them in a visual programming language (VPL), using dougong brackets as an example.

In this paper, the authors report a knowledge representation method that is aimed at creating a 3D model and a network-based representation of the traditional Japanese wooden building system. The study has two themes: first, considering a node that composes a network-based representation to obtain a formally structured representation and, second, describing features of this building system by analysing the represented network. These themes are studied through the creation of a 3D model of a traditional Japanese wooden gate.

2. Related works

As previously mentioned, there have been many studies on traditional Japanese wooden architecture related to kiwari. Several of these represent traditional wooden architecture using 3D models. However, the research mentioned above is the only example that represents a systematised method as a parametric algorithm and organises the method as a body of knowledge, focusing on its cultural value.

There are several examples of research on traditional Korean "hanok", in which wooden architectural structures are represented in a parametric manner. In the study by Park et al. (2011), the researchers demonstrated a method for parametrically creating 3D models for the purpose of spreading and industrialising the production of architectural structures built using this method. This report describes the parametric characteristics of hanok and creates a hierarchical organisation of structures that are formed by collections of parts. Kim et al. (2011) also proposed a method for parametrically creating 3D models of hanok. However, their study focused on units for efficiently creating 3D models of several variations of hanok, and it had a different purpose from this research. In the report by Lee et al. (2017), the researchers described the automatic generation of a 3D model of the Daengung-jeon of Sudeoksa Temple. The researchers reported that the dimensions of the parts that make up this structure could be derived from the relation between the depth and width of the whole scale and the height of the column, and they also presented a network representation. This result is extremely interesting. Unfortunately, it is unclear whether this phenomenon is based on traditional design methods or on the rationalisation that was performed to generate the 3D models automatically. However, the result implies that it is possible to analyse construction methods that form the basis for this phenomenon through algorithm creation and visualisation.

3. Method

In this work, the focus is on a "yotsuashimon" quadruped gate that was built using a traditional wooden building system. A 3D model and network representation of the quadruped gate was created based on *Daiku Tera Hinagata* (*Carpenter's Temple Handbook*), a handbook on traditional kiwari (Togashi, 2004). This handbook is based on archives of the *Zouhoshoshinden* and includes techniques

of other craftsmen, and it has been organised and edited for modern carpenters. Conducting research based on descriptions in the archives themselves was thought to be valuable, but it was estimated that a large number of person-hours would be spent on supplementing portions that lacked information, such as interpretation and details. Therefore, an approach was chosen in which the handbook was used as a reference.

The composition of the representation system for the 3D modelling and network representation is shown in Figure 1. The C/C++ class library includes the variable class, which handles dimensions, etc.; the PoseMatrix class, which handles pose; the Section class, which handles planar shapes and cross-section shapes of components and cut-outs in particular; the Shape class, which handles basic geometric information; the DesignMethod class, which handles design methods of components; the Part class, which handles component templates; and the Instance class, which handles actual instances of the components. One unique aspect of this 3D modelling method is that each class implements functions that can record the interactions that arise in the 3D modelling algorithm as dependencies. Executing programs that were written using this class library will output a network. The network is output in the DOT language, which is a language for describing data structures in network/graph form. This network was visualised using Graphviz, which is a visualisation tool for the DOT language. The 3D model is output in the Geometric Definition Language (GDL) format, which is the object description language used by ARCHICAD, a 3D computer-aided design (CAD) package for architecture developed by GRAPHISOFT. Figure 2 shows a legend for the classes described above for representing the classes as nodes in the network representation. Because using a VPL to write the program results in the program description itself being represented as a network, the proposed system may appear to be a roundabout way of programming. However, this method was chosen so that it would be easy to switch and analyse the elements output by the network. Another reason for this decision was that general-purpose VPLs for 3D modelling are not well-suited to systematically handling the relations found in traditional wooden architecture (Kado, 2016).

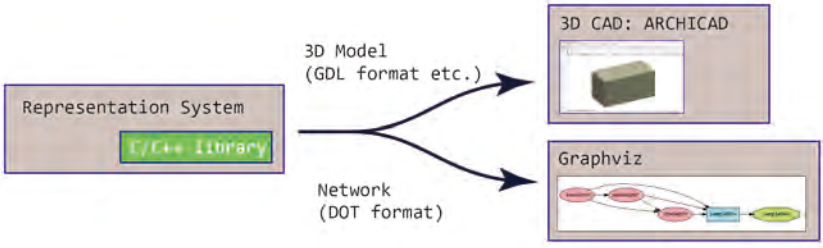


Figure 1. Overview of the representation system.

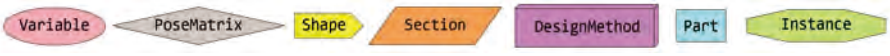


Figure 2. Legend of nodes representing classes.

3.1. VARIABLE CLASS

According to the handbook, in traditional Japanese wooden architecture, the dimensions of the various components are determined based on the width of the taruki rafters. In the quadruped gate, the height of the rafters is defined to be 1.2 times their width. The distance between the rafters, called “isshi” is defined to be the height plus the width of the rafters. The interval referred to as “hashirama” between the “hashira” pillars is defined as 24 times isshi, and the width of the pillars is defined as 11/100 of hashirama. The Variable class represents those elements that can be expressed as numbers, including dimensional relations such as these. The relation between the width of the rafters and the width of the pillars is shown in Figure 3.

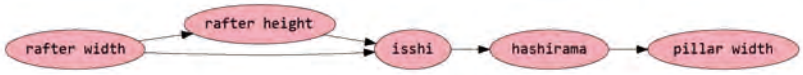


Figure 3. Relation between the width of the rafters and the width of the pillars.

3.2. DESIGNMETHOD CLASS

The DesignMethod class represents traditional design methods. The class is composed of one Shape class object, which represents the shape of the wooden material (“class” is omitted in the following discussion and is represented as “object”), a PoseMatrix object that describes its position and an arbitrary number of pairs of Shape objects and PoseMatrix objects that represent the shapes of cut-outs made during processing. This composition is defined as the base class, and specific design methods are implemented as subclasses of this base class. By providing base classes such as these to handle the common characteristics that each element must handle, it was possible to organise and formally represent the elements. This policy also applies to the Part and Instance classes, which are described later.

Figure 4 shows a network representation of the DesignMethod for a polygonal pillar with chamfering. The Section object denoted as “work section”, is determined by the width of the pillar, and the Shape object denoted as “work shape” is based on this section and the height of the pillar. The cut-out for the chamfering is represented by the four dashed lines, pairs 1-4. Although traditional wooden architecture also includes components with decorative designs known as “eyo”, in this research, only the outline of these components is represented in the DesignMethod object to the extent that these components did not affect other parts. In addition, these definitions do not include the shapes of joints between parts.

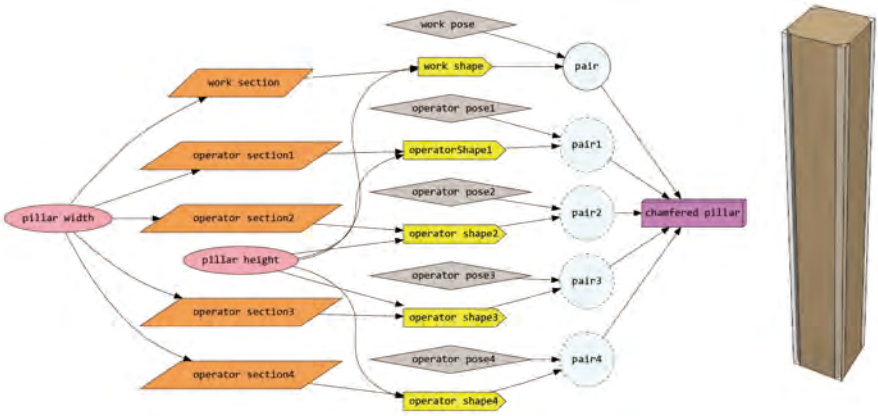


Figure 4. Relation in the DesignMethod of Chamfered Pillar.

3.3. PART CLASS AND INSTANCE CLASS

The purpose of the Part class is to handle the behaviour of the component. The base class has a DesignMethod object, a dictionary of combinations of PoseMatrix objects that represent the relative position and pose of the part when other parts are connected to it, and keys for identifying the objects. For example, the Part class for pillars with attached "koshi-nuki" and "kashira-nuki" beams can be represented by the chamfered pillar DesignMethod mentioned previously and a PoseMatrix object regarding the koshi-nuki and kashira-nuki beams, as shown in Figure 5.

The base class of the Instance class, which represents instances of components, is composed of a Part class object, which forms the template for the instance, a PoseMatrix object, which represents its position and pose, and an array of Instance objects. This array stores the Instance objects that this instance object connects to when it is assembled. The inputs for representing specific components consist of a Part class object, which serves as the template, and several Instance objects for the objects that connect to that instance, and the keys for their connecting positions.

Figure 6 shows an example of a framework composed of pillars and beams, represented as a network using these classes. The inputs for specifying the position and pose were not shown in this network in the arrangement of the instances; this was because the position and pose were determined based on to which instances a given instance was connected. As described above, the fact that the Part object possesses the relative position of the part when another instance is connected to it represents this characteristic. A 3D model was constructed by multiplying the PoseMatrix objects that represent the position and pose of the arranged instances to derive the positions and poses of each instance and create a scene graph.

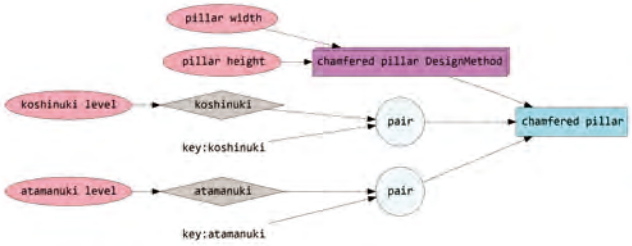


Figure 5. Relation in the Part class of Chamfered Pillar.

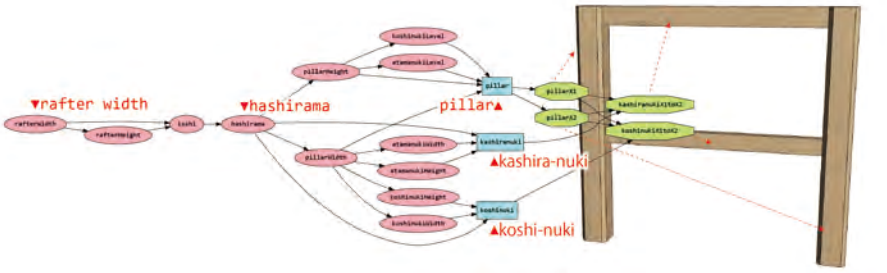


Figure 6. Relation in a Sample Framework.

4. Study Case

Figure 7 shows a 3D model of the quadruped gates that was created using this representation system. The relations between the Variable, Part, and Instance objects of the network representation for this quadruped gate were visualised, and the systematised method that was used to form this gate was analysed.

Figure 8 is a visualisation of the relation between variables and parts. The nodes are connected by directional branches. A hierarchical layout that flowed from left to right was chosen. There are many Part objects that require a large number of inputs when performing 3D modelling, and it was expected that the network would be deep. However, as shown in the figure, the network was shallow, with only 10 levels, and wide. It is widely known that the width of the rafter is the reference point for the other variables. The width of the pillar, which is derived based on the rafter width, serves as a hub and is referenced by many other variables. The figure also shows that such parameters as the slack of the roof, the gradient of the roof, the gradient of the "hien-taruki" rafter, and the gradient of the "ji-taruki" rafter were independent variables.

The Part objects that composed the framework consisting of pillars and penetrating tie beams tended to reference the pillar width, and the roof section tended to reference the width of the rafter width. As a result, the Part objects that composed the framework were concentrated at the top of the network, and those that composed the roof section were concentrated at the bottom of the network.

This shows that it is possible to organise the Part objects by the variables that are required to define them.

This network also included the variables that were calculated by the design method of the part object affecting other variables. These relations are denoted as green branches. There is a common point that these part objects have an established design method. "Masu", such as the "makito" and the "daito", are known to be designed with an established design method named "itsutsu-wari" or "itsutsuhan-wari". Detailed dimensions of masu that are denoted as "toguri height" and "shikimen level" are referenced by other variables. The design method for the curve of the eaves has also been established as the design method for the "kayaoi". Variables that determined the curve were also outputs from the kayaoi node. The network shows that the systematised method does not necessarily flow to details from the whole.

It is also interesting to note that the part objects for the pillar and the side pillar were defined last in this network. Figure 9 shows the instances network. The network provides a visualisation of the dependencies, following the order of assembly from left to right. The pillar and the side pillar instance objects appear in Levels 2-3 in the network, which consists of 20 levels. This implies that they were assembled at an early stage. Similarly, for the roof section, the other part objects were defined after the kayaoi part object, which specifies the curve of the eaves, had been defined. In the arrangement order of the instance objects, the kayaoi instance object appeared later. No method was used in which the structure was designed as it was being assembled. This implies that the systematised method functions to specify the entire quadruped gate.

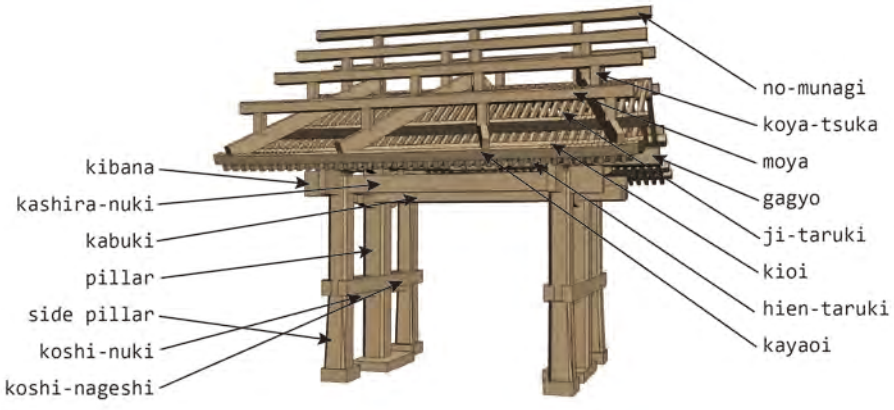


Figure 7. 3D model of Quadruped Gate.

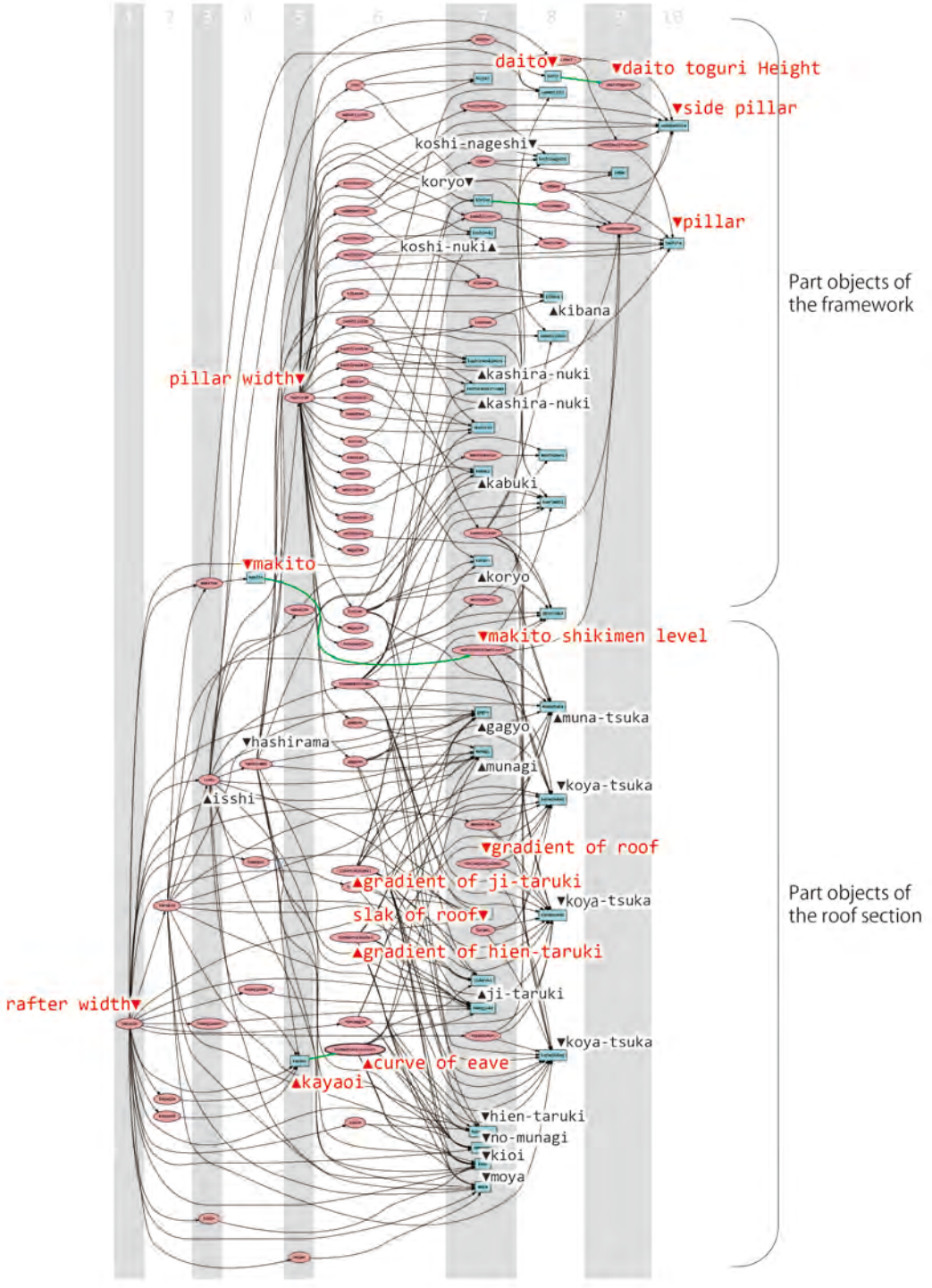


Figure 8. Relation between Variables.

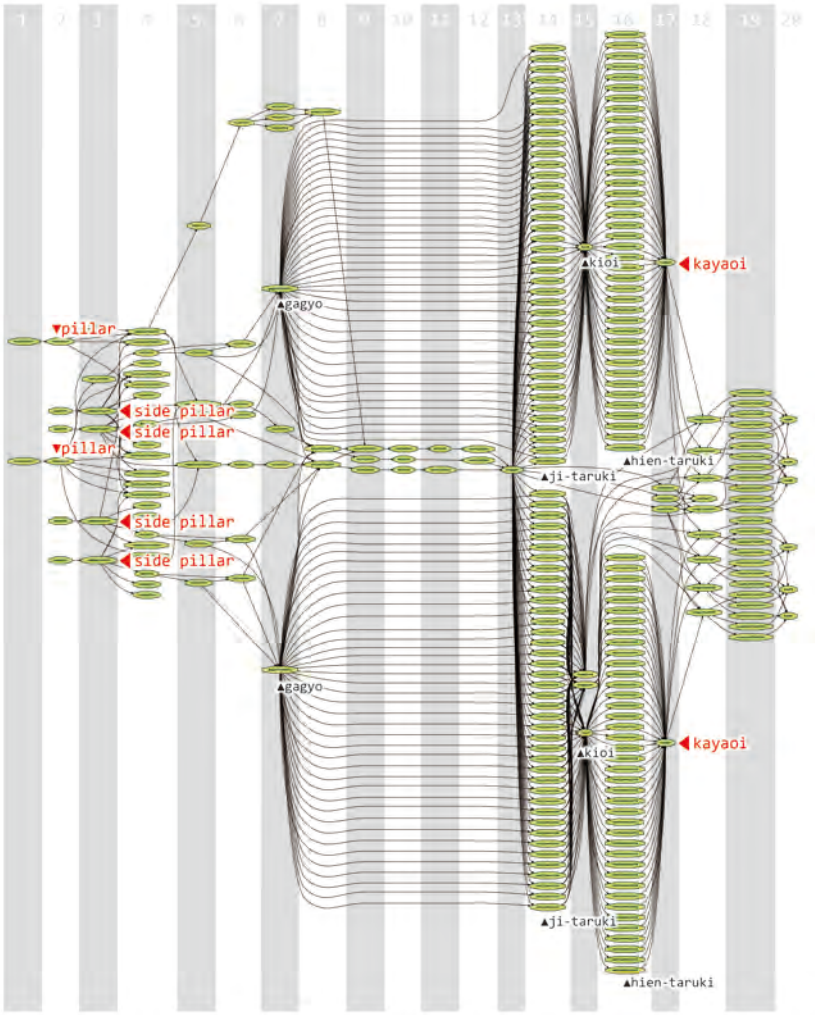


Figure 9. Relation between instances.

5. Conclusion

In this work, an overview of a representation system was presented for the purpose of creating 3D models and network representations for traditional wooden architectural structures, and the system was used to create and analyse a network representation of a quadruped gate.

In Section 3, an overview was given of the representation system. Seven classes were presented, and how to use them as nodes in a network representation was described. In particular, it is believed to be necessary to have an organised class structure to represent the systematised method formally as a network, which

is formalised as building system.

In Section 4, three network representations were shown: the relation between variables and parts, and the relation between instances. In the relation between variables and parts, variables that were calculated based on part objects that possessed established design methods, such as masu and kayaoi, appeared in the network. This showed that the systematised method does not necessarily flow in the direction from the overall design to the details. Furthermore, the part objects were arranged such that they appear to be pulled by the variables that need them as inputs, and that the parts were organised in clusters. This observation is more obvious if a spring layout is used, rather than a hierarchical layout. Observing this relation, together with the relation between instances, shows that in the relation between variables and parts, the part objects for the pillar and the side pillar are defined in a later layer. However, in the relation between instances, the instance objects are arranged in an early layer. The opposite result was found for the kayaoi. These results showed that the systematised method could be used to specify the overall quadruped gate.

By using the custom-developed representation system, it was possible to create a network to visualise the relations between the compositional elements that arise during the creation of a 3D model, from the variables to the instances. It was thus possible to analyse the systematised method that enables the construction of the quadruped gate using a traditional Japanese wooden building system. Future work is planned that will include an investigation of whether it is possible to use this method to represent and analyse architectural structures that were built using other construction methods, by attempting a similar analysis on other types of traditional wooden architectural structures.

References

Kado, K., Aono, T. and Hirasawa, G.: 2017, Study on Representation for Tokyo-Bu by Visual Programming -Knowledge representation for traditional wooden building system with computer language-, *Journal of Architecture and Planning (Transactions of AIJ)*, **Vol.82 No.742**, 3259-3268.

Kado, K. and Hirasawa, G.: 2011, Part Classes and Their Instances on Digital Archive of Traditional Wooden Architecture, *Journal of Architecture andPlanning (Transactions of AIJ)*, **Vol.77 No.662**, 877-886.

Kim, J. and Jeon, B.H.: 2012, Design Integrated Parametric Modeling Methodology for Han-ok, *Journal of Asian Architecture and Building Engineering*, **vol.11 no.2**, 239-243.

Lee, H.J. and Lee, H.: 2017, Automatic 3d Modeling of KoreanTraditional Architecture, *Proceedings of the22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017*, 231-241.

Mizoguchi, A.: 2006, On the Dimensional Plan of The Column Spacing in Houryu-Ji Pagoda - Study on the Dimensional Plan of the Column Spacing and the Rafter Spacing in The Ancient Architecture Part 3, *Journal of Architecture and Planning (Transactions of AIJ)*, **No.608**, 135-141.

Park, J.: 2011, BIM-Based Parametric Design Methodology for Modernized Korean Traditional Buildings, *Journal of Asian Architecture and Building Engineering*, **vol.10 no.2**, 327-334.

Shimizu, T., Kawata, K. and Naito, A.: 2005, A Study on the Design System of Tahoto Pagodas in Japanese Traditional Architectural Reference Books, *Journal of Architecture and Planning (Transactions of AIJ)*, **591**, 155-160.

Togashi, S.: 2014, *Daiku miya hinagata (Template for Miya)*, Rikogakusha Publishing Co.,Ltd.

ARCHITECTURAL COMPUTING

Pedagogical Experiments at the Intersection of Architectural Design and Mechanical Computation

DIMITRIS PAPANIKOLAOU
[1]*University of North Carolina at Charlotte*
[1]*dpapanik@uncc.edu*

Abstract. This paper describes the development of a pedagogy that aims to engage architecture students in principles of mechanical computation and to develop critical thinking on how information and computation can be manifested and performed tectonically. I pose the question: Can we create architectures that compute?

Keywords. Mechanical computation; computing machines; architectural education; architectural computing.

1. COMPUTATIONAL DESIGN VS. DESIGN COMPUTATION

Since the birth of computing, two intertwined directions dominate the discourse on architectural computing in education, research, and practice. The first, coming from design studies, inquires design as a process, asking the question "is designing computable?" The second, coming from cybernetics and systems theory, inquires design as an artifact, as well as its relationship with its user(s), asking the question "is inhabiting computable?" While the relationship between computing and designing has retained strong connections with design theories, the relationship between computing and inhabiting has not. Designing architectural typologies from shape grammar rules (Stiny and Gips 1972; Mitchell 1989) has been paralleled to the process of composing syntactically valid sentences from language grammar rules (Chomsky 1964), evolving into a procedural theory of designing. In contrast, since the MIT Architecture Machine Group's Media Room (Bolt 1980), designing intelligent environments has done little more than appending computing technology (sensors, actuators) to architecture and assigning it anthropomorphic behaviors, with no critical theories on how computing technology, materials, and building typology affect each other.

There are two reasons, I argue, for this. The first is that the medium with which information is manifested (electric voltage) is invisible and the speed with which it is processed by a computer is imperceptibly fast. As a consequence, the actual workings of computation are experientially unnoticeable and difficult to express architecturally. The second reason is that, when architecture students learn programming for Interactive Computing, they are trained in high-level languages that further mask the machine code that drives computation. The invisibility

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 511-520. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

of information and computation and the de-contextualization of programming from the mechanics of computing, miss the opportunity to use computation as a medium to drive design, and mask the potential contribution that architectural design theories can make in computing.

This paper describes the development of a pedagogical approach in a project-based seminar at the University of North Carolina at Charlotte (UNCC) that aims to engage students in principles of mechanical computation and develop critical thinking on how information and computation can be manifested and performed tectonically, through architecture. The course poses the question: What if the built environment could compute? Can we design computation instead of computing design? Can we, and if so, how should we, design environments that compute? Selected student projects are presented and discussed.

The rest of this paper is organized as follows. First, I trace the origins of mechanical computation and I show examples of mechanical computing devices, arguing that information manifestation and computation are inseparable from physical form. Next, I discuss how the concept of mechanical computation and the design of mechanical logic gates can extend to design architectural machines that can compute by changing their states from human movement and natural forces. I then describe a seminar assignment in which students created a binary adding machine, in order to learn principles of computing and logic circuits. Finally, I conclude by discussing my insights and reflections on teaching computer sciences to architects based on input from students' feedback.

2. FROM MECHANICAL TO ARCHITECTURAL COMPUTATION

While traces of the history of computing and informatics extend as far as the first bonfire relay telecommunication systems in the 12th century BC in Greece (Holzmann and Pehrson 1994), the first working digital computer ever constructed is thought to be an ingenious arrangement of ropes and pulleys in the jungle of Apraphul in New Guinea dating back to 850 AD (Dewdney 1988). Apraphulians used a binary system by using positions of ropes instead of electric voltages. Other early examples include the 18th'century's internet of optical telegraphy (Papanikolaou, n.d.). Optical telegraphs were mechanical devices of architectural scale that could store, transmit and process information through physical form for hundreds of miles distance within a matter of few minutes (Holzmann and Björn Pehrson 1994). The first automatic mechanical calculator, called the difference engine, was invented by Charles Babbage. The Tinker Toy Computer, a 1975 mechanical computer that plays tic-tac-toe made by MIT students (Dewdney 1989). In 1994, Chalcraft and Greene, published a paper showing that train sets can be Turing complete (Chalcraft and Greene 1994) and designed railway layouts that simulate the operation of a computing machine (Hayes 2007). Basically, a railway layout represents a program. Turing trains consist of a set of loops and joints. As the train locomotion moves forward, it opens and closes switches and gates, changing the registries. By configuring railway layouts, any program and any problem can be computed. Digi-Comp II, a marble computer designed by John T. Godfrey in 1965, was an automatic binary digital mechanical computer capable of performing basic arithmetic operations such as addition, subtraction,

multiplication and division. By rolling marbles through gravity through latches and gates. The configuration of the gates creates registries and the consecutive passes of marble spheres changes the states of the logic gates. One year later, Godfrey designed Dr. Nim, a plastic digital mechanical computer toy that was published by EST Inc. to be played by one player that was claimed to be unbeatable. Like the Digi Comp II, Dr. Nim consisted of flip-flops (mechanical latches that story memory by their state) that, when combined in cascades, determine the path of a marble. As the marble moves it changes the state of the flip-flops and concurrently the state of the flip-flops determines its path.

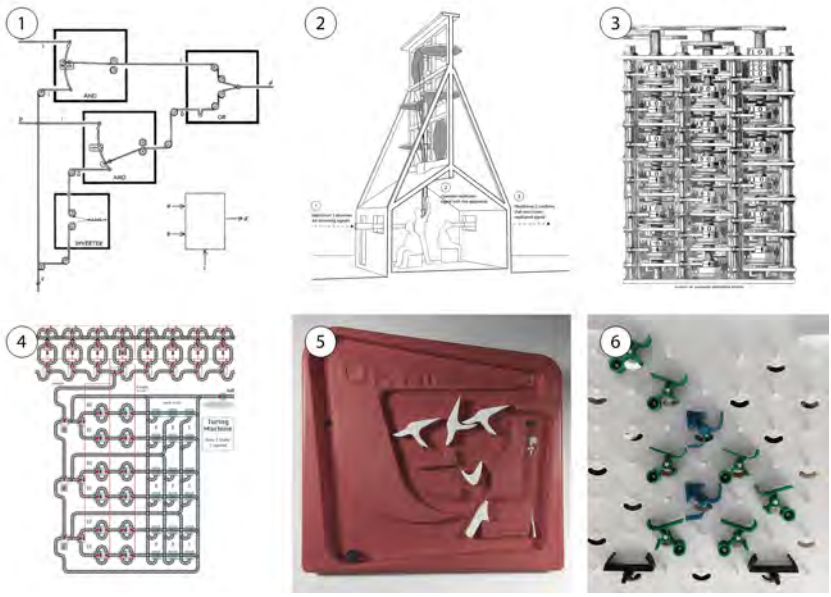


Figure 1. Examples of mechanical computing devices: 1: An Apraphulian multiplexer; 2: Optical telegraph building that changes the configuration of its panels to encode 6-bit characters; 3: The Babbage differential engine; 4: Turing Trains, implementation of the Digi-Comp II; 5: Dr. Nim marble-powered mechanical computing toy by J. T. Godfrey; 6: Turing Tumble marble-powered mechanical computer toy by Paul Boswell.

A recent example of a mechanical computer is Turing Tumble which teaches basics of computing. Other examples include fluidic logic circuits with air bubbles (Prakash and Gershenfeld 2007) and mechanical binary adding machines by folding linkages ("The Linkage Computer | Xiaoji Chen's Design Weblog" n.d.). Most recently, mechanical computing automata can be designed to create 3D-printed intelligent digital mechanical meta-materials (Ion et al. 2017). By 3D printing a cell-structure consisting of logic gates, materials can be designed so that they compute and control their shapes based on their deformation due to applied loads. Despite the physicality of computing, mechanical computation is absent from current discourses in architectural education.

3. A PEDAGOGICAL EXPERIMENT

The pedagogical challenge for students was straightforward. If we can create computation by trains, marbles, linkages, ropes and pulleys, fluids and bubbles, and mechanical latches, then why can't we create computation with architecture, using as energy sources things such as flow of people, tidal forces, wind, traffic of vehicles, and in general any other natural or anthropogenic source of energy? To further explore this issue practically at an object-scale, a design assignment was developed as part of a project-based seminar taught at UNCC's School of Architecture (SoA) during fall 2018. Participating students were graduates from Architecture, Computer Science, and Software Information Systems backgrounds. In what follows, I describe the general pedagogy of the assignment and how it was interpreted in selected representative student projects.

3.1. MECHANICALLY COMPUTING ARTIFACTS

The seminar challenged students to imagine the built environment as a computational medium to connect humans and to design a project that supports their thesis, through the following premise: *"What if the built environment could intelligently sense and mediate our interactions?"* The seminar surveyed foundational skills in mechanical computing while emphasizing critical thinking and tradeoffs between technical complexity, design decisions, functionality, and quality of craft. Working in teams of 2-3 persons, students were asked to design and create a mechanically computing device that can interact with a user using a physical medium of their choice. In designing their devices, students ought to specify what the device does, how it interacts with a user, and how it uses energy to compute. In doing so, students ought to first understand the concept of a switch, a relay, and a gate. Students were presented with the following premise.

Is it possible to design a physical mechanism such that it tells us "yes" for some input configurations while "no" for others? Suppose input configurations to be combinations of simple questions that can have a "yes" or "no" state. If such mechanism existed and its inputs were configured by some properties of the environment while its outputs used energy from the environment to configure some other properties of it, then the system would be able to make decisions based on environmental changes, and interact logically with the environment, utilizing natural energy. Consider each input as a switch with two states. On one hand, the state of a switch can control flow of energy; on the other hand, flow of energy can control the state of a switch. By using the flow of energy that is controlled by one switch to control another switch, cascades of switches can be created that work as relays. Depending on the configuration of the states of two linked switches, a relay can be forward, meaning that a change in the state of the input switch causes a similar change in the state of the output switch, or reverse, meaning that a change in the state of the input switch causes an opposite change in the state of the output switch. By combining forward and backward relays, logic gates can be created. Logic gates take two inputs and produce an output and they are the fundamental blocks for building logic circuits.

The duration of the assignment was three weeks. Teams first studied principles

of Boolean logic, logic circuits, and studied examples of mechanical computation. Next, they developed design ideas for a switch, a relay, and the three basic logic gates (AND, OR, and NOT) for creating logic circuits. Next, using their relays, they developed functional prototypes of the three basic logic gates. Finally, they combined their logic gates to create a more complex mechanically computing machine. In designing their relays and gates, teams were asked to consider the following questions: How does your relay harvest, store, and release energy in order to change another relay? Does the output of one gate have the same format as the input? How can multiple relays connect in a cascade such that when one relay changes its state, it triggers its connecting relay to change its state as well? Considered forms of energy included mechanical movement, fluidic movement, wind flow, vehicle traffic, electrical current, sound, and pressure.

3.2. CREATING LOGIC GATES MECHANICALLY

Mechanical computing machines can be created by inventing analog ways to create logic gates and to connect their outputs to their inputs. A mechanically computing machine describes inputs using components that can take two states (bits) and computes by manipulating the state of each component procedurally, using energy from the environment. Figure 2 shows how a logic circuit can be physically simulated by trainsets ("Computational Train Track Layouts" n.d.). The train track consists of loops, that reverse the direction of the train, and of intersections with switches that act as flip-flows: if a train traverses them from one direction, it changes their state; if it traverses them from the opposite direction, they determine its direction. By configuring loops, intersections, and switches, any computer program can be simulated by a railway layout and a train that traverses it.

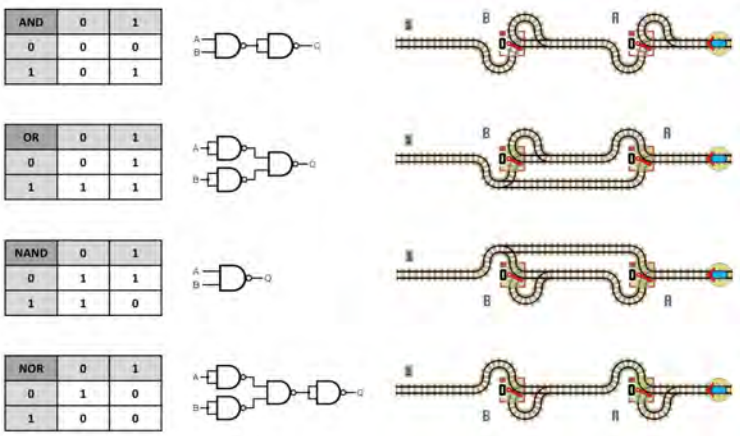


Figure 2. Examples showing how the four basic gates AND, OR, NAND, and NOR (left), can be mechanically simulated by trainsets (right).

3.3. ADDING BINARY

In order to narrow down the design exploration, teams were asked to design and prototype a binary adding machine using gravity and marbles as a source of energy. A binary adding machine takes two numbers as binary inputs and outputs their sum. The simplest binary adding machine -a half-adder- adds two binary digits and outputs their sum and carry bit. A half-adder can be thought of as two separate functions: sums and carries. Figure 3 shows how adding two binary numbers is divided into two Boolean truth tables, the first representing the carry bit and the second representing the sum bit. The carry bit is used as an overflow to the next digit, if numbers with more than one digits are added. As Figure 3 shows, a binary adding machine can be constructed by combining an Exclusive OR (XOR) and an AND gates: the carry bit is an AND gate while the sum bit is an XOR gate.



Figure 3. A binary adding table of two digits (left) can be decomposed into a table for the carry bit (center) and a table for the sum bit (right). The two tables are an AND and an XOR gate.

4. RESULTS

Three teams developed three designs shown in Figures 4 and 5. The first team developed a half-adder (the basic module that comprises a binary adding machine) using a design strategy for flip-flops similar to Digi-Comp II's. One interesting aspect of this design is that the type of the inputs is different than the type of the outputs. While inputs are configured by the positions of the flip-flops of each unit, outputs are determined by the positions of the exiting marbles (Figs. 4:1, 5:1).

The second team developed a binary adding machine consisting of cubic modules. Instead of configuring flip-flops, this machine is programmed by inserting a 3D-printed ribbon-shaped piece, the form of which configures the logic circuit in a similar manner that punch cards were used to program early-generation computers (Figs. 4:2, 5:2). The machine uses marbles dropped from the top to perform computation. The entry and exit positions of the marbles indicate its inputs and outputs respectively. The XOR gate of the half-adder is bigger than the AND gate, and it is constructed by a NAND, an OR, and an AND gates. The full-adder consists of two half adders and one reverse half-adder. The carry bit generated from the first half-adder indicates whether the second half-adder or the reverse half-adder will be used to complete the computation. The third team developed a machine that resembled a vertical labyrinth carved in a planar sheet of plywood (Figs. 4:3, 5:3). This machine could not be reprogrammed. To guarantee proper sequence of computational sub-procedures, the third team designed zig-zag paths that slowed down the trajectories of some of the marbles (delays).

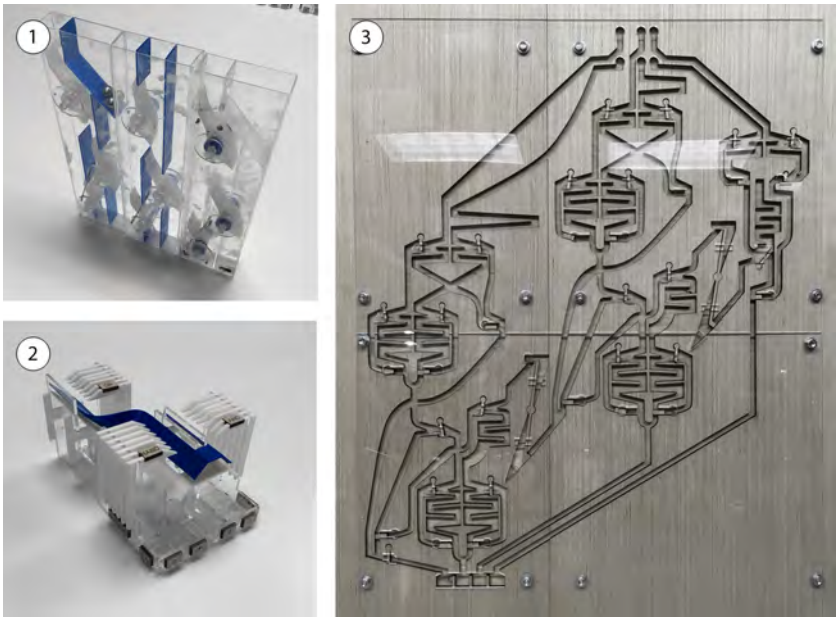


Figure 4. Student projects for mechanical binary adding machines. The machines add two 3-bit binary numbers and consist of logic gates. The logic gates consist of flip-flops that change their binary state as marbles pass through them and control the paths of the marbles. .

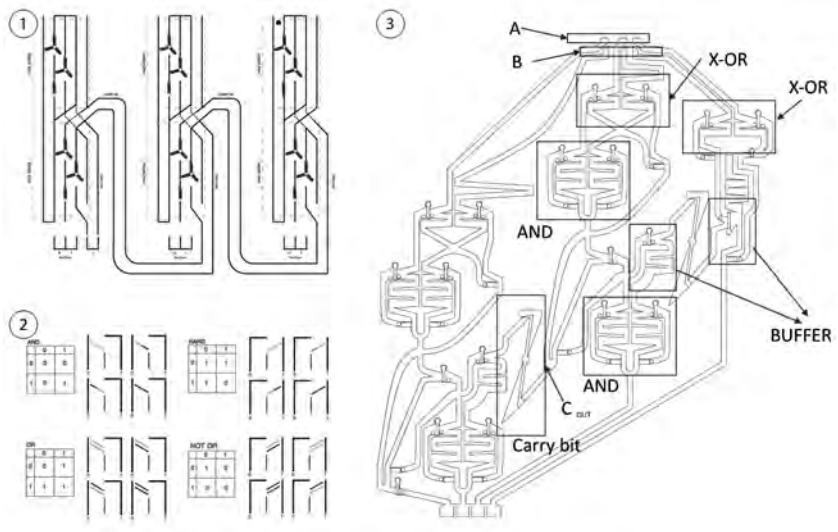


Figure 5. 1, 2: Diagrams showing the connection of the half-adder modules. The carry-out marble from a module becomes the carry-in marble to the next module. 3: Diagram showing the location and type of logic gates. A and B are inputs while buffers are delay mechanisms.

5. DISCUSSION

Several teaching and learning challenges emerged during the assignment, most of which related to preconceptions from digital electronics. One challenge was to conceptually distinguish between state of information and source of energy, when designing logic gates. State is something that stays constant over time until it is changed by flow of energy. State and energy may or may not be of the same medium: in electronic computing, they are both manifested by electricity; in Chalcraft and Greene's trainsets, however, states are represented by switches while energy is transferred by trains. Moreover, state may or may not need energy to be preserved: electronic flip-flops need energy to preserve their state (high/low voltage); mechanical switches, however, need not. Failure to distinguish between state of information and source of energy caused some students to confuse flow of trains with flow of electrons, assuming that designing a logic gate with trainsets would require two or more trains to enter a box and one (or none) train to exit.

Another challenge was to understand that state of information and flow of energy must each manipulate the other in order to create computing machines in which inputs and outputs have the same types. In logic circuits consisting of logic gates, inputs and outputs must have the same types so that the output from one machine can become the input of another. In order to achieve this, state of information must manipulate flow of energy, and flow of energy must manipulate state of information. For example, in Chalcraft and Greene's trainsets, the state of switches (information) manipulate flow of trains (energy), and the flow of trains manipulates the state of the switches; in Digi-Comp II, the state of latches (information) manipulates flow of marbles (energy), and the flow of marbles manipulates the state of the latches. Likewise, in digital electronics, the state of flip-flops (information) manipulates flow of electrons (energy), and the flow of electrons manipulates the state of the flip-flops. This feedback interaction between state of information and flow of energy allows inputs and outputs to be of the same type. Failure to understand this relationship caused some students to design machines with inputs and outputs of different types that could not be combined into more complex logic circuits.

Another challenge was to understand that computation may be slow and asynchronous as opposed to fast and synchronous. Since mechanical latches can store information in their state, change the flow of energy with their state, change their state from the flow of energy, or keep their state unchanged if energy is not flowing, computation steps can advance when energy is available and pause when energy is unavailable, creating asynchronous systems in which inputs need not be entered simultaneously. In contrast, in most digital electronics, computation is performed synchronously in cycles determined by a computer clock.

Another challenge for architecture students was to learn to design systems that store and use energy to "do something," as opposed to objects that passively afford "being used for something". This required from students to simplify their designs to the extent they could build them and prove their functionality, introducing a success criterion that were not being used to during their design education. To prepare students with the necessary technical skills, two assignments on

engineering design were introduced. The first, asked students to reverse engineer a mechanically actuated toy by disassembling it, listing all parts and their interconnections, and explaining how parts interact in a causal relationship to actuate the toy. The second assignment asked students to work in teams designing a functional mechanically actuated toy car. Toy cars ought to be designed for laser cutting and manual assembly with no adhesives or fasteners. One student that missed these two assignments, struggled more than others, afterward.

Finally, another challenge was contextualization. While most students could understand how logic gates work, when they were asked to design a computing machine that does something meaningful, they found the task too open-ended. To address this, students were asked to create a computing machine that performs a particular task (add two numbers). In a future iteration of this course, more open-ended design assignments will follow these prescribed design problems.

5.1. LEARNING COMPUTING WITH HANDS

In discussing teaching of computer sciences to architects, Nicholas Negroponte emphasized the importance for architecture students to learn computing tactilely with their hands (Negroponte 1975). This was precisely the motivation and objective of these experimentations. The combination of the Boolean logic truth tables and the hands-on assignments, aimed to give students a different perspective on what computation is. In the own words of the students:

Survey Question (author): *In the first part of the class we focus on computation and information theory not digitally but mechanically. In what ways does this approach affect or challenge your understanding or existing preconceptions of computation, specifically in relation to architecture?*

Student A: *At first, I didn't know computation from this deep perspective. Now I really understand the vastness of computation. The first 2 projects were quite different and many aspects and quite similar many. Both of them were enjoyable. I really liked the relation of computation and architecture in the last project.*

Student B: *Computation is always thought to be this mystic and difficult field to get into. The Mechanical computation, certainly helped in demystifying it and helped in understanding that static structure can do complex computations. The concept of space, time, form, composition, functionality, etc which are central to any architectural project were applicable to the design and understanding of mechanical systems and for making a mechanical adder.*

Student C: *It is definitely a side I have yet to experience in architecture. Most of my experience is purely digital and theoretical, so applying it to real life is an interesting challenge.*

Student D: *Specifically, being a CS student, the concept of computing using physical media has not only been a complete 180 in terms of approach but also has made me broaden my understanding of computation capabilities overall.*

My purpose through this pedagogy is not to suggest that computation in architecture should be mechanical instead of digital but rather to engage students in thinking that computation is not an abstract notion but rather something that can be designed physically. As such, its connection to architecture may extend

beyond that of a host of computing to that of a medium of computing. As this investigation is still in progress, it is early to provide comprehensive conclusions. Insights, however, are valuable in the discourse of architectural computing education. As computing and informatics become inseparable aspects of social life, their academic disciplines become increasingly more influential on the built environment. In contrast, a reluctance of Architecture to embrace these changes critically, may slowly push the discipline out of its own domain. Independently of the degree of elaboration of each project, all student investigations provided a tactile perspective on the mechanics of computation that helped students not only to deepen their understanding on the topic but most importantly to challenge their preconceptions about what intelligent architecture is and about what (if any) the boundary between architecture and computation might be.

ACKNOWLEDGEMENTS

The work of the following students is shown (listed in order of appearance): Seyedehsan Aboutorabi, Gavin Reeb and Saquib Sarwar (collaborative work); Manoj Deshpande, Rachel Lutes and Carlos Martinez (collaborative work); Nicklaus Williams and Sri Yeswanth Tadimalla (collaborative work).

References

Bolt, R.A.: 1980, "Put-that-there": Voice and gesture at the graphics interface, *ACM SIGGRAPH Computer Graphics*, **14**(3), 262-270.

Chalcraft, A. and Greene, M.: 1994, Train Sets, *Eureka*, **53**, 5-12.

Chen, X.: no year given, "The Linkage Computer | Xiaoji Chen" . Available from <http://www .xiaoji-chen.com/2010/the-linkage-computer> (accessed 24th September 2018).

Chomsky, N.: 1964, *Syntactic structures*, Mouton, The Hague.

Dewdney, A.K.: 1988, COMPUTER RECREATIONS, *Scientific American*, **258**(4), 118-121.

Dewdney, A.K.: 1989, A Tinkertoy computer that plays tic- tac- toe. (Computer Recreations) (column), *Scientific American*, **261**(4), 120.

Hayes, B.: 2007, Trains of Thought, *American Scientist; Research Triangle Park*, **95**(2), 108.

Holzmann, G.J. and Pehrson, B.: 1994, *The Early History of Data Networks*, Wiley-IEEE Computer Society Pr.

Holzmann, G.J. and Pehrson, B.: 1994a, The First Data Networks, *Scientific American*, **270**(1), 124.

Ion, A., Wall, L., Kovacs, R. and Baudisch, P.: 2017, Digital Mechanical Metamaterials, *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 977-988.

Miller, G.L.: 1990, Charles Babbage and the Design of Intelligence: Computers and Society in 19th-Century England, *Bulletin of Science, Technology \& Society*, **10**(2), 68-76.

Mitchell, W.J.: 1989, *The logic of architecture : design, computation, and cognition*, MIT Press, Cambridge, Mass..

Negroponte, N.: 1975, *Soft architecture machines.*, The MIT Press, Cambridge, Mass.

Papanikolaou, D. 2015, Choreographies of Information: The Architectural Internet of the Eighteenth Century's Optical Telegraphy, *in* A. Fardi and T. Meshkani (eds.), *New Geographies*, Harvard Graduate School of Design Press, Cambridge, MA, 45-55.

Prakash, M. and Gershenfeld, N.: 2007, Microfluidic bubble logic, *Science (New York, N.Y.)*, **315**(5813), 832.

Stiny, G. and Gips, J.: 1972, Shape Grammars and the Generative Specification of Painting and Sculpture, *Information Processing*, **71**, 1460-1465.

ROBOTIC FABRICATION OF DOUBLY CURVED FAÇADE SYSTEM

Constructing intelligence in the digital fabrication workflow

PAUL LOH[1], DAVID LEGGETT[2] and DANIEL PROHASKY[3]
[1] *University of Melbourne*
[1] *paul.loh@unimelb.edu.au*
[2] *Architectural Research Laboratory*
[2] *david@llds.com.au*
[3] *Swinburne University of Technology*
[3] *dprohasky@swin.edu.au*

Abstract. This paper presents a novel advance digital fabrication method to produce doubly curved concrete panel with no immediate waste as a facade system. Using a bespoke CNC adjustable mould frame system coupled with robotic trimming techniques, the research examines the streamlining of data within a cohesive fabrication workflow. The paper concludes by reviewing an integrated workflow that points towards a multifaceted system of design, engineering and advanced manufacturing that propel research to design application.

Keywords. Digital Fabrication; Design workflow; Robotic.

1. Introduction

With the increased use of computation tools in architecture, architects are increasingly exploring the use of complex curvature surfaces in their designs. However, standard industry means of casting doubly curved concrete panels requires extensive formwork commonly using Expanded Polystyrene Foam that is computer numeric controlled (CNC) milled. This is often discarded after use (Lavery 2010) and generates an enormous amount of construction waste which contributes directly to the cost of the panel, making forms with complex surface geometry costly to manufacture and not feasible to produce. What if, we can manufacture doubly curved concrete panels with minimal construction waste? This paper presents new techniques in the production of the doubly curved panels with no immediate waste using a bespoke CNC machine invented by the authors titled PAM. This is coupled with robotic milling to fabricate a 1:1 scale rainscreen cladding as proof of concept.

This paper builds on knowledge previously published on the technology (Loh et al., 2018). Here, the authors present new research from the next phase of development. The paper focused on the workflow using a robotic manipulator arm to trim concrete panels cast from PAM technology to form a rainscreen cladding system. In the previous publication, the authors had outlined the design of the

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 521-530. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

technology and its background, including the mathematical model, the descriptive geometry, and a process of verifying the panel accuracy against a 3D scanned virtual surface; the cast panel was within ± 3.5mm tolerance; ± 0.5mm from the acceptable tolerance prescribed in AS3850.1 (2015) for pre-cast concrete elements. Through the integrated robotic workflow, the new research to achieves precision machined doubly-curved panel edges instils a more comprehensive intelligence in the digital fabrication process to transform the cast panels into a practical construction system. This is coupled with a structural analysis of the supporting frames to the 1:1 scale prototype. The paper concludes by reviewing a multifaceted intelligent system of design, engineering and advanced manufacturing that propel research to design application.

2. Background

Variable mould systems have been of research interest in recent years. However, most designs are based on single-direction multi-point stretch-forming processes, where actuated pins or armatures to define the surface curvature (Schipper 2015); such system is complex and has multiple moving parts (Wang et al. 2012).

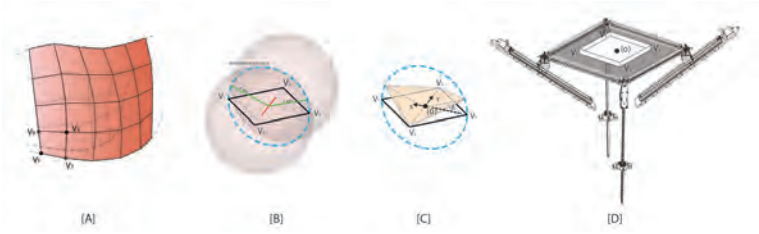


Figure 1. Descriptive geometry of PAM .

PAM provides an alternative method to fabricate doubly-curved concrete panels. It consists of a single CNC adjustable mould frame that can be used to produce accurate doubly-curved fibre-reinforced concrete panels. The mould frame does not utilise the multi-points system. Instead, it deploys the descriptive geometry of a second order geometry, namely the hyperbolic paraboloid. As Burry (2011) pointed out, one of its key characteristics is that surface can be fragmented into individual components which, when combined, can still form a seamless surface. The technology used four numeric controlled actuators to produce variable shaped cast concrete panels with nominal 10mm thickness. The single adjustable mould received translated digital information from a panelised surface using a custom script to actuate the mould into desired positions for concrete casting. The converted data of the virtual surface is made possible through the transformation of the doubly-curved ruled surface geometry. Figure 1 illustrates the procedure from a given free-form geometry to actuation of the mould frame for individual panels. We have identified in a previous publication that the panel can be described using three fundamental parameters. The first is the edge length of the panel. The second is the skew ratio of the rhombus panel. The third is the fold angle along one axis of the rhombus (V0 and V2)

called the Beta angle, Figure 1[C]. Figure 2 illustrates the fabrication process of a doubly-curved concrete panel using PAM technology; step 1 to 5 were previously published. Step 6 and 7 will form the principal focus of this paper. Concrete is poured into a square-shaped silicone mould, Figure 2[2]. Using a custom interface developed using Processing v3.4 [3], the skew and beta parameters of each panel are translated into travel distances of the linear actuators to transform the mould frame [4]. Once cured, the concrete panel is removed from the mould with no immediate waste [5].



Figure 2. PAM fabrication procedure.

PAM technology is effective and accurate in producing doubly-curved concrete panels, more specifically the surface curvature of a hyperbolic paraboloid quadrilateral surface with equal edge length. However, it is not able to articulate the edge of the panel. The research highlighted in this paper is to resolve the edge of the panel so that the shape of the panel can be different. The resolution of the edge described the shape of the panel as distinct from the curvature of the panel. This allows such fabrication technique to be made useful for construction applications either as a rainscreen system or for interior use as a wall, ceiling or hybrid of the two. The design team tested PAM to produce a 1:1 prototype of a free-form surface as a rainscreen cladding system within the limits of the current machine configuration. The prototype highlights the challenge for unequal edge length panels and panels with a skew ratio.

2.1. THE PROBLEM OF SKEW PANEL

Let us consider a typical free-form surface, see Figure 3. The surface can be penalised into quadrilateral surfaces which is non-developable (Pottmann et al., 2007). Depending on whether the surface is panalised from the centre of the

surface or one corner of the surface, it will typically result in area where equal edge length panels are not obtainable. At the same time, all the equal edge panels are typically rhombus in the plan. In line with the research hypothesis to fabricate concrete panel with minimal waste, we have avoided the wasteful solution of producing new silicone moulds for every rhombus shape; which is also financially impractical.

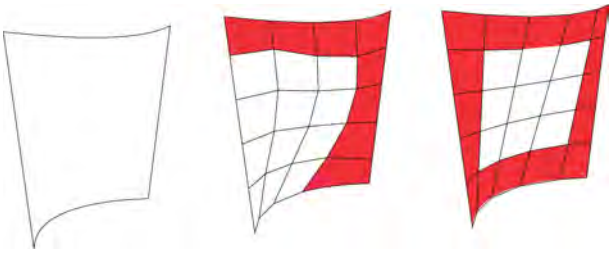


Figure 3. Left, free-form surface. Center, panelisation from the corner of a surface. Right, panelisation from centre of the surface. Red area indicates panel that is unequal edge length.

To resolve the issue, we utilised a Kuka KR120 robotic arm with a separate floor mounted rotating base as the 7th axis; it is equipped with a router and a diamond saw blade as an end effector to trim the panel. This approach presented two problems. Firstly, by adding another digital fabrication process on PAM technology, we will need to ensure that the data stream from the initial virtual model is carried across both systems. As described earlier, the PAM machine performs the difficult task of moulding surface curvature of the quadrilateral surface, and the robotic workflow performs the task of defining the shape of the panel; both are integral to the precision of the fabricated panel. The second problem is the relocation of the cast panel on the robotic system to ensure accurate positioning of the panel for trimming.

3. Design of CNC Fixture for Robotic Arm

To ensure the data stream is consistent throughout the fabrication procedure, the authors have designed and constructed a numerically controlled fixture to the 7th axis to mirror the data input from the PAM machine. The novel CNC fixture eliminates the need for multiple jigs in the trimming process. The fixture utilised a data feedback procedure concurrent with the moulding process to construct intelligence in the digital fabrication workflow. Figure 4 illustrates the design of the CNC fixture. It consists of an MDF base frame [B] that is fixed to the axis rotary table [A] associated with the Kuka robotic arm [J]. The base supports four sets of actuators, each consisting of a vertical leadscrew [D] and a horizontal leadscrew [C] driven by a stepper motor [E]. The end of the vertical leadscrew is fitted with a 3d-printed end stop on which the casted concrete panel [H] will rest. An acrylic tray [G[over the base frame collects and drains the water from the cutting process.

The concrete panel is cast with an cast-in threaded inserts as close to the centre point (O) refer to in figure 1[C]) on the back face of the panel which is screw fixed

to the centre threaded rod [K]. The centre point (O) is an important reference point as it is the only common point among the variably shaped panels. The skew and beta data are converted to travel distance, and the armatures [C & D] is moved into position of the panel's corners. We discovered that the position of the panel is not entirely accurate due to factors such as the varied thickness to the panel's back face and achieving full contact with the end stop [H]; misalignment will cause a tilt in the panel position. This will result in an accumulative error if panels are to be butt jointed to produce a seamless surface.

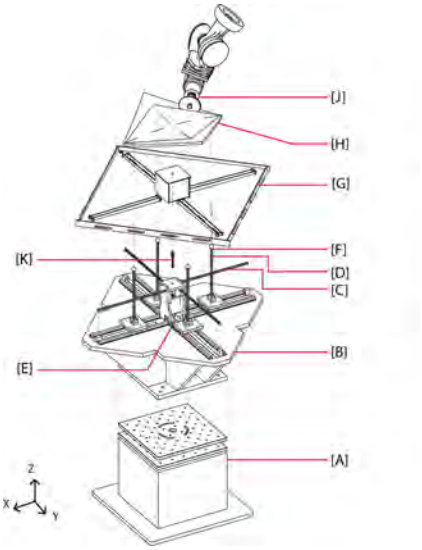


Figure 4. CNC fixture for Robotic Arm.

4. Constructing feedback and intelligence

In order to position the cast panel accurately on the fixture, we need to construct a feedback workflow between the robotic arm, the physical casted panel and the skewed virtual surface used to drive the fabrication of the panel through the PAM machine. The interaction between the three sets of information produced accurate positioning of the panel for trimming as well as enabling the team to match the data stream from the PAM machine to the robotic workflow.

4.1. INTERNALISING DATA THROUGH ROBOTIC INTERACTION

The authors cast a new set of panels using the PAM machine. A pin was used to mark the (O) of the panel and to locate the cast-in threaded inserts at the centre point. When we positioned the panel on the fixture, the CNC fixture guided the panel to an estimated position. The panel was tightened to the centre threaded rod (Figure 4 [K]). In this round of investigation, the team allowed the panel to tilt out of plane as we would rely on the robotic interaction to find its position in relation to the global position of the robot arm.

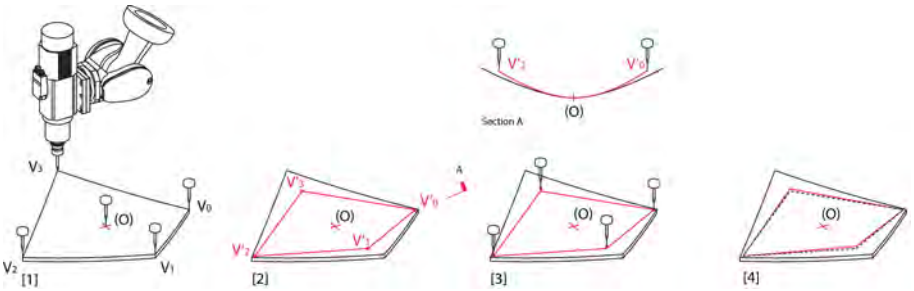


Figure 5. Internalising data through robotic interaction.

The first and second author performed a four-step procedure to internalise the positional data by using robotic interaction methods, see Figure 5. This allowed the physical artefact to be aligned with the global position of the robot arm which in turns was aligned with the virtual surface of the skew panel. This enabled the robotic arm to perform accurate cut to produce the skew panel. The robotic arm fitted with a marker pen on the spindle was calibrated to the global coordinate of the robotic cell and was manually jogged to the four corners (V0, V1, V2, V3) and the marked centre point of the cast panel [1]. The x, y and z coordinates of the tool centre points at each location were recorded in McNeel Rhino 3d which defined the positioning of the panel in relation to the robot positioning coordinate system. The skewed virtual surface was aligned to the recorded points, using its (O) as a reference position [2]. However, while we accurately aligned the position of the virtual surface in the x-y plane, the z dimension was not known as the virtual hyperbolic paraboloid surface was different from the cast ruled surface hyperbolic paraboloid surface from PAM machine [3]. The team plotted the skewed panel surface physically on the casted panel (V'0, V'1, V'2, V'3). We used a marker pen to draw on the located panel, bearing in mind that the concrete panel was not aligned rotationally on the X-Y plane of (O). The cut plane to the trimmed edge was aligned with the predicted physical location of the skewed surface [4]. The above procedure was scripted in Grasshopper3D, a plug-in to McNeel Rhino 3D.

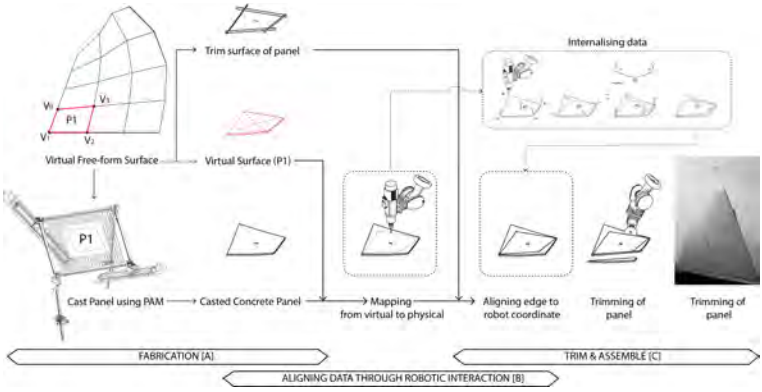


Figure 6. Overall workflow from Virtual Surface to fabricated panel.



Figure 7. Four panels prototype.

We used SprutCam to program the robotic operation where the trimmed edges were defined as drive surfaces for the saw end effector. As the panel was nominally 10mm thick, the cut operation was performed once on each edge. Running water over the saw acts as a coolant to the cutting operation. The 7-axis rotary table was rotated 180 degrees to perform a trim operation on the two edges furthest from the robotic arm. Figure 6 illustrates the complete workflow from the free-form virtual surface to the trimmed panel with minimal waste to the entire fabrication procedure. The workflow highlighted the need for robotic interaction during the calibration procedures as a critical aspect of this workflow. The data-stream from the virtual and physical models was aligned to produce a feedback system that instils the ability to intelligently account and correct for spatial imprecision in the precast concrete panel fabrication workflow. Figure 7, illustrates four trimmed panels butted together to form a seamless surface with a 2mm step between one of the panels which result from the 1mm inaccurately of the 7th axis along its YZ plane. From this, we learn that the robotic interaction needs (Figure 5) to be performed every time the 7th axis is rotated.

5. Structural analysis of frame and panel system components

A 1:1 prototype cladding system composed of 12 concrete precast panels (with nominal edge length of 500mm) was proposed to further test the design application, refer to Figure 9. Typically, a façade system of such geometric complexity will have a simple background framing system. However, this is typical as the structural elements need to be simplified for structural analysis purposes and can sometimes be an afterthought e.g. the architectural form is typically designed prior to engineering. To further integrate the design workflow of the construction system the authors proposed that the structural frame of the prototype be parametrically optimised to suit the free form surface with straight tubular

sections (Figure 9) and a planar steel bracketing system. It is a more efficient structural system rather than a standard orthogonally framed system with struts extended to accommodate curvature on the cladding surface.

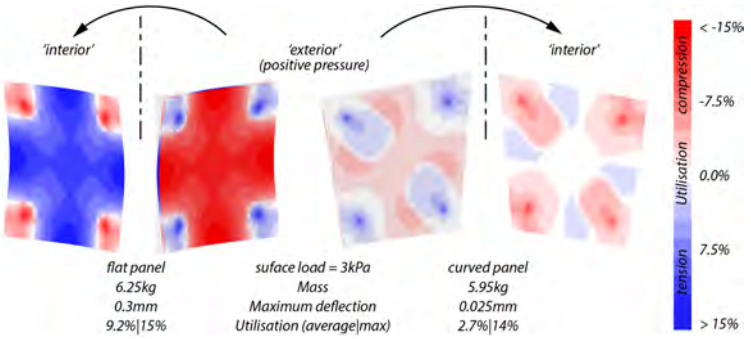


Figure 8. Structural resistance of panels (edge length=500mm; thickness=10mm); results of a curved panel (skew=0.88; beta=-18.04°) compare to a flat concrete panel under 3kPa area load.

Acting as a rainscreen system, the secondary structural system needs to resist gravity loads, lateral loading (e.g. wind and earthquake loads) and to prevent disproportionate collapse. The panels function as a protective layer subject to wind loading, potential impact, thermal influence and rainwater. Each panel was connected to the frame in 4 locations near each corner of the quadrilateral panel. Hence, the panel was loaded at these locations due to gravitational loading and influence from lateral forces. The externally exposed concrete panels are typically designed for extreme localised wind pressures both in suction and positive pressure (AS1170.2, 2011). These pressures were applied to the panel and transferred through the 4 rigid connections (see Figure 8). The structural challenge was the panels' ability to resist flexural stress along the span between connections. The negative curvature or saddle-shaped geometry of each panel exhibits anticlastic curvature. A panel under an area loading condition parallel to its surface normal(s) is more capable of resisting said loads by always having an approximately parabolic-curved region of the panel exhibiting compression in the panel. These chords of compression are activated in their respective convex form (see section A in Figure 5) to the positive pressure load (e.g. Figure 8) which allows us to reduce the thickness of the concrete relative to a planar panel.

The 'Smart Nodes' project demonstrated that using 3D printed metal nodes one could apply volumetric topological optimisation strategies to the design of the node to reduce its mass (Seifi et al., 2016; Prohasky et al., 2015). However, it was still challenging to implement 3D printed metal building components on building projects due to its high cost, slow production rate and unpredictable structural integrity such as the risk of internal stresses caused by anisothermal conditions during printing (Williams et al. 2015). However, an alternative surface-based manufacturing approach was proposed in this research project (Figure 10). 2-dimensional steel brackets were used to create moment resisting connections

between CHS members. The technique required a geometric manipulation of the structural frame to allow for planarised connection detailing.

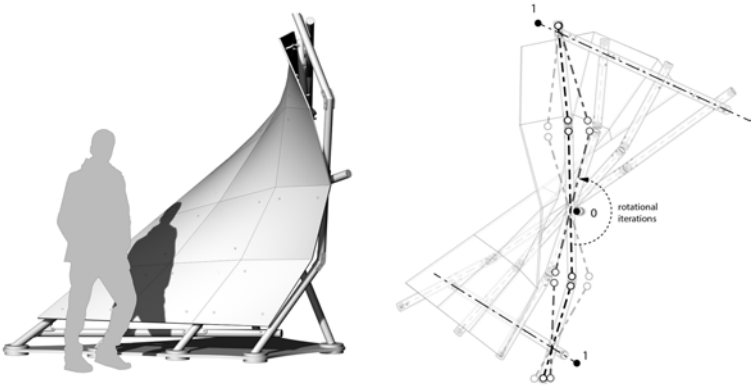


Figure 9. Left, proposed prototype. Right, structural frame logic defining the algorithmic hierarchy for the rotational corrections for the 'vertical' members of the frame.

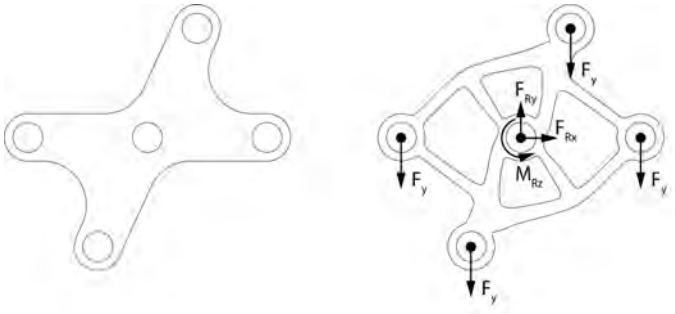


Figure 10. Mass-optimised moment resisting topologically optimised bracket example showing 30% mass reduction for a simplified gravitational load case.

This was achieved for the 1:1 scale prototype by defining continuous lateral members approximated to follow the concrete panels' form. Vertically oriented members were then generated through a process of rotational manipulation about the centroidal axes of the respective laterally oriented member (see Figure 8). The next in-line connecting vertical member was then generated to coordinate with the next lateral member to intersect at the vertical member's approximate mid-point. The kink between the 2 vertical members always allowed for a planar connection. The intersection of the lateral and vertical members only involved 2 straight members crossing one another which also allowed for a planar connection detail. The structural system of assembly, though reasonably complex in its conception, provides a simplified and structurally reliable method of fabrication and assembly which coordinated harmoniously with the doubly-curved light-weight fibre-reinforced concrete panels.

6. Conclusion

The paper discusses an integrated advanced fabrication workflow using a custom CNC machine and robotic method to fabricate doubly-curved concrete panels with no immediate waste. The research extends to address a multifaceted systems of design, engineering and advanced manufacturing; demonstrating a 'smartness' in fabrication workflows through internalising physical shape data using robotic interaction, as well as optimisation of the secondary structural framing with surface-based connection detailing. The paper demonstrates the critical need to streamline design to fabrication data within a continuous fabrication workflow to overcome inevitable physical imprecisions within the system of fabrication. Future research will examine the potential to shape the panel within the PAM machine itself as a complete system. The contribution of this paper is the novel robotic trimming procedure and fixture that enables the investigation to combined data and fabrication workflow to construct intelligence in digital fabrication. The paper points towards an integrated form of advanced manufacturing in architecture that propels research to design application.

Acknowledgement

Robotic workflow and fixture design research is conducted by first and second authors at the Architectural Research Lab, Melbourne with assistance from Ryan YuanYe Huang.

References

Standards Australia, -: 2015, *AS 3850.1:2015 Australian Standard, Prefabricated Concrete Elements, Part 1: General Requirments*, SAI Global Limited, , Sydney, Australia.

Burry, M.: 2011, *Scripting Cultures: Architectural Design and Programming*, Wiley & Sons.

Lavery, C.: 2013, Spencer Dock Bridge, *Concrete International*, **June**, 28-31.

Loh, P., Leggett, D. and Prohasky, D.: 19-21 September 2018, CNC Adjustable Mould to Eliminate Waste in Concrete Casting, *Computing for a better tomorrow - Proceedings of the 36th eCAADe Conference, Lodz University of Technology, Lodz, Poland,*, **1**, 735-742.

Pottman, H.: 2007, *Architectural Geometry*, Bentley Institute Press.

Prohasky, D., Williams, N., Crolla, K. and Burry, J.: 2015, SmartNodes:'Light-weight'parametric structural design process with BESO, *Proceedings of IASS Annual Symposia*, 1-12.

Ruiz-Geli, E.: 2018, "Enric Ruiz-Geli, Projects: Built projects, Media-ICT" . Available from < www.ruiz-geli.com/projects/built/media-tic> (accessed 9th December 2018).

Schipper, H.: 2015, *Double-curved precast concrete elements*, Ph.D. Thesis, Delft University of Technology.

Wang, S., Cai, Z., Li, M. and Lan, Y.: 2012, Numerical simulation on the local stress and local deformation in multi-point stretch forming process, *The International Journal of Advanced Manufacturing Technology*, **60**(9), 901-911.

Williams, N., Prohasky, D., Burry, J., Crolla, K., Leary, M., Brandt, M., Xie, M. and Seifi, H. 2015, Challenges of scale modelling material behaviour of additive-manufactured nodes, *in* M.R. Thomsen, M. Tamke, C. Gengnagel, B. Faircloth and F. Scheurer (eds.), *Modelling Behaviour*, Springer, 45-51.

Standards Australia International ; Standards New Zealand, -: 2011, *Structural design actions. Part 2, Part 2,*, Standards Australia International , Sydney, NSW; Wellington, N.Z..

ORIOLE

A Parametric Solution for Robotic Videography

EBRAHIM POUSTINCHI
[1]*Kent State University*
[1]*mpoustin@kent.edu*

Abstract. Oriole is a parametric tool that enables designers to visualize/simulate the robotic videography, the camera path, and the camera aim digitally and in a precise way. Designers using Oriole are able to use Rhino 3D and its node-based visual programming plug-in, Grasshopper 3D-as native design software, to design a robotic camera motion with a fixed or animated target.

Keywords. Robotics; Software Development; Representation; Parametric Design; Videography.

1. Abstract

This paper presents a project-based research study using Oriole-a custom-made plug-in for grasshopper 3D software, as a new tool for robotic videography. Oriole is a parametric tool that enables designers to visualize/simulate the robotic videography, the camera path, and the camera aim digitally and in a precise way. Designers using Oriole are able to use Rhino 3D and its node-based visual programming plug-in, Grasshopper 3D-as native design software platforms, to design a robotic camera motion with a fixed or animated target (Figure 1, and 2). Using a digital model and robotic simulation platforms for different industrial robots such as KUKA, ABB, and Universal, Oriole enables designers to design/create a precise interaction between the robotic "camera" and the physical environment.



Figure 1. Screen-shots of Oriole plug-in simulation platform in Rhino 3D and Grasshopper environment.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 531-540. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.



Figure 2. Photos of Oriole robotic videography set-up at Kent State College of Architecture and Environmental Design, using KR6 R900 Robot and an action camera.

By investigating design students‘ and designers’ experiences in using Oriole platform, this study demonstrated the potential of a digitally controlled physical robotic camera, not only as a representational tool but also as a new outlook to interactively evaluate the tangible outcome of the design process through the lenses of the robot as an architectural/design-oriented take on Machine-Vision.

2. Introduction

From the early 1990s and by the introduction of digital design tools, the dialogue between digital design environments and physical/analogue design and experience platforms has always been a critical component of the contemporary digital design discourse. By investigating new design possibilities brought into the design conversation, following the notion of “digital design” and almost simultaneously, an increasing desire to duplicate digital design outcomes in the physical world of materiality has become a driver for digital fabrication investigations.

By introduction of robotics in the form of Computer Numerical Control machines (CNC) and later six, seven and eight-axis industrial robotic arms, and through additive and/or subtractive manufacturing methods, the boundary between digital design outcome (digitally designed) and physical replication of it (digitally fabricated) became more and more blurred. Today, and as part of the cyber-physical dialogue of digital design and fabrication, It is almost accepted that we are capable of “translating” any digital design to its tangible duplicates, through digital fabrication techniques. This translation-in the context of this paper, can be understood as bridging between two different mediums of digital design and physical experience of design outcome.

Through this workflow, designers are almost capable of translating every virtually designed elements/components, into the physical space, as means of bringing the digital representation / “proposal”, to form and space as user experience, but there is a significant component from the digital design environment that has not been considered as part of this translation workflow: Digital Camera.

One of the unique components of the digital design environment that usually

gets lost during the "translation" from digital design environment to the physical space is the digital "camera" and curated "controlled" perspectives. Given the importance of the digital camera as part of how designer understands, designs and represents the design and its experience, it seems to be crucial-when it comes to the translation of digital design environment into the physical through robotics, to consider the possibilities of translating "point of view."

In his book "Robot House" Peter Testa (2017) explains how view/perspective- and ultimately image is not limited to be a representation but can become a design/experience tool itself. The "Impossible Objects" design series by Kruysman-Proto and Curime Batliner (2011), and the "Aether Project" by Guvenc Ozel studio (2013) at University of California Los Angeles are some other examples of similar thinking about spatial qualities of perspective and imaging. Another familiar example of the use of robotic videography to curate an atmospheric spatial effect is the work of Bot and Dolly (2013), a creative robotic studio in designing and shooting special effects of the movie Gravity.

3. Research questions and methods

Developing based upon earlier studies in robotic controlling and creative robotics, Oriole is part of ongoing research that questions two potentials of robotically controlled/manipulated perspectives:

1. Possible new ways of interaction and user experience development with physical/tangible mediums to enhance the continuity of the cyber-physical experience.
2. A new design tool to produce design feedback based on robotically controlled camera in interaction with physical models, as a way to modify the digital design.

To the mentioned questions, there is a need for communication between the digital design-camera in the design software and the robotic camera inside and outside of the computer. On the other hand, and due to the diversity of the possible users, to maximize the usability, Oriole, needed to be adaptable with different controlling platforms for industrial robots including KUKA, ABB, and Universal.

To achieve the goal of adaptability, Oriole can work independent from the robotic/controlling software/plug-ins and act as an addition to the digital simulation. In another world, Oriole uses the digital camera path and converts it into a parametric "animation" to generate a motion path for robot arm (regardless of the robot brand) as a mean of communication between the digital camera and the robot path generator.

Developed for the use in the context of a graduate research studio at Kent State University's College of Architecture and Environmental Design, Oriole has three main components: (a) Camera Path, (b) Camera Aim, and (c) controlling planes/path for the robot. In addition to these three main components, Oriole can directly generate controlling codes for KUKA industrial robots or can use any other parametric robot controlling platforms such as KUKA|Prc, HAL, and Taco-to name a few, to drive the robot. This adaptability is one of the distinct advantages of Oriole.

For the current research, we produced a platform to use Oriole as a component

of a research studio, using KUKA KR6 R900 Sixx robot arm and with a focus robotic videography as a means of representation. In addition, some students used Oriole -as a method to study formal, spatial, and compositional qualities of the design through the physical model and as a feedback system to inform the digital design (Figure 3).



Figure 3. Screen-shots from the video footage captured using Oriole simulation plug-in.

We then observed as volunteer designers at Kent State University endeavored to learn how to work with Oriole platform as both representational and design tools. The primary goal of the experiment was to observe the practicality of Oriole plug-in in connection to robotic controlling and design platforms and to make some initial observations about how its use affects the design process. This paper demonstrates how the use of Oriole, enhanced students' representational techniques and in some cases their design process. Later, this paper discusses the potential applications of Oriole as a digitally controlled physical "design/experience-interface."

4. Oriole: A Parametric Solution for Robotic Videography

As part of its core requirements, Oriole serves as a plug-in for Grasshopper 3D environment-a node-based visual programming add-on for Rhino 3D. Communicating between Rhino 3D design/modeling environment and Grasshopper 3D code-generating platform, Oriole allows for robotic code-generating platform-KUKA|Prc in this paper, to understand the position of the camera and its normal vector in Rhino and send it to the robot-KUKA KR6 R900 Sixx in this research, as KRL code (Figure 4).

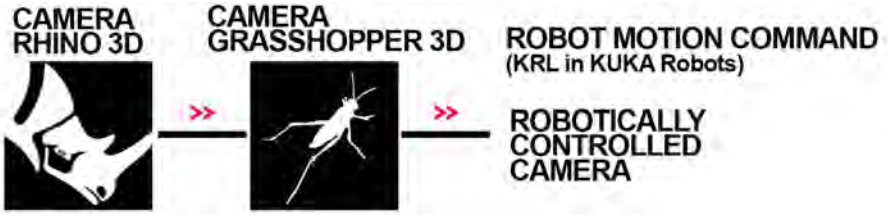


Figure 4. Camera/Software platform general workflow.

4.1. ORIOLE COMPONENTS: CAMERA PATH

As a strategical logic to develop a controlling mechanism for the robotic camera, Oriole follows the logic of almost any animation software platform: Camera path as a way to define camera position/orientation. As part of Oriole plug-in there are two main ways to generate a camera path: (a) Camera path as a curve/poly-line that defines series of positions of the camera on that curve, or (b) Camera plane that determines the location of the camera one point at a time. The significant difference between these two methods can be explained using animation lens and language. In method A, where the path of the camera movement is designed and predefined, based on the given time-window for the "shot" / videography, Oriole parametrically divides the path/curve of the motion into points that later define the position of the camera based on time. In this method-since only the position of the camera is defined, there is a crucial need for defining the "Camera Aim"-discussed in further detail below. Camera Aim, in connection, will define the orientation of the camera (Figure 5). In method B however, Oriole receives numbers of three-dimensionally oriented planes, as a way to identify both the position of the camera, as well as its orientation–through the normal vector of the plane (Figure 5). Although method B has the advantage of independency from the camera aim, it losses the fluidity and continuous quality of the camera path simulation, since each plane has its own position and orientation. In the current version of Oriole, Oriole 1.0, there is a limitation for a maximum of 30 planes/frames in method B.

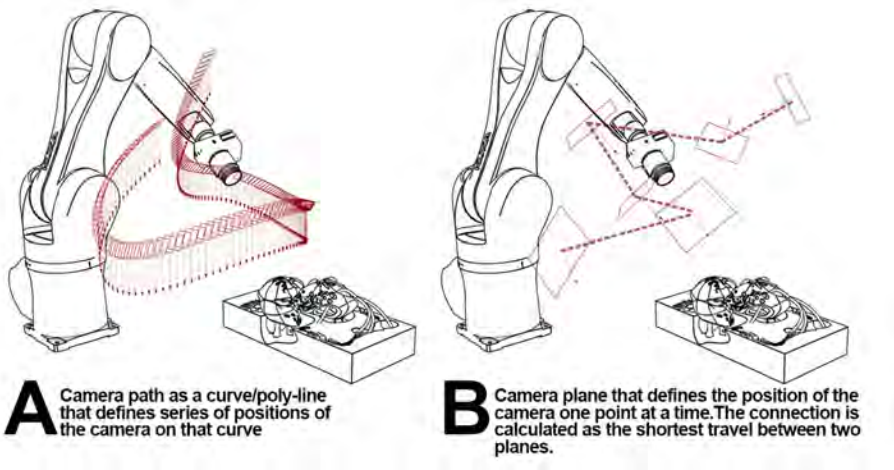


Figure 5. Different path-based or plane-based “animation” strategies for Oriole camera path. .

4.2. ORIOLE COMPONENTS: CAMERA AIM

Based on the Camera Path strategy, and as briefly mentioned above to define the orientation of the camera in relation to its target-especially in camera path method A, there is a need for an aim to define the target of the camera. This possibility becomes even more vital when the focus of the camera is also animated. The Camera Aim component of Oriole plug-in enables the user to not only define the static target of the videography as a way to ensure the precision of the videography but also opens up possibilities for animating the robotic camera as a more dynamic yet controlled point of view (Figure 6).

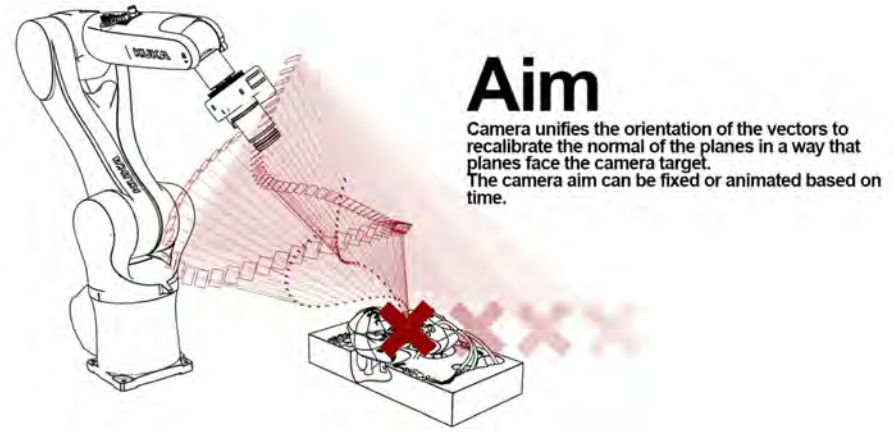


Figure 6. Camera Aim as part of core components of Oriole unifies the orientation of plane normal to faces the videography target.

4.3. ORIOLE COMPONENTS: CONTROLLING PLANES | PATH

To move the robot arm-KR6 R900 Sixx in this research, we used KUKA|Prc Plug-in (Braumann, and Brell-Cokcan, 2015). To communicate data from Camera Path and Camera Aim components to KUKA|Prc plug-in, there is a need for two sets of information: (a) position and (b) orientation. Mathematically a plane with an origin-center of the plane and its normal vector, can host both of these parameters. As the last main component of Oriole and to generate motion-commands for the industrial robot arm, Oriole converts the three-dimensional information of position and orientation, into sets of plane information. Later, KUKA|Prc plug-in uses these plane data sets, to generate KRL code/commands to animate/move KUKA robots.

5. Operation and Testing

To test the plug-in, and as part of a graduate research studio at the College of Architecture and Environmental Design at Kent State University, we used Oriole as a representational tool to videography the physical models of the projects as a way to communicate the digital "design-camera" with the audience. During and as part of the design process, each student has been asked to digitally develop a fly through/digital design-camera in Rhino 3D that represents their project the best. Students used the design-camera as a tool to focus on different formal and topological qualities of their design/digital model, as well as hiding some other ones. Through these back and forth processes and negotiations between the digital design and the digital design-camera/point of view, students developed a digital model of their project in Rhino 3D environment and using digital fabrication techniques, produced physical models of those projects.

Later in the process, and to communicate the representational digital design-camera path with the audience-to fully translate the digital experience into a physical one, each student started to develop a robotic camera path via Oriole. Based on the different camera paths in Rhino 3D, students decided to use method A (path-based simulation) or method B (plane-based simulation) in Oriole as explained above. By precisely assigning the same points of view to Oriole planes or path set-ups, as the next step to design the final robotic camera path, each student defined one static or dynamic aim for the camera.

Ultimately, each student developed a camera path as a set of plains with origin and normal vector that defines the location and orientation of the camera. For KUKA robot to understand its particular configuration-different from CNC machines with G-code and because of the six-axis of freedom, it is necessary to provide two sets of information: X, Y, and Z for position and A, B and C for orientation. The origin of Oriole plains, defines the location of the 6th axis of the robot-X, Y, and Z for the end effector of the robot in KRL code, and the normal of the Oriole plane, defines the orientation and at where the 6th axis points-the A, B and C parameters of the KUKA robot in KRL code (Figure 7). Using KUKA|Prc plug-in for grasshopper 3D, this information later converted to KRL code that is understandable for the KUKA robot.

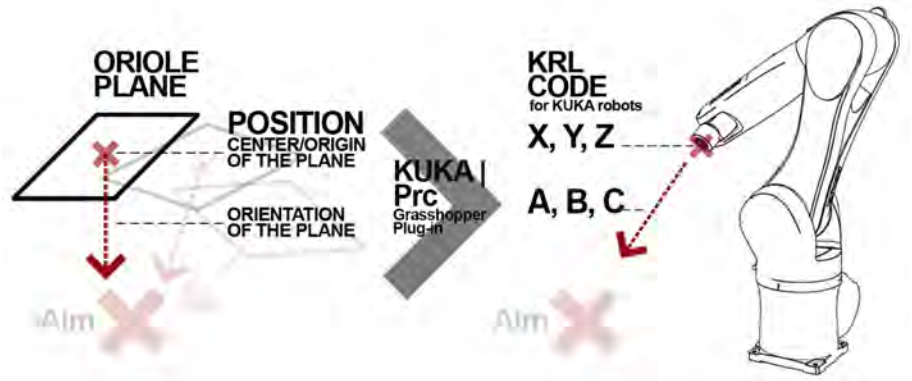


Figure 7. Using KUKA|Prc plug-in for Grasshopper 3D, Oriole Plane information can be translated to KRL code for robot position and orientation.

After generating the KRL code for KUKA robot arm, students used their physical models and positioned the model in a similar relationship with the robot as digitally simulated. With the real camera mounted on the KR6 R900 Sixx robot and the camera path loaded to the robot controller as KRL code, each student studied their physical model through the physical replication of their digital design-camera: a physical model. As a result of this set-up, the audience of the project could also experience the project in its physical representation and through a controlled perspective (Figure 8).

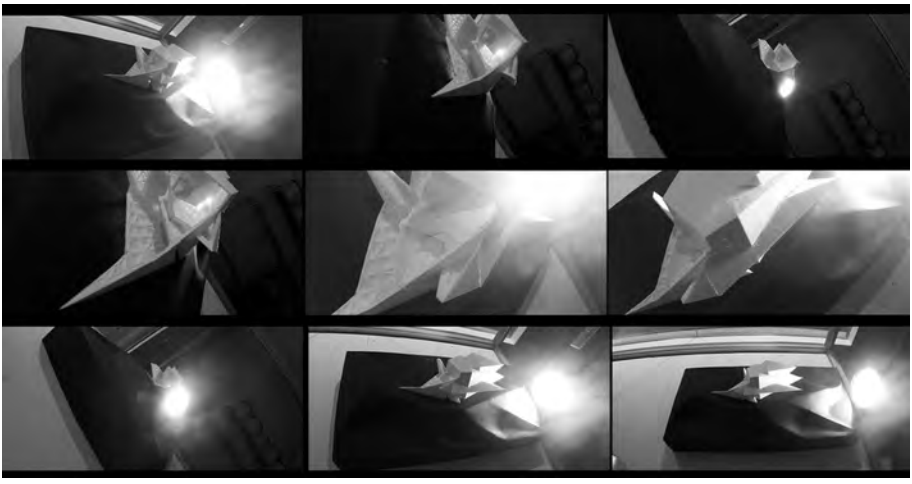


Figure 8. An example of robotic videography using Oriole plug-in for Grasshopper 3D.

As the next step of the design process and through precise matching of the digital design-camera and the physical robotically controlled camera, some of the students started to study their physical models to translate some of the material and fabrication qualities back into the digital model. Keeping the same point-of-view

more or less correlated in the digital file and the physical set-up, enabled students to acknowledge the difference and some imperfections from the 3D printing or CNC milling process, and use them as drivers for design decisions digitally (Figure 9).

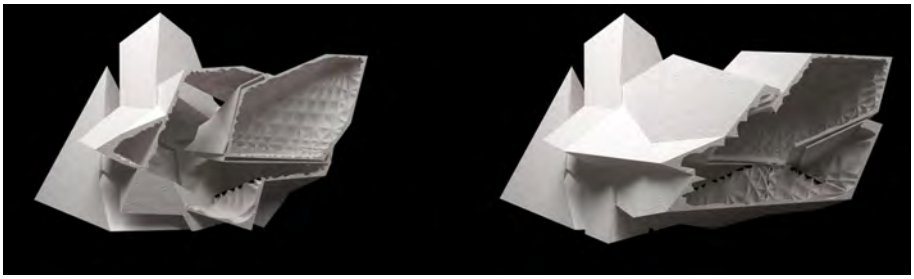


Figure 9. Feedback from physical videography and 3D printing resolution informed the digital design as feedback. The surface detailing is a result of this back and forth.

6. Conclusion

Oriole as a parametric robotic videography plug-in affects the design and representation process from three different viewpoints:

6.1. ORIOLE AS A REPRESENTATION TOOL

At its minimum-which was the main focus of this paper, and as a platform, Oriole enables designers to document the physical design and representation of the design, precisely and with almost the similar "resolution" of digital design environments. Curating highly accurate perspective views as well as the introduction of high-level of precision in relation to time, makes Oriole a tool that can be used as a representational tool to document the project or to conceptually amplify some aspects of it.

6.2. ORIOLE AS A USER-EXPERIENCE PLATFORM

Due to its tangibility, Oriole is a platform that negotiates between qualities and freedom of point of view in digital design environment and materiality of the physical world. As a user-experience platform, Oriole can become a curated/curate-able point of view in the hands of the designer, from the story-telling point of view. Through its controller camera, Oriole becomes a bridge between the designer and the audience, where the designer not only defines the design but also "directs" the audience on how to experience the design, through pre-designed views.

6.3. ORIOLE AS A POST-DIGITAL DESIGN TOOL

Because of its direct and close connection to the digital design environment, Oriole as cyber-physical videography tool becomes a platform to carefully study difference and friction between a digital "thing" and its physical replica. Matching the perspective and the camera path in both mediums, Oriole opens up the

possibility for closer study of materiality, resolution, miss-fit and post-digital materiality, to name a few. Components from the current research looked into some of these possibilities as students started to reuse the aesthetics of the robotically videographed model, back into the digital design process.

7. Limitations and Suggestions for Future Research

The main limitation of this study was the limitation on the scale as the research was limited to the use of KUKA robot KR6 R900 Sixx. From both technical and conceptual viewpoints, it would be beneficial to examine the research agenda of this paper-from a representational point of view, in different scales.Oriole as a parametric videography tool/plug-in for Grasshopper 3D is fully functional and tested. At this point of this ongoing research and as part of the future research plans, we are interested in examining Oriole in more depth and as a user-experience tool in conjunction with augmented reality tools. Another component of Oriole that needs a lot more studies in depth is its use as a post-digital design tool. Having the technical difficulties solved, we are interested in testing Oriole in more conceptual set-ups and not only as a translator of digitally pre-defined camera paths but as a tool through which explore the physical model/space. We are currently working to enhance Oriole as a plug-in by including some of these feedback components as part of the process and by introducing some other parameters from digital design environments such as focal point of the camera and lighting.

References

"Bot & Dolly Fuses 3D Animation and Industrial Automation" : 2013. Available from robotics business review<https://www.roboticsbusinessreview.com/consumer/bot_dolly_fuses_3d_animation_and_industrial_automation/> (accessed 26th, September 2018).

Abrons, E. and Fure, A. 2017, Postdigital Materiality, *in* G.P. Borden and M. Meredith (eds.), *Lineament: Material, Representation, and the Physical Figure in Architectural Production*, Routledge, New York, NY, 185-195.

Braumann, J. and Brell-Cokcan, S.: 2015, Adaptive robot control: new parametric workflows directly from design to KUKArobots, *Proceedings of the 33rd international conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)*, Vienna, 243–250.

Kruysman, B. and Proto, J.: 2014, Impossible objects, *Architectural Design*, **1**(no 227), 106–111.

Ozel, G.: 2015, Case for an Architectural Singularity: Synchronization of Robotically Actuated Motion, Sense-Based Interaction and Computational Interface, *Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Los Angeles, 399–408.

Testa, P.: 2017, *Robot House*, Thames & Hudson Inc. , New York, NY.

DESIGN CYBERNETICS AND CAAD RESEARCH

Aspects of our shared interests

CHRISTIANE M. HERR[1] and THOMAS FISCHER[2]
[1,2]*Xi'an Jiaotong-Liverpool University, Suzhou, China*
[1,2]*{christiane.herr|thomas.fischer}@xjtlu.edu.cn*

Abstract. In this paper, we offer an overview of several aspects of cybernetics that are relevant to CAAD research. We present key cybernetic ideas, the development of the field and its relationship to design research, followed by a brief mapping of eight intersections between cybernetics and CAAD, covering design cognition, design computing, design process, design management, design production, design outcomes, design research and design values.

Keywords. Design cybernetics; systems; interdisciplinarity; CAAD research; metaphor.

1. Introduction

Half a century ago this year, Gordon Pask proclaimed "the architectural relevance of cybernetics" (Pask 1969). Cybernetics as a discipline had emerged a few decades earlier during and after World War II. Propelling – and propelled by – technological advances of "scientific" warfare for example in cryptography and missile guidance, cybernetics became known as the science of "communication and control" (Wiener 1948). By the mid-twentieth century, its focus on technology and rational determinism rendered cybernetics a prototypical, dominant paradigm for various areas of science, engineering, social science and governance. Cybernetic thinking in these fields was technical and, in one way or another, based on the idea of the closed technical control loop between a sensor and an actuator. Cybernetics also became closely associated with computing, especially of the digital kind. This is, amongst other reasons, because the universal machine computer lends itself as a tool for symbolic modelling and control systems, and because key originators of digital computing, including Alan Turing and John von Neumann, were also key figures in cybernetics. Many founders of the discipline, including Norbert Wiener, Margaret Mead, Gregory Bateson, Heinz von Foerster, Warren McCulloch and Ross Ashby, however, were more concerned with the intricacies of living and social systems than with technology *per se*. They tended to consider and to build technical and computational systems as metaphors to illustrate or model behaviours of higher organisms.

Design research, likewise, emerged from the application of "scientific" methods to the pressing problems of World War II, alongside operational research

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 541-550. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

methods and management decision making techniques (Cross 2006, p. 1). Like cybernetics, design research would develop the status of an academic discipline in the decades that followed. Design research and cybernetics began to engage with one another when Ashby's (1957, p. 121ff) notions of *variety* and *constraint* were first used to describe the design process. Ashby had introduced variety as a quantitative measure of the number of states systems may assume, whereas constraints are limitations on variety. These concepts and their application to the design process are discussed further in section 4 below. Independently, these cybernetic "sparks" jumped from cybernetics to design research twice: once in the work of Gordon Pask (1961) and once in the work of Horst Rittel (Protzen and Harris 2010). Various lines of design cybernetic thought have developed since then, to coalesce in recent years under the umbrella of Design Cybernetics (Glanville 2007, Fischer and Herr 2019).

In the 1970s, cybernetics underwent an extension from its early focus on technical systems ("observed systems") to a broadened attention to "observing systems" (Varela 1984, p. xviii). Having embraced circular causality already with its early interest in technical control loops, cybernetics now also acknowledges the notions of observer-dependence and non-determinability, thereby departing yet further from conventional natural science (Dent and Umpleby 1998). Within the field, this expansion from so-called first-order cybernetics to the less orthodox second-order cybernetics is understood as an unfinished revolution (Müller and Müller 2007). Meanwhile, design research focused on design methods in the mid-twentieth century, but soon abandoned this focus for being too simplistic and mechanistic (Alexander 1984, pp. 312–313). It underwent a transition from "first generation" to "second generation" design methods, which recognise that design problems are observer-dependent with problems and concepts of their solution are circularly interdependent (Rittel 1984, p. 321).

From the design cybernetic viewpoint, cybernetics and design research share a key commonality: a concern for process and performativity in time. This sets both cybernetics and design research apart from natural science and its basis, formal predicate logic, whose arguments conclude in atemporal terms of truth and falsity (Bateson 1979, p. 117). As will be detailed below, the temporal, performative perspective of design cybernetics manifests itself in various aspects of CAAD. These various lines of design cybernetic thought are, however, not yet uniformly recognised in the CAAD discourse. CAAD literature presently tends to focus on two aspects of design cybernetics, which descend along two lineages of thought from Pask's and Rittel's aforementioned early adoptions of variety and constraint: In the Rittel-tradition, this is an interest in design as open-ended and "wicked" as opposed to "tame" (Rittel and Webber 1973, pp. 160ff) and in the design process as an alteration between variety amplification and variety reduction (Protzen and Harris 2010, p. 107). In the Paskian tradition, this is an interest in cybernetically (computationally) enhanced design outcomes such as the homestatically or non-deterministically adaptive architectural designs of Cedric Price, to which both Gordon Pask as well as Julia Frazer and John Frazer have been consultants (Frazer 1995).

To offer CAAD researchers a more comprehensive introduction to the overlaps

and shared interests between cybernetics and CAAD research, and to facilitate cybernetically informed CAAD research, we offer in the following an overview of the relevance of cybernetics from several CAAD perspectives.

2. Cybernetics and design cognition

Cybernetics has grown beyond its early focus on simple feedback loops that exercise technical control to loops that include the observer, who, as a *self* engages *others* in "conversational" loops of acting and understanding (Glanville 2014). This extension of cybernetics is retrospectively described as the transition from first-order cybernetics to second-order cybernetics. An important milestone in this transition was the Conversation Theory by Pask (1976), which Glanville and others developed into today's design cybernetics (Glanville 2007, Fischer and Herr 2019). As in everyday conversation, "conversants" engage in circularly-causal back-and-forth to soon arrive at subjects and points that moments ago were unanticipated. Conversation is a prototypical notion of epistemic practice through which we arrive at the previously unknown, and which unifies the processes that are of central concern to CAAD: learning, researching and designing.

Radical constructivism, a close relative of second-order cybernetics, assumes that we construct subjective realities. This view does not rule out the possibility of sharing a found reality as such (in other words: this view is not solipsistic). It simply avoids epistemological claims that cannot be rigorously justified from within systems whose experiences are entirely mediated along neural pathways, with any attempt at testing the faithfulness of neural mediation, in turn, being dependent on neural mediation. This avoidance of difficult-to-justify epistemological claims is of particular value in developing and defending academic theses in the view of adversarial rigour. In the second-order cybernetic and radical-constructivist view, cognition is the process of "computing a reality" (von Foerster 2003, p. 215). Here, the term computing is not used in the narrow sense of symbolic processing by machine, but in the sense of concerted (lat. *com*) contemplation (lat. *putare*). Realities, in this view, are subjective descriptions, whereas "description" is understood in the sense of embodied performance, not in the sense of symbolic representation (Segal 1986, p. 83–109).

From within a subjective reality, engaging with anyone or anything else, it is virtually impossible to match their reality exactly, to have the same number of possible states, i.e. in cybernetic parlance, to achieve requisite variety. Requisite variety, the same number of states on both sides of a feedback loop, however, has been identified as a necessary condition for effective control (Ashby 1957, pp. 206ff). Hence, our every-day engagements with others (including imagined others, technology, pen and sketching paper etc.) are, in the absence of requisite variety, by definition out-of-control (Glanville, unpublished). This is why conversation can take us to the as-yet unknown, the new – be it the new at the individual or at the social level (Boden 2004, p. 43). Differences between *self* and *other*, and noise on the channels between them are therefore, from this perspective, not nuisances to be minimised and avoided but potentials to be pursued and valued. Self finds herself in out-of-control engagements with others, challenged to expand her own variety to accommodate (construct concepts of) the encountered as-yet-unknown.

Her reality is thus in a state of constant expansion (Glanville 2009, p. 122).

3. Cybernetics and design computing

Cybernetics is commonly associated with computing, as is evident in the general association of the prefix "cyber" with all things digital and online. Indeed, cybernetics and computing grew up together, with each depending on the other, and the development of both analogue and digital computing machinery owes much to cyberneticians such as John von Neumann, Norbert Wiener, and Alan Turing. Different basic blueprints for computing machinery are referred to as "computer architectures", whereas CAAD investigates the application of computing machinery in the processes of designing and operating built environments, i.e. "architectural computing". In *cyberspace* (Spiller 2002), interest in computer architecture intersects with interest in architectural computing.

According to the linear, syllogistical thought patterns engrained in modern culture and formal science, the computer is often thought of as a linear system that takes input and processes it into some output. In the cybernetic view, however, with its particular interest in the relationship between man and machine, computing is considered a circularly-causal activity that involves an observer, as Bateson (1972, p. 317) points out: "The computer is only an arc of a larger circuit which always includes a man and an environment [...]." Winograd and Flores (1986), accordingly, present a view of computing that is based on the notion of *structural coupling*, focusing on the relation between systems and their environments. Design computing investigates both human-machine design interaction that harnesses the variety-generation capabilities of the computer (Chan et al. 2001) as well as use interaction with digitally enabled adaptive built environments. These areas of shared interest are further described in Sections 4 and 7 below.

4. Cybernetics and the design process

Concerned with processes of navigation towards (as well as with the negotiation of) goals, cybernetics has much to offer to the study of design processes. As widely agreed in current design research discourse, designing can be characterised as a circular process generated by recurrent feedback loops. This circularity allows for ongoing reflection and adjustment throughout the design process, and results in unpredictable dynamics: the outcomes of such processes are not determinable from the outset and are often considered surprising and innovative. Conversation Theory (Pask 1976) describes circular exchanges along paths of alternating amplification and reduction of variety as a way of enquiring, developing shared understanding and reaching the new. Characterising the circularity of sketching as reflective conversation with a situation, Schön (1985) developed a theory of architectural practice and education that employed concepts from both cybernetics and constructivist theory. The "reflective practice" model offers an alternative to the rationalist focus on linear problem solving that Schön saw as inadequate to describe design practice. Building on Pask's work, Glanville (2007) describes the design process as a cybernetic activity, where

cybernetics is understood as the theory of design, and design is understood as the practice of cybernetics. Glanville's cybernetic account of designing shows how conversational exchanges can create novelty from differences in understanding among conversation participants. Design conversations with *others* can take place between human conversants, but may also involve exchanges with objects and imagined or virtual *others*.

In the cybernetic view, novelty-generating processes are of a circular, open-ended, conversational nature, and grounded in differences in interpretation among conversation participants, such that newly arising interpretations can offer insight, surprise and delight. These characteristics distinguish design processes from the kinds of processes which limit feedback loops to the enactment of narrow sets of predetermined choices and options. While 'error' and misunderstanding are regarded as problems to be avoided in other areas, they are recognised as endemic and fostered as stepping stones towards the previously unknown in design conversation (Glanville 2007, p. 1181). The surprising, variety-amplifying quality of design conversation is referred to, in cybernetic parlance, as *interactive*. *Interactive* technologies in this sense are referred to as *media* and distinguished from pushbutton-responsive, predictable *tools*: "A medium is a tool that kicks back" (Glanville 1997, p. 48). This distinction is of broad relevance to the field of CAAD research, where digital design support during the early, novelty generating stages of design remains an important area of interest. Key strategies by which digital technology engages in variety-amplifying conversation are by generating options for designers to choose from (based typically on the re-combination or geometric transformation of design elements) or by being creatively re-appropriated (Glanville 1992, Fischer and Herr 2007).

5. Cybernetics and design management

The cybernetic perspective on management extends the scope of management strategies beyond linear problem-solving approaches. Management cybernetics recognises that organisations are typically involved in two kinds of feedback processes, pursuing the parallel goals of maintaining stability and at the same time adapting to changing contexts. Management cybernetics fosters this balance by examining and organising circular feedback loops to encourage processes of self-organisation. To this end, Beer (1972) proposed the Viable System Model as a conceptual tool that allows the assessment and structuring of recursive processes within an organisation with a view to the longevity of the system, and without resorting to centralised control. Beer emphasised the necessity of understanding an organisation's status quo as a starting point for any intervention rather than focusing on expectations or presumptions: the purpose of a system is what it does. This approach is familiar to designers who recognise the necessity to adapt to and work with the dynamics of found contexts in order to achieve viable and sustainable results.

CAAD research addresses various aspects of professional architectural practice that are related to management cybernetics, such as collaborative processes mediated by digital tools. A cybernetic perspective introduces a concern for the autonomy of self-organising circular processes and offers models to work

with them. Cybernetic approaches seek to balance the dynamics of autonomous systems with purposeful intentions of steering these systems in circular and interconnected feedback loops. Following on from the Viable System Model, Beer (1994) developed *syntegrity*, a non-hierarchical process designed to create synergetic processes of shared learning among teams. In CAAD research, similar attention to circular processes can often be found in descriptive studies examining sketching during the early design stages, but less in work focusing on the design of systems for collaborative exchange. While cross-disciplinary collaboration and data sharing workflows facilitated by BIM technology have come a long way to approach the *syntegrative* management vision, Beer's proposals for creating viable and sustainable conversational systems remain under-explored in CAAD research.

6. Cybernetics and design production

With advanced digital tools increasingly becoming commonplace in architectural design practice, much recent CAAD research has focused on tools and workflows for design production, ranging from geometry rationalisation to digital fabrication. Cybernetics relates to a broad range of aspects of design production, from deterministic control systems found in artificial intelligence to human- and user-centered participatory systems. Cybernetic approaches typically inform the procedural aspect of design production by offering models and terminology supporting efficiency in realisation on the one hand, and viability in organising processes involving many actors on the other hand. A cybernetic approach to design production was presented by Scheurer (2007), showing how artificial intelligence methods can be employed to organise parametric digital models. In addition, materialisation processes benefit from cybernetic feedback cycles at various stages of the production chain as these processes are not of a linearly-deterministic nature and adjustments are routinely required to deal with constraints as they arise. The cybernetic concept of variety can be employed to describe both linear processes of narrowing down options as well as conversational (design) processes that can both increase and decrease variety. In geometry rationalisation, for example, the process of reducing a large number of options to a smaller number according to given constraints can be framed cybernetically as a reduction of variety. In a broader perspective on geometry rationalisation, Fischer (2012) however also describes such processes as embedded in circular processes of reflection, demonstrating the role of designers and researchers in steering such processes.

Thinking through the framework of variety control makes it possible to determine the nature and dynamics of production processes. Linear deterministic control processes maintain or reduce variety, as for example in digitally controlled robotic fabrication where robotic tools are typically not expected to influence the production in open-ended ways. When circularity is introduced in the form of dialogical exchanges, such processes can potentially generate novelty and surprise. Processes that increase variety are however rare in control-focused digital production and more common in processes that involve human interaction. Design production can be structured to encompass both, as the cybernetics-informed work of Pratschke (2007) and dos Santos Cabral Filho (2013) shows: both

discuss cybernetics-informed processes of architectural production that involve user participation and collaboration.

7. Cybernetics and design outcomes

Throughout their life cycles, buildings, and the products and services they are comprised of, become hosts to various regulatory processes addressing ongoing needs and requirements of both buildings and users. These include, among others, building services and maintenance systems as well as automated capabilities to adapt to changing internal and external conditions. Extending the scale of the classic example for homeostatic cybernetic control processes of the thermostat that keeps room temperature constant, these performative "soft" services, added to "hard" architectural structures, are increasingly important in architectural design and research. While the operation of self-adaptive systems in our built environment has long relied on predetermined thresholds and processes of operation, "smart" buildings are introducing increasingly sophisticated technology to create more efficient and more comfortable environments for their inhabitants. Similarly, façade systems are increasingly conceived as adaptive façade systems that can change their configuration in response to changing environments. Cybernetic frameworks provide a basis for designing the operation of building services and façades as feedback loops in terms of positive (reinforcing) and negative (decreasing) feedback. From a cybernetic perspective, such systems could be designed for increasing levels of independence and autonomy in the future, as envisaged by early cybernetics-inspired architects such as Price (Matthews 2005).

CAAD research proposes a range of technologies for virtual, augmented and networked spaces. These technologies are inherently cybernetic as they involve exchanges between humans and digital tools. From a cybernetic perspective, the performative and procedural aspect could be employed to achieve qualities beyond predetermined interactions, as Haque argues (2007). One example is contemporary media façades, which increasingly populate large areas of urban vertical spaces, but are mostly employed as trivial large display screens (Herr 2011). Suggesting the possibility of expressive interaction between buildings and populations at the urban scale, media façades promise new opportunities for novelty, surprise and delight once opportunities for circular feedback with urban inhabitants are introduced.

8. Cybernetics and design research

As mentioned above, cybernetics departs from some basic assumptions underlying natural science. This allows cybernetics an alternative perspective for enquiry that, rather than proceeding through the natural scientific paradigm, can critically evaluate the natural scientific paradigm. From this perspective, Glanville (1999, p. 88; 2007, p. 1179) rejects the general notion that design is a subset of scientific research. Instead, he argues that science is a particularly constrained form of the more general human activity of designing.

The cybernetic perspective furthermore allows a relative positioning of the

observer, the observed and its description (Fischer 2011, p. 629), which in turn permits the relative positioning of key science-philosophical traditions (pragmatism, idealism and empiricism) and thus of key research agendas (usefulness, meaningfulness and predictability) to offer a theory of enquiry as a methodological guide for CAAD research.

9. Cybernetics and design values

As digital coding determines the performance of computing machinery, so do design processes determine design outcomes. In this relationship between composition and performance, designers make choices on behalf of *others*. These choices may be restricting or enabling, both in physical as well as in cyberspace. However, designers are typically removed from the situations they shape. This gives rise to a dilemma between competences of users who are situationally aware on the one hand and competences of designers who are professionally trained on the other hand. The fault lines that separate them are the systemic boundaries (Fischer and Richards 2017, p. 37) of design and application contexts. In recognition of these boundaries, cybernetics is deeply committed to the autonomy of *others* (von Foerster 2003, p. 298) and, therefore, to designing with, as, and "through the eyes of" those designed for. This applies to CAAD research where design tools are developed for others, and to general design practice where built environments are developed for others. Ethical considerations apply at both levels accordingly.

The commitment to the autonomy of others results in a reliance on (and trust in) internal guidance where ethical questions are addressed (Sweeting 2016). This reliance recognises the uniqueness of design contexts, the non-repeatability of design and the absence of clear success criteria (Rittel and Webber 1973). The cybernetic conception of ethics is thus grounded in the subjective responsibility of the *self*, as defined by his/her systemic boundaries, ascertaining a fundamental individual freedom of choice. Von Foerster (2003, pp. 287–304) argues that this freedom engenders responsibility for one's choices, such that ethics is primarily addressed to oneself ("I shall...", "I shall not..."). He distinguishes ethics from morals, which involves instructing others what to think and what to do ("thou shalt...", "thou shalt not..."). Ethics, therefore, is manifested primarily through action. To help propagate the requisite freedom, von Foerster proposes his Constructivist Ethical Imperative: "I shall act always so as to increase the total number of choices." (2003, p. 295). Aiming to increase the total number of choices, both CAAD research and cybernetics encourage ways of addressing design challenges that involve open source, collaborative and participatory design approaches. While these may require greater efforts to produce results, these results promise greater viability and sustainability in the long term.

10. Conclusion

In this paper, we have offered CAAD researchers a concise and up-to-date introduction to cybernetics, with a view to its relevance to CAAD research. Previous literature in the CAAD field tends to focus on two particular interactions

of cybernetic and CAAD thought, namely a view on the design process as an alternation between variety amplification and variety reduction, and a view on design outcomes as cybernetically (i.e. computationally) enhanced adaptive spaces. We have shown that there is further shared interest between cybernetics and CAAD in the areas of design cognition, computing, management, production, research, and values. These areas are already frequently discussed or implied in CAAD discourse, but as yet often without consideration of those aspects that tie cybernetics to design while setting both apart from natural science: observer-dependency, circular causality and non-determinability.

References

Alexander, C. 1984, The state of the art in design methods, *in* N. Cross (ed.), *Developments in Design Methodology*, Wiley and Sons, Chichester, 309–316.

Ashby, W.R.: 1957, *An Introduction to Cybernetics*, Chapman and Hall, London.

Bateson, G.: 1972, *Steps to an Ecology of Mind*, Ballantine Books, New York.

Bateson, G.: 1979, *Mind and Nature. A necessary unity*, E. P. Dutton, New York.

Beer, S.: 1959, *Cybernetics and Management*, English University Press, London.

Beer, S.: 1972, *Brain of The Firm*, Penguin Press, London.

Beer, S.: 1994, *Beyond Dispute. The invention of team syntegrity*, Wiley, Chichester.

Boden, M.A.: 2004, *The Creative Mind. Myths and mechanisms*, 2nd ed. Routledge, London.

Chan, H.K., Frazer, J.H. and Tang, M.X. 2001, Interactive evolutionary design in a hierarchical way, *in* C. Soddu (ed.), *Proc. 4th International Conference on Generative Art*, GA, Milano.

Cross, N.: 2006, Cross, N 2006, Editorial. Forty years of design research, *Design Studies*, **28**(1), 1–4.

Dent, E.B. and Umpleby, A.S. 1998, Underlying assumptions of several traditions in system theory and cybernetics, *in* R. Trappl (ed.), *Cybernetics and Systems '98*, Österreichische Studiengesellschaft für Kybernetik, Vienna, 513–518.

dos Santos Cabral Filho, J.: 2013, The ethical implications of automated computation in design, *Kybernetes*, **42**(9/10), 1354–1360.

Fischer, T.: 2012, Geometry rationalization for non-standard architecture, *Architecture Science*, **5**, 25–47.

Fischer, T. and Herr, C.M.: 2007, The designer as toolbreaker? Probing tool use in applied generative design, *Proceedings of CAADRIA 2007*, Nanjing, 367–375.

T. Fischer and C.M. Herr (eds.): 2019, *Design Cybernetics. Navigating the new*, Springer, Cham.

Fischer, T. 2011, One-behind-the-many metaphysics and the myriad things, *in* C.M. Herr, N. Gu, S. Rudavski and M.A. Schnabel (eds.), *Circuit Bending, Breaking and Mending: Proc. 16th CAADRIA Conference*, CAADRIA, Hong Kong, 623–632.

Fischer, T. and Richards, L.D.: 2017, From goal-oriented to constraint-oriented design. The cybernetic intersection of design theory and systems theory, *Leonardo*, **50**(1), 36–41.

Von Foerster, H.: 2003, *Understanding Understanding. Essays on cybernetics and cognition*, Springer, New York.

Frazer, J.H.: 1995, *An Evolutionary Architecture*, Architectural Association, London.

Glanville, R.: 1992, CAD abusing computing, *Proceedings of eCAADe 1992*, Barcelona, 213–224.

Glanville, R.: 1997, The value when cybernetics is added to CAAD, *Proceedings of AVOCAAD 1997*, Brussels, 37–50.

Glanville, R.: 1999, Researching design and designing research, *Design Issues*, **15**(2), 825–833.

Glanville, R.: 2004, Desirable ethics, *Cybernetics & Human Knowing*, **11**(2), 77–88.

Glanville, R.: 2007, Try again. Fail again. Fail better: The cybernetics in design and the de-sign in cybernetics, *Kybernetes*, **36**(9/10), 1173–1206.

Glanville, R.: 2009, A (cybernetic) musing: Design and cybernetics, *Cybernetics & Human Knowing*, **14**(3/4), 175–186.
Glanville, R.: 2014, Acting to understand and understanding to act, Kybernetes, *Kybernetes*, **43**(9/10), 1293–1300.
Glanville, R.: unpublished, "On being out of control" . Available from <http://www.mom.arq.ufmg.br/mom/arq_interface/3a_aula/on_being_out_of_control.pdf> (accessed 15 Dec 2018).
Haque, U.: 2007, Haque, U 2007, The architectural relevance of Gordon Pask, *Architectural Design*, **77**(4), 54–61.
Heims, S.J.: 1991, *The Cybernetics Group 1946–1953. Constructing a social science for postwar America*, MIT Press, Cambridge MA.
Herr, C.M. 2012, Non-trivial interactive façades, *in* T. Fischer, K. de Biswas, J.J. Ham, R. Naka and W.X. Huang (eds.), *Beyond codes and Pixels. Proc. 17th CAADRIA Conference*, CAADRIA, Chennai, 99-108.
Matthews, S.: 2005, The Fun Palace: Cedric Price's experiment in architecture and technology, *Technoetic Arts: A Journal of Speculative Research*, **3**(2), 73–91.
Maturana, H.R.: 2002, Autopoiesis, structural coupling and cognition: A history of these and other notions in the biology of cognition, *Cybernetics & Human Knowing*, **9**(3/4), 5–34.
A. Müller and K.H. Müller (eds.): 2007, *An Unfinished Revolution? Heinz von Foerster and the Biological Computer Laboratory 1958–1976*, edition echoraum, Vienna.
Pask, G.: 1961, *An approach to cybernetics*, Harper, New York.
Pask, G.: 1969, The architectural relevance of cybernetics, *Architectural Design*(September 1969), 494–496.
Pask, G.: 1976, *Conversation Theory. Application in education and epistemology*, Elsevier, Amsterdam.
Pickering, A.: 2011, *The Cybernetic Brain. Sketches of another future*, The University of Chicago Press, Chicago and London.
Pratschke, A.: 2007, Architecture as a verb: cybernetics and design processes for the social divide, *Kybernetes*, **36**(9/10), 1458–1470.
Protzen, J.-P. and Harris, D.J.: 2010, *The Universe of Design. Horst Rittel's theories of design and planning*, Routledge, London.
Rittel, H.W.J. 1984, Second-generation design methods, *in* N. Cross (ed.), *Developments in Design Methodology*, Wiley, Chichester, 317–327.
Rittel, H.W.J. and Webber, M.M.: 1973, Dilemmas in a general theory of planning, *Policy Sciences*, **4**(2), 155–169.
Scheurer, F.: 2007, Getting Complexity Organised: Using self-organisation in architectural construction, *Automation in Construction*, **16**(1), 78–85.
Schön, D.: 1985, *The Design Studio. An exploration of its traditions and potential*, Royal Institute of British Architects, London.
Segal, L.: 1986, *The Dream of Reality. Heinz von Foerster's constructivism*, Norton, New York.
N. Spiller (ed.): 2002, *Cyber_Reader. Critical writings for the digital era*, Phadion, London.
Sweeting, B.: 2016, The ethics of ethics and the ethics of architecture, *P. Jones (ed) 2016, Proceedings of Relating Systems Thinking and Design (RSD5) 2016 Symposium. 13-15 October*.
Varela, F.J. 1984, Introduction. The ages of Heinz von Foerster, *in* F.J. Varela (ed.), *Observing Systems*, Intersystems Publications, Seaside, xiii–xviii.
Wiener, N.: 1948, *Cybernetics; or, control and communication in the animal and the machine*, MIT Press, Cambridge, MA.
Winograd, T. and Flores, F.: 1986, *Understanding Computers and Cognition: A new foundation for design*, Ablex, Norwood.

TRIANGULATED SHELL FOAM STRUCTURES BASED ON ROBOTIC HOT-WIRE-CUTTING

A design, geometry rationalisation and fabrication workflow

THOMAS FISCHER[1], CHRISTIANE M. HERR[2] and MICHAEL GRAU[3]
[1,2]*Xi'an Jiaotong-Liverpool University, Suzhou, China*
[1,2]*{thomas.fischer|christiane.herr}@xjtlu.edu.cn*
[3]*RFR Consulting Engineers, Shanghai, China*
[3]*michael.grau@rfr-shanghai.com*

Abstract. This paper presents an interim report of an investigation into a digital design and production workflow to generate, rationalise and fabricate triangulated extruded shell foam structures. It reports on a speculative form-finding and geometry-generation process, a rationalisation approach, a new type of hot-wire-cutting robot and early findings gathered regarding technical and design strategies, geometric and fabrication constraints, as well as an outline of related future work.

Keywords. Generative design; geometry rationalisation; hot wire cutting; robotic fabrication; process automation.

1. Introduction

While architectural design depends on physical model-making and prototyping, digital prototyping is currently limited by both the scale and the cost of available machinery. To help overcome this disconnect, we have developed and tested a system and workflow for the medium-scale and low-cost digital prototyping of triangulated architectural shell structures aimed at both educational and industrial applications. We applied a hot-wire-cutting robot and a related suite of script-based tools for geometry rationalisation and fabrication control developed by Michael Grau in the experimental production of an indoor shell sculpture. The robot, with its geometrical as well as material constraints, served as the foundation of the project. The sculpture then served as a speculative test object to probe the possibilities as well as the limitations of the robot (Beorkrem 2017, p. 9–11). The geometry of the sculpture was developed using Rhino3D, Grasshopper and custom GHPython scripts, with a view to realising it as a shell structure from triangular extruded-polystyrene (XPS) foam tiles cut using the robot. This required the approximation of the double-curved surface by way of triangular tiling (Pottmann et al. 2007, p. 219–220). The purpose of this design-driven research approach is to generate knowledge relating to generalisable aspects of the new kind of robot as well as of its associated geometry rationalisation and fabrication workflow through

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 551-560. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

the speculative production of physical outcomes. We are planning to further develop the tool kit used, and to refine the described associated workflow in the future and to continue their application in further speculative design projects.

2. Hot-wire-cutting robot

The hot-wire cutting robot is a tabletop-mounted configuration of two two-axis gantries and a turntable. By moving on their two respective vertical planes, the gantries guide a spring-tensioned 0.2mm resistor wire. This configuration allows the cutting of ruled surfaces. It is comparable to, albeit simpler than, an approach described by Rust et al. (2016). Between the two gantries rests the motorised turntable. It holds flat polystyrene sheets and rotates them between cutting operations (see Figure 1). The resulting five (two times two linear and one rotational) degrees of motion are actuated by five stepper motors driven by an Arduido-based controller board. The controller board, namely an Arduino Mega with a Ramps shield, an alphanumeric LCD and Marlin firmware, has been developed by the open source 3D printing community. The Marlin firmware is a G-Code interpreter written specifically for 3D printers. With some work-arounds it was possible to repurpose this system to operate a general 5-axis CNC controller. G-code is supplied to the controller via an SD memory card slot. The resistor wire is heated continuously using a separate, heavy-duty power supply during the operation of the robot. Flat polystyrene sheets, in the case of our sculpture project 50mm thick, are fixed on the turntable by weighing them down with a metal weight placed at their centres. The robot was designed with a view to simplicity during both assembly and operation. It consists of affordable standard components as well as easy-to-manufacture laser-cut acrylic parts. The cutting time for a single triangular tile with a thickness of 50mm and medium density (25kg/m^3) is around 60 seconds.

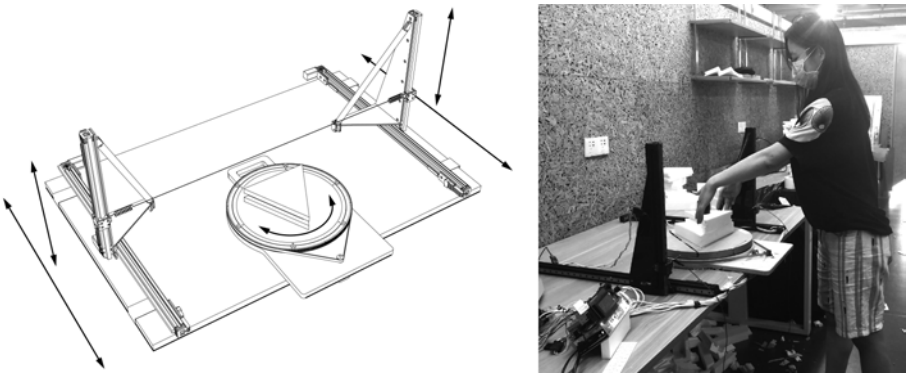


Figure 1. Hot-wire-cutting robot setup and operation.

3. Sculptural form finding

With the aim of creating a curved shell structure from triangular XPS tiles as both as a test object for this project and as a locally meaningful indoor sculpture,

our design exploration departed from a focus on pearls farmed in the local Taihu Lake. Pearls with unusual, non-spherical shapes were of particular interest as they promised to offer both intriguing geometrical challenges as well as an avenue towards a structurally sound closed convex shell affording the execution as a triangulated prototype (Fischer et al. 2005). Exploring further, however, we also considered the shapes of the Unionidae (freshwater shells) in which the pearls are grown. We noticed that the shape of the shells, when opened, corresponds with the image of initial distinction and naming in Daoist creation mythology "*wúmíng tiāndì zhī shǐ*" (Ames and Hall 2003, p. 77; Spencer-Brown 1979, p. xxxii) as well as with the 'owl's face' appearance of the Lorenz attractor (Lorenz 1963). We hence decided to investigate the expression of opened shell shapes as a metaphor for a primordial distinction gesture, using the Lorenz attractor as a parametrically controllable geometrical basis (see Figure 2).

For this purpose, we implemented the Lorenz attractor in GHPython in Grasshopper and extended this with a three-dimensional parametric morphing system based on transformations described by Thompson (1942, p. 1026–1095) and Fischer (2014, p. 373), also implemented in GHPython. The Lorenz attractor depends on seven input parameters, while its geometrical transformations depend on ten parameters in each of the three spatial dimensions. This offers an immensely large range of parametric combinations (Fischer 2019), which we explored interactively and playfully (Fischer and Herr 2015) using Grasshopper to arrive at twelve candidate shapes in the first instance, from which we finally selected one we agreed has the most appealing form, shown at the bottom-right of Figure 2. Using rough prototypes, we decided to produce this shape as an indoor sculpture measuring 3.10 metres across its longest dimension.

The geometry rationalisation (Fischer 2012) required to prepare this shape for robotic hot wire cutting involved several steps, both 'manual' and automated. The numbers in the following description of this process refer to the numbers shown in Figure 3. We first translated the morphed attractor shape (1), which at this stage still consisted of a continuous curve, into a surface (2). We then simplified this surface by removing bifurcations between the two attractor trajectories to arrive at a single continuous ribbon shape (3). Both these operations were performed manually in Rhino3D. We then divided the ribbon surface into triangles. For this purpose, we used a relaxation algorithm implemented in VBScript, which moves randomly distributed points on the ribbon surface so as to equalise the distances between the points as much as possible – a technique sometimes referred to as 'bubble packing' (Fischer 2007). This procedure identifies the closest neighbours for each point and, from their individual directions, calculates a resulting movement vector. Neighbours that are farther than the desired target distance exert a weak attraction while neighbours closer than the target distance exert a strong repelling force. This process is repeated until the algorithm or the user is satisfied with the result. The bubble packing algorithm was implemented such that it allows the even distribution of points not only on single NURBS surfaces but also on NURBS patches (Breps or multi-surface solids). The desired target distance is visualised in (4) and (5) as 'bubble' intersections with the ribbon surface before and after relaxation respectively. We abandoned an initial attempt

to generate triangles from the resulting set of points via delaunisation (Delaunay 1934) as this resulted in overlapping triangles that proved difficult to sort. Instead, the script generates a 3D Voronoi structure (Voronoi 1908) from the point set. This structure is then intersected with the surface by a script. The resulting polygonal packing pattern on the surface is then used as the input for another script which identifies closed loops (polygons), marks their centre points and then connects each of the centre points with those of neighbouring polygons. The result is an equalised triangular pattern that covers the entire surface. A further script optimises the edge lengths of said triangles to further smoothen the pattern, which then approximates uniform triangle sizes, angles and edge lengths.

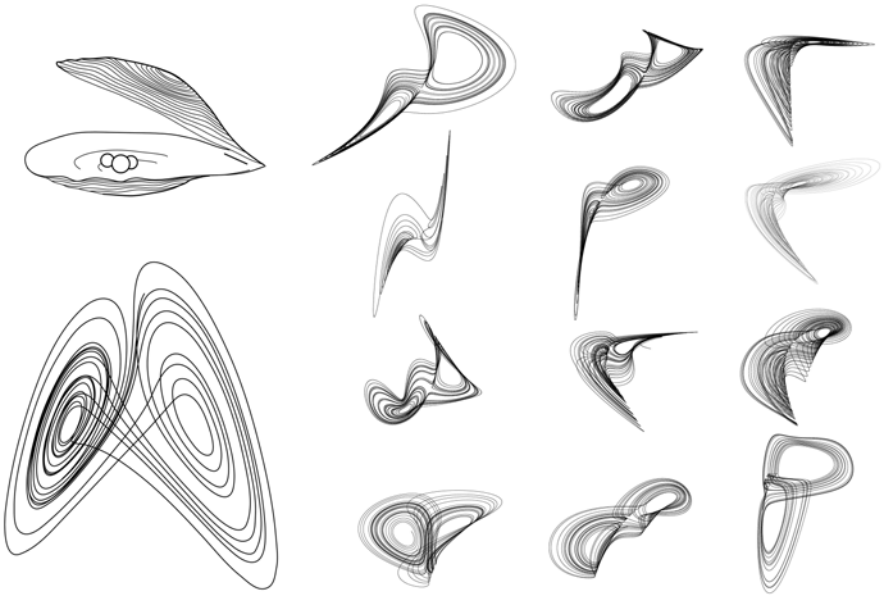


Figure 2. Initial conceptual and parametric design development.

Determining a suitable triangle size for a given overall shape and scale requires, as a minimum, some care and iterative refinement. In our case, it also necessitated some local adjustments to strike a balance between the high triangle count required to ensure a good approximation of the intended surface on the one hand and a low triangle count to increase structural integrity and to reduce the duration of the fabrication process. For this purpose, it is possible to manually add new triangles where necessary and to locally relax their edge lengths with the same script as in the previous, overall relaxation step. Using this feature, we manually increased the triangulation density in some areas to allow a closer approximation of tight surface curvatures. The resulting division of the intended sculptural surface consists of 825 triangles with sizes ranging between that of the palm of a hand and that of a dinner plate (6). Using a separate VBA Rhino Script, we then expanded the triangles to obtain volumetric triangular prism bodies corresponding to the desired tiles (7), and finally added tongue-and-groove joints between the tile prisms (8).

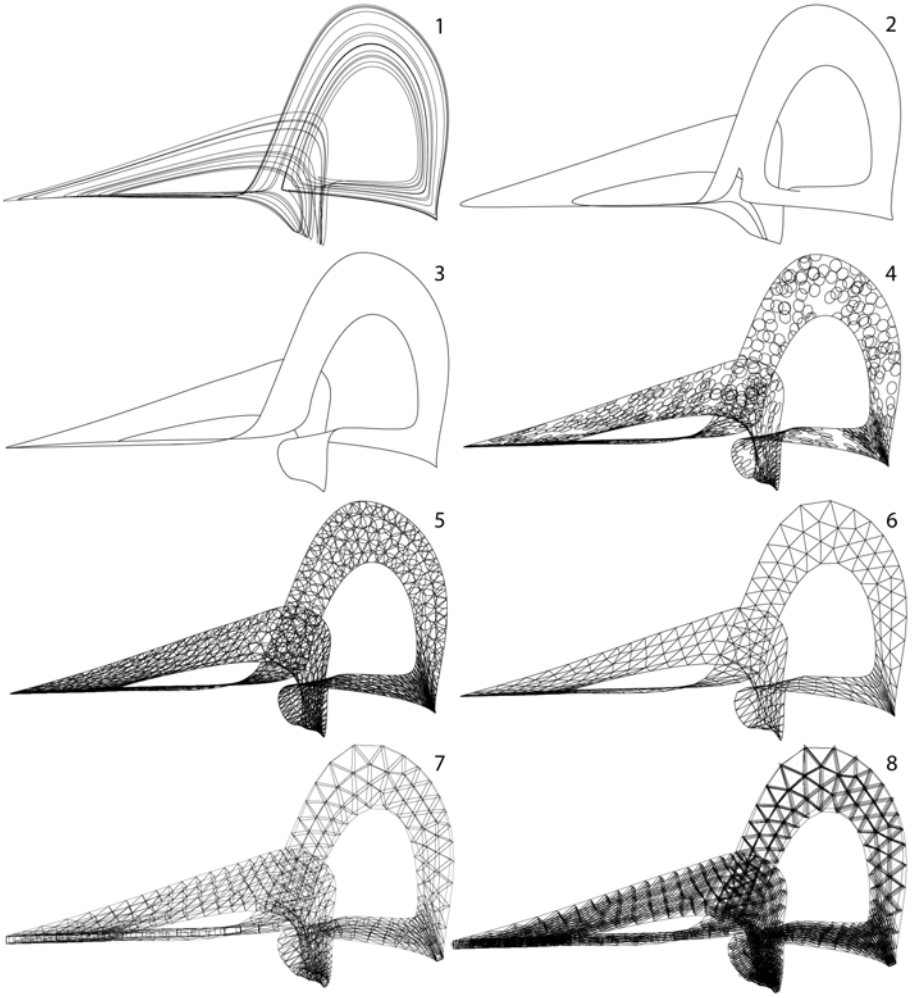


Figure 3. Geometry rationalisation: morphed Lorenz attractor line (1), translated into a surface (2), opened to form a looped ribbon (3), random bubbles distributed on the ribbon surface (4), 'relaxed' bubbles distributed on the ribbon surface (5), triangulated ribbon based on relaxed bubble locations (6), expanded tile bodies (7), and expanded tiles with joints added (8).

The geometry of the resulting 3D tiles was then translated, again using a custom VBA script, into G-code to drive the wire-cutting robot via its Arduino-based CNC controller. Besides geometry data, the generated G-code also contained instructions to display each tile's ID number and neighbouring context on the controller LCD while the respective tile is being cut. The robot operator manually copied the displayed information onto adhesive labels and affixed these to each respective tile to facilitate the subsequent assembly process. All labels were applied to the tiles while they were still mounted (weighed down) on the wire-cutting robot's turntable to ensure the correct identification of upper and

lower prism faces within the overall assembly. The labels are visible in the lower-left part of Figure 4.

We divided the overall sculpture into seven fragments, each of which being small enough to handle easily and to fit through doors and into lifts. We assembled these fragments manually from the prism tiles. To bond the prisms, we applied common white polyvinyl acetate (PVA) glue along the tongue-and-groove joints. This process was successful in the case of each of the seven fragments. The overall assembly of the fragments into the fully constructed sculpture, however, proved too challenging for a number of reasons, which are outlined in the following section, and which we intend to address in future work.

4. Insights gained and future work

The work described here has much potential for further development and more applications in the future. The scales of structures produced with the described approach and machinery can be varied considerably – not only because of the additive assembly process but also because the hot-wire-cutting principles and the robot itself allow scaling in size. The processed material is affordable and light, with as-yet unexplored applications, for example in thermal and acoustic insulation and as lost formwork. It can also form the basis of strong and lightweight sandwich structures when combined with epoxy/fibre or sprayed with high-performance concrete.

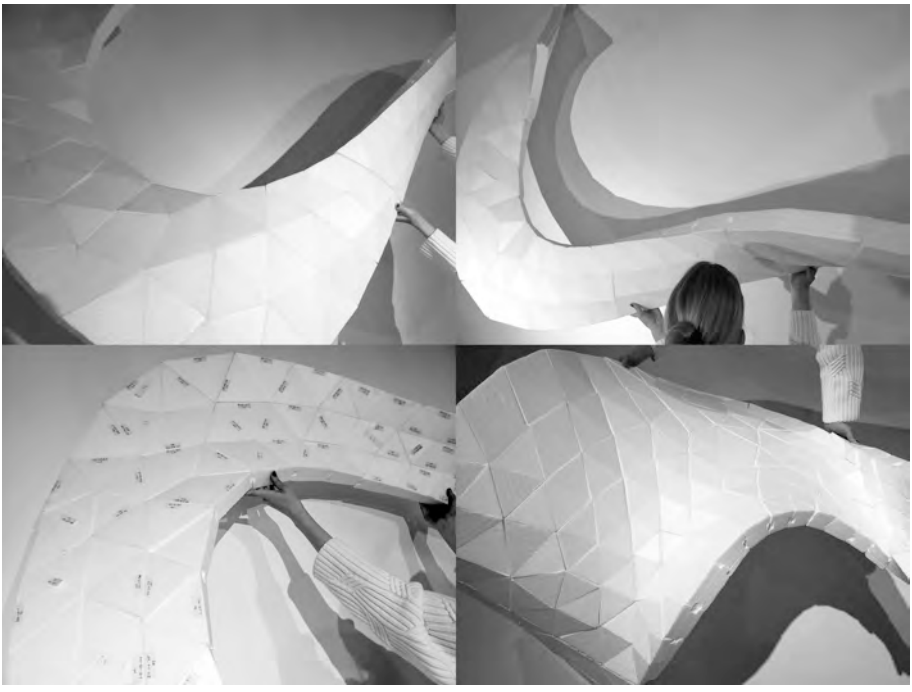


Figure 4. Triangulated XPS shell assemblies.

Through the investigation undertaken so far, we gained several insights, which will be taken into consideration in future work. Although we garnered these insights by way of experimentation and observation, they are not entirely unexpected. Challenging the limits of processes, systems, materials and structures involved, we knowingly and deliberately avoided conservative choices and took risks. Some of these risks led to success, such as the production and assembly of a large set of XPS foam tiles in a short period (thanks to the support of our student researchers). Other risks we took require further work and development. These include:

4.1. HOT-WIRE-CUTTING PRECISION

Spring-mounting the hot wire on both ends compensates for the distance variations caused by independent movements of both gantries, and it practically eliminates wire sagging. However, the relationship among cutting temperature, cutting speed and kerf is challenging to control. The long cutting wire is sensitive to air-conditioning activity as well as to the cooling effects of ventilation and to the mass (size and density) of polystyrene being cut at a given time. As a result, overall cutting precision is lower than the visual inspection of individual tiles might suggest. The limited cutting accuracy results in less-continuous-than-anticipated joint surface contact, rendering glue connections less effective than hoped for. We have addressed this problem by thickening the PVA glue with shredded polystyrene to also act as a filler and thereby achieved more continuous clue connections and thus better structural integrity – a makeshift and less than ideal solution. Ventilation control during the hot-wire-cutting process appears to be a key challenge in achieving cutting precision. A complicating factor in this regard is the need for generous ventilation to remove the toxic fumes given off by the cutting process to ensure the health and safety of the cutting robot operators.

4.2. TONGUE-AND-GROOVE JOINTS AND DOUBLE-CURVATURE

Tongue-and-groove connections are joined by linear motion along a single plane. Such joining motions are rarely possible between triangular tiles that approximate double-curved surfaces. We expected the elasticity of the polystyrene, in combination with some fiddling, to overcome this problem. This expectation turned out to be correct, but only to some degree. It was possible to assemble seven large fragments of the sculpture in this way (shown in Figure 4). In combination with the wire-cutting imprecisions discussed in Section 3.1 above, however, inaccuracies accrued to such an extent that the assembled fragments could not be joined together. This challenge requires additional measures to establish connection lines where assemblies can be joined along motions. Such measures, however, may conflict with requirements for visually appealing triangulation patterns.

4.3. JOINT PROCESSING

Each prism tile has three edges, executed as grooves extending into the tile edges or as tongues protruding out from the tile edges. Tiles thus have one or another of

two tongues and one groove, one tongue and two grooves, three tongues, or three grooves. As an exception to this rule, tile edges that form the edge of the ribbon surface are executed as flat faces with neither a tongue nor a groove. We failed to anticipate that, without taking appropriate measures, tongues can protrude farther than desired near the tile vertices. This is particularly the case at tile vertices where two tongued edges meet. This results in two kinds of unintended effect. On the one hand, tongue protrusions of multiple tiles may intersect near vertices so that tiles cannot be joined around these vertices (see upper row in Figure 5). On the other hand, tongue protrusions can extend from the ribbon edge, which, in our case, was visually not desired (see lower row in Figure 5). These unanticipated effects may best be addressed by introducing additional cutting operations into the tile fabrication process to limit the length of all tongues to the vertices of the main tile body.

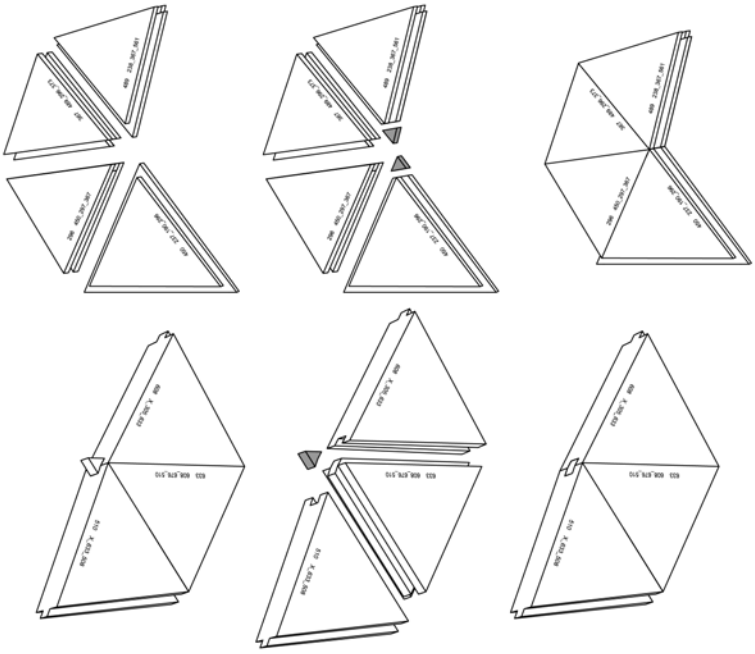


Figure 5. Tongue trimming at interior vertices (upper row) and at ribbon edge (lower row).

4.4. MATERIAL SUPPLY AND WASTE REDUCTION

The quality of structures produced with the described tools and processes depends significantly on the quality and preparation of the raw foam material used. To save manufacturing time, we ordered XPS foam sheets with the desired thickness of 50mm pre-cut to standard-sized prisms. Unfortunately, however, the material we received was cut with thickness variations far beyond the precision limits of our robot, which went undetected until well into the assembly stage and which

affected overall precision negatively. We also falsely presumed that the supplier would triangulate the raw prisms in a material-efficient way. Instead, however, the supplier produced an unfortunate amount of material waste. In these regards, the affordability of the XPS foam is a disadvantage because slim profit margins disincentivise material suppliers from paying attention to detail. We intend to address these aspects of our project in the future by improving our upstream communications and negotiating better material preparations at higher rates.

5. Conclusion

In this paper, we presented interim results of an investigation into a digital design and production workflow to generate, rationalise and fabricate triangulated extruded shell foam structures. We discussed a speculative form-finding and geometry-generation process for a test sculpture, a rationalisation approach, a new type of hot-wire-cutting robot and early findings gathered regarding technical and design strategies, geometric and fabrication constraints, as well as an outline of future work. We achieved some success in fabricating fragments of the intended test sculpture, but also encountered some challenges which require further research and development efforts. These challenges relate to raw material preparations, cutting precision control, execution of joint connections and processing of geometric exceptions in the tongue-and-groove joints near tile vertices. The described tools and processes promise further possibilities and applications, for example in the production of lost formwork and strong and lightweight sandwich structures. We intend to address these observations and potentials in our future work, through further speculative design and fabrication projects.

Acknowledgements

We gratefully acknowledge the collaboration of our student researchers Wei Shubo, Ze Mingxuan and Yu Xinning, as well as the tooling and 3D printing support from the XJTLU Design Building workshop staff. This project was funded by the XJTLU Summer Undergraduate Research Fund under project code SURF-2018-02.

References

Ames, R. and Hall, D.: 2003, *Dao De Jing. A philosophical translation*, Ballantine Books, New York.

Beorkrem, C.: 2017, *Material Strategies in Digital Fabrication*, Routledge, New York.

Delaunay, B.: 1934, Sur la sphère vide. A la mémoire de Georges Voronoï, *Bulletin de l*, **6**, 793–800.

Fischer, T.: 2007, Rationalising bubble trusses for batch production, *Automation in Construction*, **16**(1), 45–53.

Fischer, T.: 2012, Geometry rationalization for non-standard architecture, *Architecture Science*, **5**, 25–47.

Fischer, T.: 2014, Circular causality and indeterminism in machines for design, *Frontiers of Architectural Research*, **3**(4), 368–375.

Fischer, T.: 2019, Transcomputability, (Glanville's Corollary of) Ashby's Law of Requisite Variety, and epistemic processes, *Kybernetes, https://doi.org/10.1108/K-11-2017-0457*.

Fischer, T., Burry, M. and Frazer, J.: 2005, Triangulation of generative form for parametric design and rapid prototyping, *Automation in Construction*, **14**(2), 233–240.

Fischer, T. and Herr, C.M. 2015, Showcasing the new choosing: A parametric jewellery design and fabrication exhibit, *in* W.G. Xu and W.X. Huang (eds.), *Digital Factory: Proceedings of the DADA International Conference on Digital Architecture*, Tongji University, Shanghai, 75–83.

Lorenz, E.N.: 1963, Deterministic nonperiodic flow, *Journal of Atmospheric Sciences*, **20**(2), 130–141.

Pottmann, H., Brell-Cokcan, S. and Wallner, J. 2007, Discrete surfaces for architectural design, *in* P. Chenin, T. Lyche and L.R. Schumaker (eds.), *Curve and Surface Design: Avignon 2006*, Nashboro Press, Brentwood, 213–234.

Rust, R., Jenny, D., Gramazio, F. and Kohler, M.: 2016, Spatial wire cutting: Cooperative robotic cutting of non-ruled surface geometries for bespoke building components, *Proceedings of CAADRIA 2016*, Melbourne, 529–538.

Spencer-Brown, G.: 1979, *Laws of Form*, Dutton, New York.

Voronoi, G.: 1908, Nouvelles applications des paramètres continus à la théorie des formes quadratiques, *Journal für die Reine und Angewandte Mathematik*, **133**, 97–178.

TOWARDS TO A HYBRID MODEL-MAKING METHOD BASED ON TRANSLATIONS BETWEEN PHYSICAL AND DIGITAL MODELS

A case study of the freeform architectural design

DONGCHEN HAN[1], HONG ZHANG[2], WEIWEN CUI[3] and JIE HUANG[4]
[1,2,3,4]*School of Architecture, Tsinghua University*
[1,3]*{850166206|304454559}@qq.com* [2]*zh077@sina.com*
[4]*hdcfr8@gmail.com*

Abstract. The extensive applications of digital models might decrease the capacity of physical model-making for perceptual thinking and enlarge the gap between architects and physical space with limited visual experience. This study aims to propose a reverse process for realizing translations between physical and digital model-making methods from which architects could maximize their initial ideas in conceptual design while allowing for rational digitalization in the detailed design. A review of Reverse Engineering architectural applications is presented and the hybrid method is proposed and examined in a freeform design case. The research shows that in the first translation phase, from handmade physical models to parametric digital models, freeform geometry could be better parameterized in a low degree of deformation based on photogrammetry. Meanwhile, in the second translation phase, from detailed digital models to large-scale physical models, the digitally-driven fabrication could be applied more precisely and automatically based on error handling by 3D laser scanning. Moreover, the process and algorithms developed for the hybrid model-making method indicate the possibility of being applied to further freeform architectural design cases.

Keywords. Physical models; Digital models; RE technologies; Freeform design; Accuracy.

1. Introduction

In the last decade, the emerging practice of freeform architectural design has become a worldwide blossoming in the field of contemporary architecture. These imposing buildings re-shape the skylines of major metropolitan cities with a consistent exploration of dazzling exteriors and striking structures. As the key to realizing the complexity of building forms or geometries, digital technologies, are thus becoming the most commonly used methods for current design and fabrication. It is evident that the digital-oriented design process increases the productivity and accuracy of freeform generation and manipulation as opposed

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 561-570. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

to traditional manual approaches (Aish 2005). But the extensive applications of digital models might significantly decrease the capacity of physical model-making for architects and enlarge the gap between virtual and real spatial experience.

Rather than manipulating ”flat” surfaces on a computer screen, Frank Gehry, the pioneer architect who is well-known for his geometric complexity, preferred to achieve conceptual design by making physical models and drawing sketches (Isenberg and Gehry 2009). Architects could get access to the direct manipulation of physical variables like material properties through handmade physical models, whereas digital models create a distance between architects' perceptual thinking and objects. As conceived by Arnheim (1969), good perceptions that we read from the object play an active role on the building of cognition and trigger inherently creative, freeform thoughts, a critical goal of a design process. Being concerned with the necessity for human tactile and sensory that assist producing desired aesthetic and spatial effects, architectural forms are too complicated to be reduced to solely parameters or logical algorithm as digital models represent. To avoid the over-reliance on rational digitalization, architects should regard the rising complexity of perceptive oriented criteria as their approach.

In Gehry's design process, the physicality of models maintains its prominent identity for possibilities of unexpected conception; at the meantime, the adaption of digital models further exploits the potentiality of these material constructions, exhibiting a close interrelation between digital and physical realm (McCullough 1998). From this perspective, the understanding of realizing translations between physical and digital models to utilize the full potential of perceptual and rational thinking at the conceptual and detailed level is of utmost concern to architects. Previous researches on architectural modeling have often been reported from digital to physical, especially the application of the digitally-driven fabrication process, such as CNC milling, 3D printing and robotic technologies (Dunn 2012). However, making large-scale physical models for design thinking and presentation always has manufacturing and fabrication errors just like actual construction. As to researches from physical to digital, which enables digital representations of geometry, always focus on technical applications of Reverse Engineering (RE) devices. Outcomes of 3D reconstruction like mesh and point cloud models are non-parametric and could not be used for detailed design directly (Austin 2016).

To solve these two problems and develop an iterative hybrid method, this paper introduces an updated framework that realizes the translations between physical and digital model-making methods through RE technologies and algorithm development. First of all, the study presents a review of architectural reverse methods and examines the boundaries of these existing methods. Secondly, the proposed reverse framework is applied to a case study of the curvaceous freeform surface design. Thirdly, the outcomes and core characteristics of the progress are discussed prior to the final conclusion.

2. Literature review of RE technologies in architectural design

Reverse Engineering, also called Back Engineering, is the process of extracting knowledge or design information from a product and reproducing it or anything

based on the obtained information (Eilam and Eldad 2012). Schmitzberger called architectural applications of RE through analysis of its structure, function, and operation as Architectural Reverse Engineering (Schmitzberger 2007). It's widely used in field survey, early conceptual design development (Nir and Capeluto 2005), construction site monitoring, as-built documents (Shih and Wu 2005), augmented reality (AR) and mixed reality (MR), and architectural heritage conservation (Loannidis et al. 2015), etc.

In the 1980s, Frank Gehry started to apply contact RE technologies in the early architectural reverse process to digitize physical models. With the increasingly difficult task of describing complex geometries, architects scanned the sizeable physical model by using RE devices and imported the digital outcome into CATIA for 3D reconstruction (Lindsey 2001). Digital models allowed Gehry to realize different analysis and detailed design. It also allowed his design team to carry out changes and evaluate them immediately in terms of feasibility and costing.

Nowadays, non-contact RE techniques mainly consist of multiple technologies including passive and active, range-based and image-based methods (Mateus and Ferreira, 2013). Among these techniques, photogrammetry and 3D laser scanning are the two major categories of reverse engineering widely applied in architectural applications. They could bring us with a new vision of cognition and understanding of architecture through the exploitation and manipulation of these data, not just in a practical way for surveying and modeling accurately and rapidly.

3. Methodologies

3.1. PHOTOGRAMMETRY

Photogrammetry is a kind of passive image-based RE technique which depends on a group of 2D images of the target to generate a 3D model. The emphasis of photogrammetry is taking proper photos in the data acquisition step. The quality and accuracy of 3D reconstruction depend on shooting angles, shooting positions, the number and the quality of photos. These factors are decided by the ability of spatial cognition to the target and the application experience of photogrammetry. The key is that the group of images should be taken with multiple angles covering the whole target with proper numbers and overlap rate.

Main steps in photogrammetry software are automated or semi-automated such as images matching and stitching, visual feature point extraction, structure positions calculation and optimization, camera distortion calibration, point cloud densification, and meshes generation (Mateus and Ferreira 2013), etc.

3.2. 3D LASER SCANNING

3D laser scanning is a kind of active range-based RE technique which emits light and detects its reflection passing through an object to probe a target. According to principles, 3D laser scanning can be classified as time-of-flight, phase-based, Simultaneous Localization and Mapping, and triangulation, etc. The essential difference among these categories are the various mechanisms of laser generation and principles for calculating the distance from the sensor to object.

In data processing, 3D laser scanners have the bundled software of RE devices for point clouds processing and analysis. This procedure depends on the selected software but still can be summarized as the main steps including registration, image projection, orientation, segmentation, and sampling, etc.

3.3. THE EXPERIMENTAL PROCESS OF TWO TRANSLATIONS

The process includes two translations to solve the two problems mentioned above respectively. Translation 1 is the process from the handmade physical model with perceptual design to the parametric digital model for detailed design. Photogrammetry is appropriate to reverse the small-scale physical model for a medium-definition purpose. Translation 2 is the process from the detailed digital model with rational digitization to the large-scale physical model for further design thinking. 3D laser scanning is used to get the high-definition point cloud model of the structure physical model to update the original skin digital model. The capability of the integrated application of RE devices and software is adequately demonstrated. The final specific geometry and the large physical model are not the ultimate goals. Instead, the reverse process and algorithms developed for the hybrid method are critical points of this research.

4. Results and discussions

4.1. TRANSLATION 1: FROM PHYSICAL TO DIGITAL

4.1.1. Step 1: Physical model-making

The case study performs a freeform shape with a smooth upper surface as the skin and a multiple spherical lower surface as the structure (see Figure 1). Modeling clay is used for making the freeform model so that architects can make full use of their perceptual creativities depending on the feeling of aesthetic form. For better reverse by photogrammetry in the next step, the skin and structure forms are made in two physical models separately.

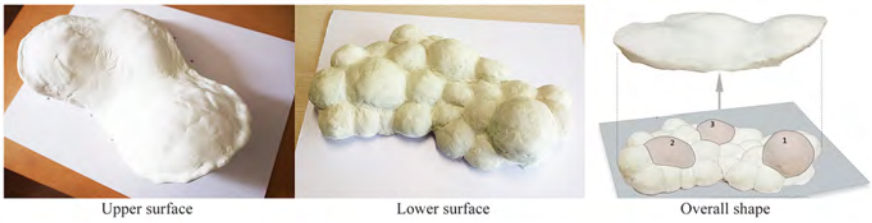


Figure 1. Physical models of the freeform surface design.

4.1.2. Step 2: From the physical model to mesh digital model

In this reverse step by photogrammetry, a mirrorless digital camera, Canon M6 with a 22mm prime lens, is used to make data acquisition. The data processing step uses Autodesk Remake to convert photos into 3D meshes. The size and complexity of the physical model decide the number of shooting. The research tries different groups of shooting angles, shooting positions and image qualities to gain the mesh

model in excellent condition with the least amount of photos. Finally, 85 photos of the upper surface and 147 photos of the lower surface in 6000×4000 resolution are taken, and Remake is used to generate the mesh model with no damage parts in appearance (see Figure 2). The study takes photos in three complete laps with vertical shooting angles of 25, 50, 75 degrees. The overlap rate of every two photos is more than 70%. The original mesh model with thousands of triangular meshes has a severe influence on the computing efficiency in Dynamo. Simplification is necessary before the next step of parameterization.



Figure 2. From the physical model to mesh digital model by photogrammetry.

4.1.3. Step 3: From the mesh model to parametric model

The critical step in Translation 1 is the parameterization and rationalization of the freeform curved surface. The upper surface serves as an example to illustrate this and next steps. A surface parameterization algorithm is developed based on Dynamo. NURBS curves are generated by projecting gridlines to the simplified mesh model. Then lofting is used to create the NurbsSurface which can be adjusted and detailed by the manipulation of splines and control points (see Figure 3). The gridline density in BoundingBox controls the accuracy of Translation 1 as the number of triangular meshes does. A checking step is designed to calculate the level of similarity in the next step. If the outcome meets the demand of the reverse accuracy, the parametric digital model can be determined, or parameter setting of meshes and gridlines should be modified to restart the parameterization step.

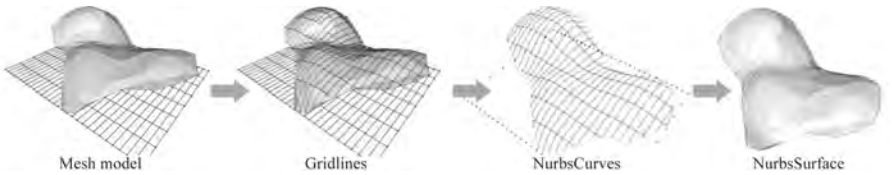


Figure 3. Generation of the parametric digital model.

4.1.4. Step 4: Similarity comparison

Although the reductions in triangular meshes and gridlines in BoundingBox decrease the computing speed of the parameterization algorithm, they will lead to the deformation and decrease the accuracy of Translation 1. The study develops a similarity analysis algorithm for this checking step. The algorithm is based on

a differential method and uses the color display to express levels of similarity between the original mesh model and parametric digital models generated by simplified mesh models. The research chooses eight simplified mesh models whose numbers of meshes in each are in an array from 50 to 400 in increments of 50, and tries 10, 20, 30 gridlines to generate parametric digital models respectively. A total of 24 parametric models are compared with the original mesh model. The yellow part represents the maximum level of similarity. The darkening of the red and blue demonstrates the increasing of the deviation value in positive and negative directions respectively (see Figure 4). The most substantial deformation exists in the surface of maximum curvature variation. The deformation rate is negatively correlating with the number of triangular meshes and gridlines. When the number of triangular meshes goes up from 300 to 400, the rate of deformation decreases slowly and is less than 0.5%. Under the circumstances, the deformation rate is nearly the same when the gridline is 20 and 30 (see Figure 5). In consideration of both precision and computing speed, the research chooses the simplified mesh model with 300 triangular meshes and sets the parameter of 20 gridlines to have the final parametric digital model for detailed design.

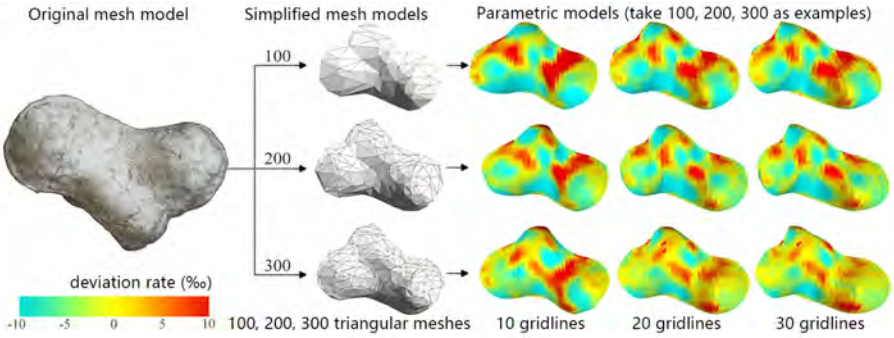


Figure 4. Outcomes of the similarity comparison.

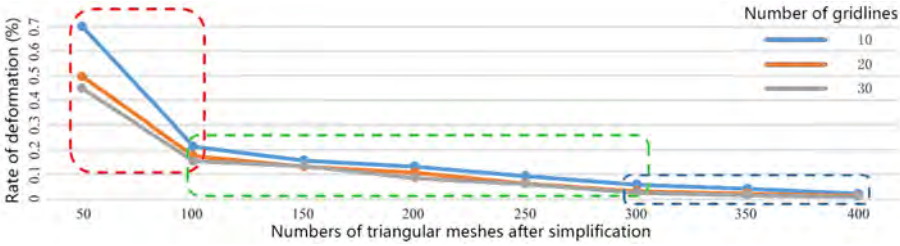


Figure 5. The rates of deformation.

4.2. DETAILED DESIGN OF THE STRUCTURE AND SKIN

The detailed design is a process of rational digitization. After optimizing to smooth both the upper and lower surfaces by adjusting splines and control points

of the parametric model, the structure and skin digital models are created by the generation algorithm which is developed based on analytic geometry methods (see Figure 6). Since the rule of the specific form is controlled by parameters and formulas, architects' abilities of rational thinking can be useful to this kind of architectural freeform generation.

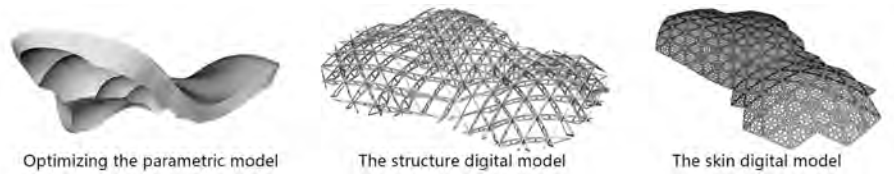


Figure 6. Structure and skin digital models.

4.3. TRANSLATION 2: FROM DIGITAL TO PHYSICAL

4.3.1. Step 1: The manufacturing and fabrication of the structure physical model

The process in Translation 2 focuses on manufacturing and fabrication (see Figure 7). The final physical model for design presentation is in length of 2.1m and width of 1.2m. To facilitate the manufacturing of the large-scale physical model, the research develops a series of algorithms for manufacturing information output. CNC cutting outlines of structure and skin components are generated with serial numbers in order. They are arranged in the same plane of MDF boards based on the automatic adjustment of UV Coordinate Systems. All the manufacturing information can be exported to SAT files for CNC cutting. The research designs a series of snap joints to fix skin components including panel and glass to the structure model. The sizes of the snap joints are 3mm in this case which is decided by the thickness of MDF boards and the diameter of CNC drill. After the manufacturing and fabrication work of the structural physical model, the generation of deformation and deviation has been perceived.

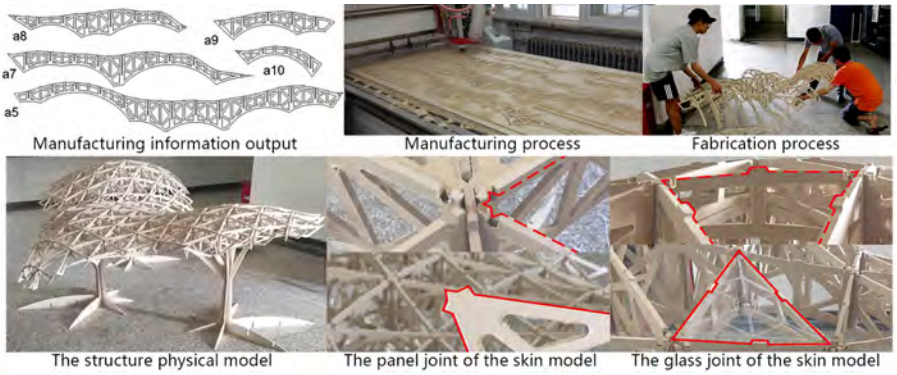


Figure 7. The manufacturing and fabircation of the structure physical model.

4.3.2. Step 2: From the physical model to point cloud model

Since the design of snap joints only allows an error of 3mm between structure and skin physical models, the skin digital model should be updated according to the structure physical model with deformation. 3D laser scanning is applied to do reverse work (see Figure 8). The research uses ZScanner 700 CX, a handheld laser scanner to make data acquisition, and pastes the dot targets to critical positions of the structure physical model for positioning of scanning. These positions are installation locations of skin components. After the scanning work, a 3D point cloud model is generated by ZScan which contains all the geometry and position information of the structure physical model. It is used to do deformation analysis and to update the original skin digital model to fit the structure part.



Figure 8. From the physical model to point cloud model by 3D laser scanning.

4.3.3. Step 3: The deformation analysis and feedback

This step provides the feedback of deviation values between digital and physical structure models. The research chooses 102 key points which are triangular vertexes of skin panels to do deformation analysis (see Figure 9). 35.30% of deviation values arrange at 0-3 mm which meet the error requirement of snap joints. On the contrary, 64.70% of key points couldn't. The maximum deviation value of the single point is 43 mm which is shown in the red dashed box. The yellow dashed box indicates the principal errors of consecutive points. Physical shape changes because of the manufacturing and fabrication methods, as well as its gravity and conjunctions of different materials, etc. cause these errors.

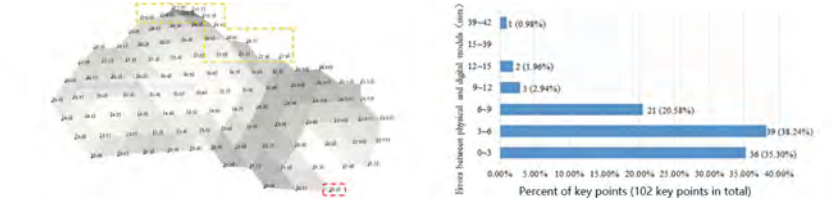


Figure 9. The deviation values between the digital and physical structure model.

4.3.4. Step 4: Updating the digital skin model and final fabrication

The research develops the algorithm to update the skin digital model based on deformation feedback. The comparison of key point positions between digital and

point cloud models of the structure is the first step to do position matching. After list sorting generates the new sequence, new key points replace the original ones to realize the updating. Meanwhile manufacturing information output of the skin part can be generated automatically by algorithms just as the last step. After the manufacturing process of the skin part, skin components including MDF panels and perspex glasses can be installed to the structure physical model accurately (see Figure 10). The outcome demonstrates the necessity of reverse work.



Figure 10. The Final physical model of the freeform Curved Surface.

The research in translation 1 aims to solve the problem of translating the intuitive design thinking explicitly into the editable digital model for detailing. Translation 2 concentrates on manufacturing and fabrication errors of the large-scale physical model for further design and presentation. RE technologies for architectural applications, like photogrammetry and 3D laser scanning, are the critical methods of the integrated experimental process (see Figure 11). Five kinds of algorithms including the parametrization of the freeform surface, similarity analysis for simplification and parametrization, generative design for detailing, manufacturing information output and automatic updating of digital model are developed for this reverse workflow to realize the whole process automatically.

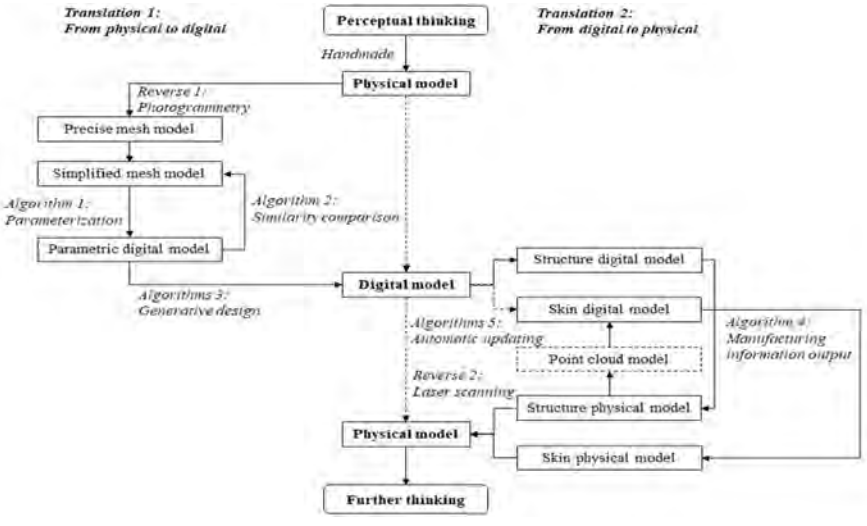


Figure 11. Summarization of the integrated experimental process.

5. Conclusion and future work

To maximize architects' abilities of perceptual thinking in conceptual design and rational digitalization in detailed design, this paper explores an experimental process of translations between physical and digital model-making methods. It demonstrates the capability, necessity, high precision and high efficiency of this workflow for the freeform architectural design. The application of RE technologies in conjunction with algorithm development enables an iterative hybrid method to optimize the reverse design workflow. The process and algorithms as the research outputs could be applied to similar design conditions.

Applications of this workflow in actual building cases can embody the values of this hybrid method. The future research will continue to develop the process and algorithms based on real building and enhance the level of automation. Meanwhile this method currently only fits for the given type of complex geometry composition as a freeform curved surface. It needs to be tested on cases of other geometry types to achieve a robust validation for future universal applications.

Acknowledgement

This work is supported by National Key R&D Program of China "Technical System and Key Technology Development of Nearly Zero Energy Building" (number 2017YFC0702600) and Tsinghua University (School of Architecture) - Zoina Land Joint Research Center for Digital Architecture (number 20172001265).

References

Aish, R.: 2005, From intuition to precision, *eCAADe 2005*, Portugal, 10-14.

Arnheim, R.: 1969, *Visual Thinking*, University of California Press, Berkeley.

Austin, M. and Qattan, W.: 2016, I'm a visual thinker: rethinking algorithmic education for architectural design, *CAADRIA 2016*, Melbourne, 829–838.

Dunn, N.: 2012, *Digital fabrication in architecture*, Laurence King, London.

Eilam, E.l.d.a.d.: 2005, *Reversing: secrets of reverse engineering*, John Wiley & Sons.

Isenberg, B. and Gehry, F.: 2009, *Conversations with Frank Gehry*, Alfred A. Knopf, New York.

Lindsey, B.r.u.c.e.: 2001, *Digital Gehry: Material Resistance/Digital Construction*, Birkhäuser-Publishers for Architecture.

Loannidis, C. and Georgopoulos, A.: 2007, Innovative Technologies for the acquisition and processing of Multisource data for the Geometric Documentation of Monuments, *International Journal of Architectural Computing*, **Issue 02, Vol. 05**, 179–198.

Mateus, L.u.ís. and Ferreira, V.i.c.t.o.r.: 2013, 3D Digitization in Architecture Curriculum, *in Proceedings of eCAADe 2013*.

McCullough, M.: 1998, *Abstracting craft*, MIT Press, Cambridge, Mass.

Nir, E. and Capeluto, G.: 2005, Smart cloud-of-points model, *eCAADe 23*, Lisbon, 687-694.

Schmitzberger, P.S.: 2007, Team-Working and Reverse Engineering: Teaching Methods for Complex Architecture, *in Proceedings of ascaad 2007*.

Shih, N. J. and Wu, M. C.: 2005, A 3D point-cloud based verification of as-built construction progress, *CAADFutures 2005*, Vienna, 193-202.

INTELLIGENT TERRITORY

A responsive cooling tower and shading system for arid environments

ALINA HRAMYKA[1], NEIL GREWAL[2], MOHAMMAD MAKKI[3] and BRITTNEY DILLON[4]
[1,2,3,4]*The Architectural Association*
[1,2]*{alinegromyko|neildsgrewal}@gmail.com* [3,4]*{Mohammed.Makki|brittney.dillon}@aaschool.ac.uk*

Abstract. Climatic change coupled with desertification processes impacting cities located around the Mediterranean, has raised serious questions for the capability of the affected cities to adapt to the rapidly changing environmental conditions. This research aims to design small-scale tower structures and shading devices in Nicosia, Cyprus through employing environmental analyses within a generative design process to create an intelligent, adaptive system. Guided by Bernoulli's principles, geometrical design parameters acquired from fluid simulations, alongside solar analyses of the existing city fabric, were used to generate an evolutionary algorithm for design. The research develops a methodology to facilitate environmental flows in urban architectural systems, generating cooling processes in arid environments that facilitate the adaptation of cities to changes in climatic and environmental conditions.

Keywords. CFD Simulation; Generative Design; Desertification; Passive cooling system.

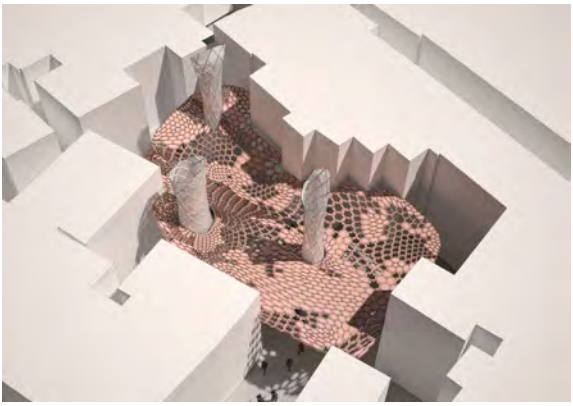


Figure 1. Tower and shading system in Nicosia, Cyprus.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 571-580. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

1. INTRODUCTION

Desertification, a process that transforms fertile land into desert as a result of rising temperatures, has driven the built infrastructure of affected cities towards being better equipped to respond to the changes in climatic conditions (Shoukri, E. and Zachariadis T., 2012). Small-scale structures have been used in both urban and rural environments to lower temperatures and increase airflow. However, while these interventions have helped cities adapt to climate change, the geometry of the structure has proven to be highly influential in how efficient they are in mitigating the changing environmental conditions (Weinstock, M., 2011).

The research presented in this paper is part of a larger body of research, conducted by Brittney Dillon and Alina Hramyka, on both urban and rural conditions in Cyprus. Specifically, the content presented will focus on the design of a responsive urban environment (Figure 1) while contributing a computational methodology for architects and designers involved in urban planning. The research aims to create a responsive architectural ecological system for border conditions susceptible to desertification that can collect, store, distribute water, provide shade, lower temperatures, and decrease evaporation levels along the United Nations (UN) Border.

A generative process is developed to design a tower structure and shading system that is driven by data gathered through solar analysis (using *Ladybug*, a grasshopper add-on) and computational fluid dynamics (CFD). Additionally, an evolutionary algorithm (the Strength Pareto Evolutionary Algorithm - 2 (SPEA-2) used in the grasshopper add-on *Octopus*) is used to develop the design of infrastructure in four impacted zones within the walled city of Nicosia through tackling a multi-objective design problem; whose solutions and relationships are catalogued and can be implemented in future responsive design interventions.

The impact of desertification in Cyprus will be explained, as it played a key role in the selection of affected zones within the city. In addition, a brief summary of the developments in the field of environmental systems will also be engaged, as its key principles play a significant role in providing a proper foundation to design small-scale tower structures and shading devices.

2. NICOSIA, CYPRUS

2.1. DESERTIFICATION

In its latest estimate, The Department of Environment in Cyprus projects that 50% of Cyprus will become a desert by 2050 (Shoukri, E. and Zachariadis T., 2012). This will result in temperatures that exceed 55 degrees Celsius (Figure 2) and a significant shortage of water (Sofroniou, A. and Steven, B., 2014). As temperatures rise, evaporation increases resulting in long-lasting droughts, especially during the summer months. Current climatic and environmental analyses being conducted have demonstrated that temperatures above 35 degrees Celsius have had a detrimental impact on the island (Shoukri, E. and Zachariadis T., 2012). Mortality rates due to higher temperatures could increase by 30,000 deaths annually by 2030 and 50,000 to 110,000 deaths annually by 2080 (Bank of Greece, 2011). Such changes directly influence the ecological system and

human habitation in both urban and rural environments. Agricultural production in rural environments is reduced due to low precipitation, leading to severe land degradation, while urban environments suffer from both production loss and inhabitability due to rising temperatures (Ministry of Agriculture in Cyprus, 2013). This is further amplified due to the urban heat island effect. The use of high thermal absorbing building materials in Nicosia, such as Yellowstone and asphalt, as well as a lack of water bodies and vegetation results in heat waves that can last up to several weeks.

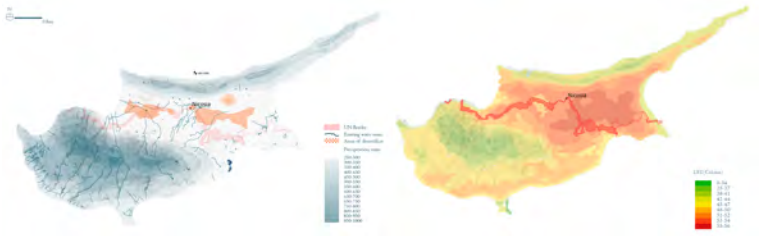


Figure 2. Land surface temperature map (left); Areas sensitive to desertification processes over the next 30 years (right).

Stagnant air is a result of the dense city fabric both within and outside the walled city, further impacting rising temperatures; resulting in significant increases of energy consumption (primarily for cooling). Moreover, it is projected that the areas shown in Figure 2, are the first patches of land that will see the impacts of desertification within the next 30 years (Ministry of Agriculture in Cyprus, 2013). These areas indicate the starting points for design intervention and played a crucial role in site selection.

3. AN INTELLIGENT URBAN SYSTEM

3.1. OVERVIEW



Figure 3. Proposed hyperbolic tower structure designed using Bernoulli's principle of fluid dynamics.

While many strategies reduce urban heat island formation, this research addresses two main factors; urban geometry and reduced vegetation. The objective is to alter the dimensions and spaces between built infrastructure and generate tower structures that will provide shade to lower temperatures, encourage vegetation growth, and promote convective air movement. Guided by Bernoulli's principle of fluid dynamics (Hydrodynamica, 1738), tower structures were designed to prevent air stagnation. Tall, chimney-like geometries allow for air movement between high temperatures and low temperatures. Even slight interventions can impact how air is exhausted, consequently, increasing air extraction efficiency. The geometry of the tower plays a significant role. A tower with negative Gaussian curvature (Figure 3) is more stable against external pressures than straight towers (Asadzadeh, E. and Alam, M., 2014).

In order to satisfy all design ambitions, an evolutionary algorithm was used to optimize a multi-objective design problem. Environmental data, solar exposure and existing wind flow conditions were collected and used as an input to drive the evolutionary simulation. In addition, urban surfaces were analysed during extensive heat periods to highlight areas needed for increased shading and air flow. Locations that have a low solar and wind performance index highlighted the areas where the tower infrastructure would impact the micro-climate towards reducing the urban heat island effect. Even a shading device can reduce surface temperatures up to 7°C (Armson, D., 2012). Solutions are generated to increase performance, and an iterative process of design and environmental analysis is performed to create an intelligent, responsive urban system.

3.2. SITE

Although the complete body of research tackles both the urban and rural environments, the research presented herein focuses on the urban condition, specifically within Nicosia's walled city. Characterized by long, narrow streets (3-6 meters) and open public squares, the city was analyzed both functionally and environmentally. In July, a day can last 14 hours and reach temperatures up to 45°C. A lack of shading on pedestrian walkways, coupled with very little vegetation throughout, make it difficult to occupy public spaces during the day. Although the city is relatively dense (almost 2,500 inhabitants per square kilometer), public spaces are predominantly empty due to lack of relief from heat. As such, four plazas were selected (Figure 4) to represent areas within the city most affected by desertification processes. Each plaza is defined by its overall area, the ratio of hard-scape to soft-scape, location of existing vegetation, public and private space, existing street network, existing wind flow conditions, and amount of shadow.



Figure 4. Four selected sites within Nicosia walled city.

3.3. GENERATIVE ALGORITHM

3.3.1. OVERVIEW

As each site needs to adapt to both environmental and functional implications, a generative algorithm was used to provide solutions to a design problem with multiple conflicting objectives. The aim is to create a responsive, urban system that strives to maximise air movement and maximise shaded area within each selected plaza through the design of a tower structure and shading system. An evolutionary solver allows the designer to edit, assess, and select a set of solutions rather than a single solution that only satisfies one objective. This gives a broader understanding of how design parameters can affect the solution's geometry.

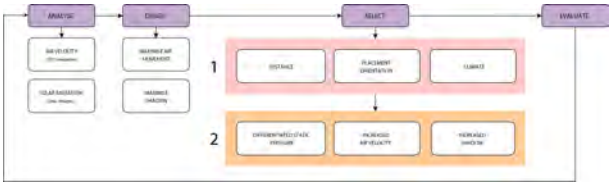


Figure 5. Genetic algorithm workflow.

The set of solutions are numerically assessed, where the evaluation is based on the solutions ability to either encourage airflow or provide shade; design relationships are derived and used as inputs for a second iteration of geometric optimisation (Figure 5). The generated feedback loop makes this methodology an intelligent one, allowing the designer and evolutionary solver to generate an air-cooling, shade-promoting design, responsive to any arid environment

3.3.2. SELECTION STRATEGY

The iterative process generated a population of solutions that respond to the environmental and climatic context for each selected plaza. Design solutions were selected based on three criteria; **1**. distance between design intervention and existing infrastructure to provide pedestrian pathways; **2**. placement and orientation of towers to provide maximum shadow; **3**. and solutions that provide a cooler micro-climate that facilitates increased vegetation growth. The selection process employs methods that are independent from the ones used to develop and run the evolutionary simulation. As such, the generated solutions were evaluated a second time according to static pressure, air velocity, and shadow, on the ground (Figure 6).



Figure 6. Selected individuals.

3.4. EXPERIMENTAL SETUP

The experiment uses both fluid simulations and solar analysis as inputs for a generative algorithm (Figure 7). The use of these tools allow for recursive experimentation that are difficult to simulate physically. Several parameters are used to facilitate airflow movement and shading techniques.

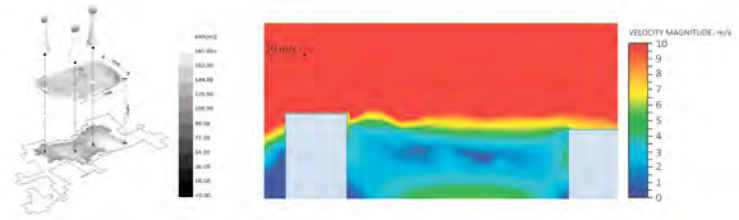


Figure 7. Solar radiation analysis; Dividing plaza surfaces into cells for calculation (left); Initial CFD simulation testing existing condition (Plaza 1): Air velocity = 10 m/s (right).

3.4.1. COMPUTATIONAL FLUID DYNAMICS (CFD)

The Bernoulli Effect can be observed through air mass movement in CFD simulations. These simulations provide quantifiable data for informed geometric manipulation of tower infrastructure. A three-dimensional analysis is computationally demanding (˜2 hours per simulation), therefore, a two-dimensional analysis was conducted using a section perpendicular to the prevalent wind direction (Figure 7). A velocity of 10 m/s was tested to simulate the maximum wind velocity in the southwest direction in July. A preliminary CFD simulation was conducted on the existing urban fabric on a simplified 3D model of the city. Tower structures were added to the model to test a range of geometric configurations that maximise air movement through the plaza. The towers' distance from the ground was incrementally adjusted to increase fluid speed. The distance between multiple tower edges were tested to control static pressure, where each edge was assigned an angle between 20 and 45 degrees to maximise wind velocity. Note that the CFD simulations show the relative difference between existing atmospheric pressure and proposed excess pressure, the values indicated in the figures are not absolute.

3.4.2. SOLAR ANALYSIS

In addition to CFD, solar analysis was used as an input for the generative process. In order to analyse solar radiation, a 3D model of the existing city fabric was divided into a series of cells (Figure 7). Each cell was assigned a sun vector and calculated the amount of sun hours exposed in July; a month that consists of long-lasting days and intensive heat. A shading device was added to the digital model to test a range of curvature and perforations on the surface to create shadow on the ground plane.

Each cell was restrained in the x and y direction and could move in both

directions. Perforations were added to the surface, where the diameter of each opening could range between 0.25 meters and 4 meters. The angle of each cell and the size of the opening worked to limit the sun exposure and maximise the shaded area within the selected plaza.



Figure 8. Tower structure parameters for generative algorithm.

The tower's placement, height, and distance above the ground facilitate global wind flow, while the shading surface curvature and porosity facilitate both local wind flow and shadow on the ground plane (Figure 8). In addition, the research conducted assumed that materials used in all experiments were of low thermal conductivity, as to ensure excess heat is not absorbed and released by the used materials, thus impacting airflow through the proposed tower structures.

3.5. RESULTS

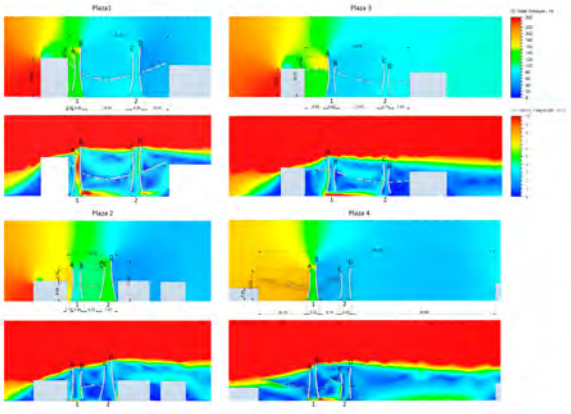


Figure 9. CFD Simulation of proposed tower and shading system measuring static pressure, air movement, and air velocities on four selected plazas.

3.5.1. AIR MOVEMENT

The results indicate that the height of the tower structure, presence of a shading surface, and the distance of the intervention from existing infrastructure, play a key role in controlling air movement. Mainly, if the height of the proposed tower exceeds existing infrastructure the tower acts as a screen resulting in global

pressure differentiated zones. The air velocity in these zones are controlled by the tower's geometry where hyperbolic geometries created zones optimal for air mass movement.

As seen in Figure 9, when A < B, and C < D, the tower **intakes** air. However, if the height of one side of the tower exceeds the other and both sides have congruent geometry facing wind direction, then a gradient of static pressure from high to low along the prevalent wind direction is created. Where A < B, A < D, and C < D, a lower static pressure is observed within the tower. Note that the results show the difference between existing atmospheric pressure and pressure created by an object, otherwise known as excess pressure.

The figure indicates that when a taller tower is placed at farther distance from its smaller counterpart in the prevalent wind direction, turbulence between both towers is increased. The hyperbolic shape of towers accelerates the influx of air, improving cooling efficiency.

In contrast, when A > B, C < D, and the diameter is increased, the tower **extracts** air. However, it is observed that when the distance between towers exceeds 18 meters, any design intervention minimally impacts the plaza's ability to increase air flow and provide more shade. The proposed tower structures are raised above the ground plane to increase air movement within habitable zones. All experiments revealed that a gap between the ground plane and bottom of the structure less than 2 meters, may have increased air velocity by 10 m/s, beyond human comfort level (Stathopoulos, T., 2009).

3.5.2. POROSITY

The diameter of an opening on the surface, as well as the distribution between openings, plays a key role in both air movement and the resulting shadow on the ground plane (Figure 10). An indirect relationship is observed, where larger openings yield lower air velocities and higher solar exposure, while smaller openings yield higher air velocities and lower solar exposure. When the opening is less than 1.8 meters, the air velocity is increased and the air pressure above and below the surface is equalized. It is observed that in plazas smaller than 500 square meters, a dense grid of openings yields larger shadow coverage (Figure 13). In plazas larger than 500 square meters, the placement, size, and shape of an opening on the surface has a greater impact on overshadowing than the number of openings.

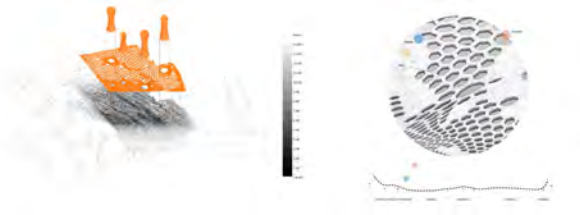


Figure 10. Solar radiation analysis measuring impact of porous canopy system on Plaza 3 (left) Density pattern of opening on curved shading surface - Plaza 3 (right).

4. ANALYSIS

The results indicate that the geometry of the tower and openings on a shading canopy can create differentiated pressure zones, catalysing air movement as well as providing shaded environments for vegetation growth and human occupation. Though reasonable results were obtained, future work should focus on the implications of geometrical variations of the hyperbolic towers, and how building materials can impact the performance of the tower system.

It is evident that the hyperbolic geometry of the tower can work to circulate air. A preliminary attempt to test varying degrees of curvature was taken. It should, however, be noted that geometrical refinement would impact air movement even more. In future, it is advised to create geometries that do not generate air velocities over 10 m/s on the ground, exceeding human comfort level.

The materials used for the experiment assumed low thermal conductivity. Although not within the scope of this study, future work should test how to minimise heat absorption and promote air movement.

5. CONCLUSION

This paper presents an ecological system that responds to climatic change and desertification processes. This topic is important for designers involved in urban planning, using environmental data and analysis as inputs for design. Using CFD simulations within the generative process mobilize precise geometrical adaption to control flows within urban environments. The strategy to design tower structures and shading devices that can adapt to rising temperatures, urban heat island formation, and stagnant air has significant potential for employing an intelligent system in areas prone to climate change. Incorporating geometrical parameters that will not only increase shadow in public spaces, but will also control the air flow for cooling within the existing city fabric, can influence the responsive system. By using hyperbolic tower structures and a connected curved, and porous shading surface, the desired environmental performance can be achieved.

While the methodology presented in the paper showcases overall improvement from the existing condition, there is still possibility for further improvement. For example, the proposed intervention has created zones where air velocity exceeded the initial input of 10 m/s. As the research aims to create a comfortable, responsive urban system, habitability should be measured. In addition to human occupancy, the tessellation on the curved, porous surface should be geometrically adapted to provide optimal conditions for vegetation growth; as discussed, increased areas of vegetation helps reduce evaporation and can contribute to a productive urban landscape.

6. FURTHER INVESTIGATION

Future research should focus on the rural conditions impacted by desertification in Cyprus (Figure 11). The methodology used to design tower structures will remain, however, the generative process will encompass water collection systems to respond to higher levels of precipitation outside the city to address water scarcity. The methodology should also consider not only built infrastructure, but also how

design can integrate with both the natural landscape and productive societies. The landscape should be evaluated based on existing topological conditions, vegetation patterns, water bodies, and interaction with local communities. This data will be quantified and used as input for the generative process outlined in this paper to provide resources for humans residing in dense city fabrics.

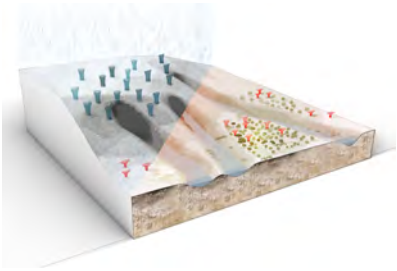


Figure 11. Water collection system within generative design process in rural conditions.

ACKNOWLEDGEMENTS

We thank Michael Weinstock, Elif Erdine, Antiopi Koronaki, and George Jeronomidis for guiding the research at The Architectural Association School in Emergent Technologies and Design Master's Programme.

We also thank Andreas Papallas, Nadia Charalambous, Pavlos Schizas for their support on-site in Cyprus.

References

"NeuroImage" : 2012. Available from <www.sciencedirect.com/science/article/pii/S1618866712000611.> (accessed 22nd November 2018).

Asadzadeh, E. and Alam, M.: 2014, A Survey on Hyperbolic Cooling Towers., *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, **8**, 1079-1091.

Enivironment Deparment, initials missing: 2008, National Action Plan to Combat Desertification, *Ministry of Agriculture, Natural Resources, and Environment, Nicosia*.

Bank of Greece, initials missing: 2011, *Environmental, Economic, and Social Climate Change in Greece*, ISBN 978-960-7032-49-2.

Michaelides, S., Retalis, A. and Hadjimitsis, D.: 2013, In-Tech Satellite and Ground Measurements for Studying the Urban Heat Island Effect in Cyprus, *InTechOpen*, **10.57772/39313**, 17.

Oke, T.R. and Johnson, G.T.: 1991, Watson Simulation of Surface Urban Heat Island Effects under 'ideal' Conditions at Night - Part 2: Diagnosis and Causation Bound., *Layer Meteorol*, **56**, 339-358.

Shoukri, E. and Zachariadis, T.: 2012, Climate Change in Cyprus: Impacts and Adaptation Policies, *Environmental Policy Research Group*, **01-12**, 23-24, 26.

Sofroniou, A. and Bishop, S.: 2014, Water Scarcity in Cyprus: A Review and Call for Integrated Policy, *Water*.

Stathopoulos, T.: 2009, Wind and Comfort, *5th European & African Conference on Wind Engineering*, Florence, Italy.

Weinstock, M.: 2011, The Architecture of Flows: Integrated Infrastructures and the, *ACADIA 2011*, 40-43.

TOWARDS AN HISTORY OF COMPUTATIONAL TOOLS IN AUTOMATED ARCHITECTURAL DESIGN

The Seroussi Pavilion Competition as a Case Study

NADJA GAUDILLIERE
[1]*Laboratoire GSA, Ecole Nationale Supérieure d'Architecture Paris-Malaquais, 75006 Paris, France*
[1]*nadja.gaudilliere@gmail.com*

Abstract. The present research proposes a method to analyse computational tools at the architect's disposal and the potential technical bias they induce in architectural design. Six case studies will be used as a demonstration of the method's ability to highlight those biases and how architects and designers manipulate those tools to translate their architectural expertise into algorithmic design. Those case studies are the six answers to the Seroussi Pavilion competition, organized in 2007 by Natalie Seroussi, a Parisian gallery owner. Having a keen interest into computational design, she invited six architectural practices specializing in this field. As the six case studies answer the same design brief, it represents a particularly suitable opportunity to analyse the intricate relationship between architectural constraints, their translation into computational data and instructions and the programming tools used to do so. Through the analysis of four different aspects of the project - algorithmic tools/method, computational set-up, organizational chart and architectural design - several issues of the computational turn in architecture are discussed.

Keywords. Digital heritage; computational design tools; architectural constraints; programming-based spatial design; Seroussi pavilion competition.

1. Introduction: toward an history of computational spatial design tools

1.1. ALGORITHMIC DESIGN AS A TOOL FOR SPACE DESIGN

Throughout the last 50 years or almost, architects, urbanists, structural engineers and designers have been experimenting with the computer's ability, given a proper set of instructions, to generate shapes and other contents on its own. But beyond the fascinating ability of computers to create geometries from nothing but a few written signs, the objective for architects has become generating a relevant spatial solution to a given architectural problem using computational design tools. To achieve this, the instrumental issue is the translation of architectural constraints into an operable set of data and instructions, or in other words, into an operable

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 581-590. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

algorithm. But the structure of algorithms, alongside the coding languages used to create them, are fundamentally different of any other tool previously used by architects for space design. Therefore, architectural constraints such as program, context, structural loads and other are dealt with in a new approach, contributing to the renewal seen in architectural design as recourse to digital design methods spreads out. In light of these changes, understanding to what extent architects and designers resort to algorithms and computational design appears to be a major issue to tackle.

In order to tackle this issue, a key element to analyse is the computational design tool itself. If at the beginning of computational experimentation, architects shaped their tools for spatial design on their own, developing specific algorithms from scratch or almost for each project, in a more recent past the emergence of software such as Grasshopper or Processing has widely simplified the recourse to computational design methods. This has been followed by a blossoming of ready-made algorithms available to architects, granting access to elaborate mathematical and geometrical tools in an unprecedented way to designers untrained in these domains. This access has however been accompanied by a less sharp control of those tools, compared to those initially shaped by digital architects themselves. Lesser control of the programming tool induces more technical biases to be aware of in the translation of architectural constraints into data and algorithmic instructions. This situation calls for an analysis of what programming tools offer regarding architectural constraints translation and technical biases, a question scarcely discussed in the field of computational design.

1.2. THE COMPUTATIONAL FIELD IN ARCHITECTURE

Although the use of computational tools has in the last few years spread to a greater number of architects and designers, seminal research in the field has been conducted by a much smaller group of digital architects and designers. This group forms the core of a specific niche that has developed computational design through research projects, teaching and architectural practice for several decades. The variety of experimentations conducted within this group resulted over the years in very diverse architectural proposals, yet these designers were brought together by a common use of digital design tools, including programming tools, therefore earning the appellation of computational movement to the group (Menges & Alquist 2011).

The computational field in architecture is characterized not only by the common resort to specific design tools, but also by conditions that enabled research on this topic to blossom. Most of its architectural production consists in paper projects, prototypes, pavilions, produced in an academic environment or for specific exhibitions. The computational field therefore organizes itself around a series of individuals, of research units and architecture schools as well as around events such as exhibitions and conferences. This academic set-up has enabled the computational field to blossom away from most of the usual constraints of the construction industry. The consequence of this is an architectural production exploring various issues raised by the development of digital technologies, an exploration benefiting from much more freedom given this distance to industrial

constraints.

This freedom and explorations make the architectural production of this field a prefiguration of the global computational turn in architectural design currently happening. The computational field as it has developed in the last 50 years and its production forms therefore an ideal set of designers and projects to study programming-based spatial design and the translation of architectural constraints in computational tools.

1.3. COMPUTATIONAL SPATIAL DESIGN TOOLS AS A RESEARCH TOPIC

The present research proposes to take a closer look at the digital tools in use in those experimentations and to turn them into a full research topic, in order to analyse the phenomenon through a new angle. If numerous archaeologies of the digital in architecture already exist, including the eponymous book by Greg Lynn (Lynn 2013), they consist in their majority of an assembly of emblematic projects presentations and texts by the architects and designers of the computational field. These project reviews rarely contain more than scarce details on the technical computational aspects and only few designers develop in their written production comments on their use of technical tools. Furthermore, most of the written production focuses on theoretical aspects and does not consider sociological data on the computational field in architecture. Finally, almost none of these productions offers a detailed overview of the actual use of algorithmic tools in architectural design. Only a few studies of the development of specific digital tools exist, such as an history of Form*Z (Serraino 2002), as well as a few very recent researches seemingly starting to open this field of research (Laurent et al. 2018).

The present paper proposes a method to analyse computational design tools at the architect's disposal, their development throughout the years and their technical peculiarities, including possible bias they could induce in architectural constraint translation. Six case studies will be used as a demonstration of the method's ability to highlight the role played by these algorithmic tools. Those case studies are the six answers to the Seroussi Pavilion Competition (SPC), organized in 2006-2007 by Natalie Seroussi, a Parisian gallery owner. Having a keen interest into computational design, she invited the following architectural practices to submit a design for her pavilion: biothing, DORA, EZCT Architecture & Design Research, IJP George L. Legendre, Gramazio & Kohler and Xefirotarch. As the six case studies answer the same design brief, it represents a particularly suitable opportunity to analyse the intricate relationship between architectural constraints, their translation into computational data and instructions and the programming tools used to do so.

The main objective of this research is to propose an analysis method and to discuss algorithmic design tools and the notion of technical bias in the SPC, but also to question the results of this study as part of larger considerations on the use of algorithmic tools for architectural design in recent history.

2. The Seroussi Pavilion Competition

2.1. CONTEXT AND BRIEF

The Seroussi Pavilion Competition's aim was to build a pavilion that would be housing part of Natalie Seroussi's art collection in dedicated exhibition spaces as well as living spaces. In addition to this double architectural program, the other peculiarity of the competition was the project's site, a particularly strong and specific context: the pavilion was to be built in the garden of André Bloc's home, property of Natalie Seroussi. The villa, located in Meudon, was designed and built in 1949 by the architect and engineer for himself, and the garden hosts as well two of Bloc's *sculpture-habitacles*, added in 1964-1966. A specific area of the estate was selected for the pavilion and is mentioned in the competition brief, along with comments on the specificities of the site, to be considered by the participating architectural practices. The brief also includes a detailed program (Guenoun 2007):

"The project will include an interior and an exterior space. The total inhabitable surface area of the project will be approximately 350 sqm. The interior will comprise 2 bedrooms, each with walk in closets; 1 living/dining room; 1 kitchen; 1 bathroom; 1 office (optional - can be included in one of the bedrooms); 1 toilet (outside the basement); 1 basement set up for purpose of video projections, 1 storage space for artworks between 20 and 30 sqm. Each of these spaces will, to the extent possible, include storage."

Two proposals, the first by EZCT Design & Architecture Research and the second by IJP, were selected as winners by the jury, chaired by Claude Parent. The winning proposals were not built as it was initially planned, but shortly after the competition, from June to September 2007, an exhibit was organised at the Parisian exhibition space La Maison Rouge, showcasing the six proposals.

Taking place in 2006-2007 in France, the competition was organised during a specific momentum of the computational turn in architecture. It accompanied a series of instrumental exhibitions, such as the *Architectures Non Standard* exhibition at Centre Pompidou (Migayrou 2003), the *Architecture au-delà des formes* ("Architecture Beyond Form") exhibition at the Maison de l'Architecture et de la Ville in Marseilles (Morel 2007) or, the same year, the *Scripted by Purpose* exhibition at the FUEL gallery in Philadelphia (Fornes 2207). In the previous years, starting in 2000, numerous practices were founded that went on to be major designers in the computational field, including those participating in the SPC. Those elements all hint to the fact that the competition took place at a moment where the designers taking part in the computational field at the time were building a community around these issues.

2.2. AN IDEAL CASE STUDY

The interest of the Seroussi Pavilion Competition as a case study, beyond it happening in a key momentum, also lies in the fact that the six participating practices are emblematic to the computational turn in architecture. Moreover, they are emblematic of a specific generation. The term "generation" will be used in this paper to designate successive groups of individuals taking part in the

computational turn. Those generations are characterized by their use of tools, as the use of algorithmic design tools in architectural design can be described by characterising the relation of designers and practices to those tools throughout the years. Although most of the individuals of a generation are younger than those of the previous generation and although a relationship of knowledge transmission exists between most of the individuals from two successive generations, some overlapping still exists. Five specific groups or generations can be distinguished.

The first generation (G0) is formed by isolated projects and experimentations, on primitive computational set-ups, such as the Generator project by Frazer & Price (Landau 1985). The second (G1) regroups individuals that launched the first paperless studios and similar academic research groups. Therefore, this generation constitutes an embryo of network of people experimenting with existing algorithmic tools and methods as well as theorising a new paradigm based on possible production conditions. The third (G2) is formed by designers having been taught by individuals from G1 and simultaneously exposed to various computational tools developed in other fields, such as analysis tools for engineering purposes. Their use of computational tools is characterized by an earlier and further training on programming tools available at the time. The enlargement of the network as well as the technical progress of modelling, simulation and analysis tools at the time results in a fine-tuned capacity to build their own tools and to experiment with the possibilities offered by computational design. The fourth generation (G3) displays a similar use of tools. But since it benefitted from the experience of G2 as well as from new technological progress, this generation has had the possibility to develop tools exploring computational design further, including handling more data and data of various kinds. Finally, the fifth generation (G4) corresponds to the generalisation of the recourse to programming tools, using the tools developed by G2 and G3 providing a simplified interface and therefore easier access to sophisticated algorithms. Technical bias is stronger in this generation given that the recourse to pre-existing tools partly erases the need for mastering scripting.

The Seroussi Pavilion Competition regroups a series of practices all part of the G2 group and is therefore emblematic of this generation. Furthermore, the competition represents an ideal case study since its brief offered a particularly suitable working environment to develop research on computation architectural design. The practices invited were all young, with particularly homogeneous profiles, similar dates of founding, similarities in the previous production and in the means of integrating research on computational tools into the practice, as well as fitting the relationship to tools described for G2. The lead architects of each practice also have similar trajectories, with involvement in academic environments and in teaching - on some occasions together. It is also interesting to note the presence of younger architects in the teams such as Ezio Blasetti, Roland Snooks or Dave Pigram as it also hints to a strong insertion of the SPC into the network of computational architectural research, since these architects went on to be prominent players in G3. Furthermore, despite its strong adequation as case study, the SPC has never been used as such in digital tools overviews or digital heritage studies. The only publications regarding this competition are

the exhibition catalogue (Guenoun 2007) and a few brief articles in magazines such as CREE (n°332), D'Architectures (Scoffier 2007) or A+U (n°455), either reports of the exhibition or succinct presentations of a specific proposal in an article dedicated to the practice who authored it.

3. Analysis methodology

The methodology defined here aims to gather a common set of data on each of the proposals, on four different aspects of the project: algorithmic tools/method, computational set-up, organizational chart and architectural design. The specific information surveyed are detailed in Table 1, as well as the matching data collected for each proposal. The data was collected by consulting the published documents for each project - credits, plans, renders, diagrams, code excerpts - and by conducting interviews with the leader of each practice. The items available for each proposal are indicated in table 1 as well.

Table 1. Data collected for the six Seroussi Pavilion Competition proposals.

		Practices					
		Ibathing	labDORA	EZCT Architecture & Design Research	UP Corporation	Gramazio & Kohler	Kokkugia
Algorithm	Family	Formal Research	Performance-driven design	Performance-driven design	Formal Research	Fabrication-driven design	Formal Research
	Type	Attractors (agent-based; magnetic fields)	Finite Element Analysis, Particle System Optimization	Genetic Algorithm	Periodic Equation	Robotic Brick Placing	Growth
	Whole or split	Whole	Split / Not related	Split / Related	Whole	Split / Related ??	Whole ??
	Main Technical Objective	Global Shape Generation	Structural Optimisation	Light Optimisation	Global Shape Generation	Detailed Shape Generation	Global Shape Generation
	Secondary Technical Objectives	/	Global Shape Generation, Detailed Shape Generation	Structural Optimisation, Global Shape Generation, Detailed Shape Generation	Mathematical Sobriety	Fabrication files generation	/
	Output	"Flower" Shells (Roofing)	Shell Shape and Structural Elements	Main Shell Shape, Structural Pattern for Surface Subdivision	Modules	Wall Shape and Bricks Placement	?
	Significant Variable	Position of Attractors	Double Shell Structure	Shape of retrieved blocks	Periodic Equation / Cylinder	Robotic Placing Constraint	?
Technical Set Up	Software	Rhinoceros + FlowerPower	Rhinoceros, Finite Element Analysis Software	Rhinoceros, Mathematica, Radiance, Maya, Blender, VTK, Polytrans, Getfem++, 3Dmax, Vray, EO, Catia	MathCAD	Maya	?
	Programmation Language	C#	C#	Python, C++, Wolfram	Mathematics	MEL	?
	Interface type	Plug-in with slider parameters	/	Scripting	Scripting	Scripting	?
	Graphic Representation Tool for Base Geometry Visualisation	Rhinoceros	Rhinoceros	Rhinoceros	AutoCAD	Maya	?
	Final Output Type	3D + 2D Drawings	2D Drawings	3D + 2D Drawings	2D Drawings	3D + 2D Drawings + Fabrication File	3D + 2D Drawings
Chart	Date of Office Creation	2001	2001	2000	2000	2003	2001
	Number of people (Team; + Consultants)	7 + 1	17 + 7	11	10	12	10
	Background of principal	Architecture	Architecture	Architecture	Architecture	Architecture	Architecture
	Background of team	Architecture, Computer Science	Architecture	Architecture, Computer Science, Mathematics, Daylight Modelling, Structural Engineering, Visual Rendering	Architecture	Architecture	Architecture
	Background of Consultants	Mathematics, Visual Rendering	Architecture, Computational Design, Structural and Environmental Design	/	Landscape Design	Structural Engineering	/
Architectural Design	Drawn Architectural Design independant of the Algorithmic Output	Yes (plan)*	Yes (structural principle)	Yes (plan)*	Yes (plan)	Yes (plan)	
	Site-Related Items (verbal mention, written mention, site plan, sculptures present on drawings)	1	2	4	3	3	4
	Brief compliance (program)	Partial	No	Partial	Yes	Partial	Partial
Available documents	Site Plan	Y	Y	X	Y	Y	Y
	Ground Plan	Y	X	Y	Y	Y	Y
	Drawings (Sections, Renders)	Y	Y	Y	Y	Y	Y
	Code	X	X	X	Y	X	X
	Diagram/Illustration of algorithmic method	Y	Y	Y	Y	X	Y
	Credits	Y	Y	Y	Y	Y	Y
	Interviews	Y	Y	Y (informal)	Y	Y	X

4. Discussion

4.1. BEYOND TECHNICAL BIAS, THE ISSUE OF TECHNICAL LIMIT

One of the characteristics of this computational generation is high awareness of potential biases contained in the algorithmic methods and digital tools relied on. This is also apparent for the practices taking part in the SPC in the comments made on the use of tools and on the development of the algorithms for the competition. The interviews also highlight a common background and convergences in the discovery and learning of computational tools, often in a learning environment with strong intellectual emulation and exposure to disciplines other than architecture. Benefitting from this training and from the feedback of previous generations, they have a fine-tuned mastery of programmation tools and therefore an ability to fully explore their potential in shape generation, constraints assimilation or performance optimisation. But each of the proposals dealt mainly with one of these aspects, as the categories of design in line 1 of table 1 highlight.

The variety of software used (Table 1 Line 11) in is a reminder of the technical complexity in play at the time to implement the algorithms, ensure bridges between specific software and different file formats, plot geometries and so on. The documents published by EZCT include a chart of the different software and file format their algorithm for the competition relied on, including 12 software and 5 file formats. Although it is the only team that detailed the technical set-up this way in written documents, other interviews point to a same scale density.

Considering these two aspects, the issue at stakes in terms of technical tools and their use appears to be the technical limit existing at the time and how to handle it, rather than potential biases of specific algorithmic methods. The selection of one exploration direction at a time is a direct consequence of this. Each of the proposal illustrates a different strategy to manage this limit and produce an architectural answer to the brief.

For the Gramazio & Kohler proposal, the constitution of a set of specific fabrication constraints enabled an architectural design developed based on those, making it an example of fabrication-driven design.

EZCT and DORA both designed a performance-driven algorithm, but the extreme difficulty at the time to implement such algorithm in its entirety led them to explore it in a different way. If EZCT chose to complete the implementation of their light-optimization algorithm, thus handling the most complex technical set-up, DORA established the possibility of such an algorithm by defining the workflow and testing parts of it, but then moved on to a reflexion on architectural reference and how to integrate it in an algorithmic project design.

As expressed during the interview, what drove the design of IJP proposal appears to be an attempt both to remain faithful to a single mathematical idea - as has been seen in most of the other projects designed by the office, such as the Henderson Waves (Hwang 2006) - and to answer as closely as possible to the architectural brief. The idea of developing a project around a single mathematical idea pairs with keeping the problem of technical limits as well as potential technical bias afar and enabling to focus on the development of the architectural design.

Xefirotarch and biothing have in common the exploration of a predefined aesthetic and spatial potential, in the sense that the architecture of their proposal is a variation based on the shapes produced by the algorithm. In both cases, the developed algorithm offers a specific formal vocabulary, that is then adapted to the architectural proposal.

During the interview with biothing, the notion of technical limit was stressed through the description of a gap still existing in architectural algorithmic designed, in opposition to the often-described goal of uniting every step of the design by means of digital tools. This gap could be described as the intervention of architectural decision making in order to guide the use that is made of algorithmic tools. The articulation between those two elements is critical both in the description of how designers resort to computational tools and in the treatment of the technical limit.

4.2. THE PLACE OF ARCHITECTURAL EXPERTISE IN ALGORITHMIC DESIGN

The design process for the proposals all show a stage at which architectural elements of the proposal were not generated by the computer but conceived and drawn by the team. In several cases, it is the plan of the proposal that was drawn upstream (Table 1 Line 21). At that point, the algorithm already being in development, the formal results that were generated by it were evidently considered while drawing the plan. But the plan was drawn without recourse to computational tools. Afterwards, in a second phase, either the plan was fed as input to the algorithm, either a series of shapes was generated and then plugged onto the previously drawn plan, to create the architectural proposal itself.

Although the issue of translation of architectural constraints and decision-making into algorithmic language is at the core of computational design, a significant part of decision-making that is relevant to space design has in the case of the Seroussi Pavilion proposals taken place in part separately. The interlocking of algorithmic development in order to obtain specific geometries and of external architectural decision making therefore appears to be a characteristic of this generation of experimentations as well.

The architectural brief and specifically the program of the pavilion as highlighted in the competition brief was in general not fully respected, or even in the case of DORA, not respected at all (Table 1 Line 23).This disregard is explained by the at the time rare opportunity offered by the competition to experiment with computational design and each practice favoured the exploration of the formal and architectural possibilities that could come out of it. But despite this disregard, deep architectural concern shows in each proposal. Notably, the importance of the building site, hosting André Bloc's villa and more importantly his *sculptures-habitacles*, was mentioned several times. The visual and historical strength of these works were mentioned by most of the architects, and they appear on most drawings (see Table 1 Lines 22, 24, 25). The EZCT proposal is particularly interesting concerning this, as the shape of the retrieved blocks in the initial genetic algorithm, informing the shape of the final pavilion, seem a direct formal reference to the surrounding sculptures.

Beyond the tension between the exploration of computational tools and the design of an architectural proposal, the ongoing changes in the profession are also apparent in this analysis (Table 1 Lines 17 to 20). The different teams present both traditional players, such as a leading architect and engineering consultancies, but also other players specific to the development of computational design, such as software designers (biothing) or a daylight modelling specialist (EZCT). Furthermore, the leading architects all have developed skills specific to designing with programming tools. The professional background and set-up of the teams for the competition is therefore an interesting example of how transitioning to computational design might happen on the professional level.

5. Conclusion: Paradigmatic consistency & technical evolution

Several comments made by the architects on the competition during the interviews referred to their current practice - in opposition to their practice at the time - and highlight how the issues at play in architectural computational design have developed at the time and how they transformed until now. As computational tools develop and the technical limit retreats, both more and more data and new types of data can be considered. Tools that are being developed currently (Salim & Haque 2015) (Sanchez 2013) as well as the evolution of the general discourse on computational design (de Rycke et al. 2018) hint to the fact that computational tools currently develop towards data not only in the domain of performance analysis, but as well elements such as aesthetical choice (Brown & Mueller 2017) or data gathered through massive participation to online platforms. All these issues can although be summarized into on single question, which is the question of automated design. Ultimately, it is this same paradigm that leads all computational experimentation, with the same theoretical background for most designers in the computational field. The evolution of architectural proposals throughout the last 45 years is due in part to the evolution of the tools themselves, more than to the evolution of the issues architects and designers deal with, a relation that can be shown through a historical study of computational tools, such as this research has suggested.

In conclusion, the research presented in this paper attempts, through the elaboration of an analysis method for architectural design integrating programming tools and through the outline of a possible taxonomy for computational architecture, to document the existing digital heritage in a new approach. The application of this method to a specific case study demonstrates its ability to lay out new socio-historical data for a better understanding of the context of emergence of programming tools in space design and of their influence on the resulting architectural objects, in order to contribute to a history of computational tools in architecture.

References

Anonymous, A.: 2007, Le pavillon d, *Architecture intérieure CREE*, **332**, 0294-8567.

Anonymous, A.: 2008, Xefirotarch / Hernan Diaz Alonso, Maison Seroussi – Paris, France, *A+U*, **455**, 0389-9160.

Brown, N. and Mueller, C.: 2017, Designing with data: moving beyond the design space catalog,

Proceedings of ACADIA 2017.
Fornes, M.: 2007, "Scriptedbypurpose : Explicit and encoded processes within design" . Available from <https://scriptedbypurpose.wordpress.com/> (accessed 17 December 2018).
Gaudillière, N.: Ongoing, *Digital Turn et projet architectural - Transmission des savoirs, croisement des disciplines et fabrication non-standard à l'ère numérique*, Ph.D. Thesis, Laboratoire GSA, Université Paris Est.
E. Guenoun (ed.): 2007, *Pavillon Seroussi : biothing, DORA (Design Office for Research and Architecture), EZCT Architecture & Design Research, Gramazio & Kohler, IJP – George L. Legendre, Xefirotarch*, HYX.
I. Hwang (ed.): 2006, *Verb Natures : What is Nature ? How Can we Modify Nature? What is the Nature of Nature*, ACTAR.
Landau, R.: 1985, A philosophy of enabling : the work of Cedric Price, *AA Files*, **8**, 3-7.
Laurent, C., Del, A., Morandi, C., Zreik, K. and Terracol, P.: 2018, De l'objectivité et du digital ; production des données et conceptions numériques – Retour sur le CIMA, *Séminaire Architecture et Culture Numérique, ENSAPVS*.
G. Lynn (ed.): 2013, *Archaeology of the Digital*, Sternberg Press.
A. Menges and S. Ahlquist (eds.): 2011, *AD Reader Computational Design Thinking*, Wiley.
F. Migayrou (ed.): 2003, *Architectures Non Standard*, Centre Pompidou.
Morel, P.h.: 2007, "Catalog of L'Architecture Au-Delà des Formes Exhibition" . Available from <https://petermacapia.com/assets/AuDelaDesFormes_Catalogue.pdf> (accessed 17 December 2018).
K. de Rycke, C. Gengnagel, O. Baverel, J. Burry, C. Mueller, M.M. Nguyen, P. Rahm and M.R. Thomsen (eds.): 2018, *Humanizing Digital Reality*, Springer.
Salim, F. and Haque, U.: 2015, Urban computing in the wild: A survey on large scale participation and citizen engagement with ubiquitous computing, cyber physical systems, and Internet of Things, *International journal of Human-Computer Studies*, **81**, 31-48.
Sanchez, J.: 2013, Gamescapes, *Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*.
Scoffier, R.: 2007, Architecture, rayon passementerie, six propositions pour le pavillon Seroussi, *D*, **167**, 1145-0835.
Serraino, P.: 2002, *History of Form*Z*, Birkhauser.

Practice & Interdisciplinary

DIVERSITY AND EFFICIENCY

A Hybrid Evolutionary Algorithm Combining an Island Model with a Steady-state Replacement Strategy

LIKAI WANG[1], PATRICK JANSSEN[2] and GUOHUA JI[3]
[1,3]*School of Architecture and Urban Planning, Nanjing University*
[1]*dg1436002@smail.nju.edu.cn* [3]*jgh@nju.edu.cn*
[2]*School of Design and Environment, National University of Singapore*
[2]*patrick@janssen.name*

Abstract. Standard evolutionary algorithms have limited use in practical architectural design tasks. This may be due to the poor search efficiency and the lack of diversity of the result. In order to overcome these weaknesses, this paper proposes a hybrid evolutionary algorithm combining an island model approach (parallel distributed technique) and a steady-state replacement strategy for maintaining a rich design diversity of the result while speeding up the search process. Through a demonstration, it is shown that the hybrid algorithm can effectively improve both design diversity and search efficiency.

Keywords. Hybrid evolutionary algorithms; island models; steady-state replacements; design diversity; search efficiency.

1. Introduction

Architectural design, according to Liu et al (2003), can be characterised as an iterative divergent-convergent process, where designers create a wide range of design alternatives at the divergent design exploration stage and then evaluate and modify these at the convergent exploitation stage. Compared to other types of algorithms, evolutionary algorithms are considered a potential technique to support such divergent-convergent processes with computers (Turrin et al, 2011). The reasons for this are twofold. On the one hand, for divergent design exploration, evolutionary algorithms take advantage of the population-based strategy and the stochastic search approach making such algorithms an explorer of the design space, which may discover unexpected design alternatives. On the other hand, for convergent design exploitation, the application of the tournament selection and the population replacement ensures the evolutionary search process focus on optimal solutions in the design space. However, evolutionary algorithms are still less widespread in real-world architectural design tasks as one might expect. The research identifies two key challenges that degrade the utility of evolutionary algorithms in architectural design practice. The first challenge relates to poor design diversity while the second one relates to poor search efficiency.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 593-602. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

With regards to design diversity, the converging nature of the evolutionary process eventually makes all individuals become more and more similar (Figure 1 left). In other words, the population loses design diversity soon after the process discovers a subspace with local-optima and starts fitness exploitation. The convergent search process and the lose of design diversity undermine the divergent design exploration process. In this regards, instead of searching only for optimum design solutions, it is more relevant for designers to execute an evolutionary process that can identify a wide variety of design alternatives with acceptable performance. By comparing these design alternatives and identifying patterns and trends, designers can learn more about the design problem and come up with creative design solutions (Woodbury & Burrow, 2006).

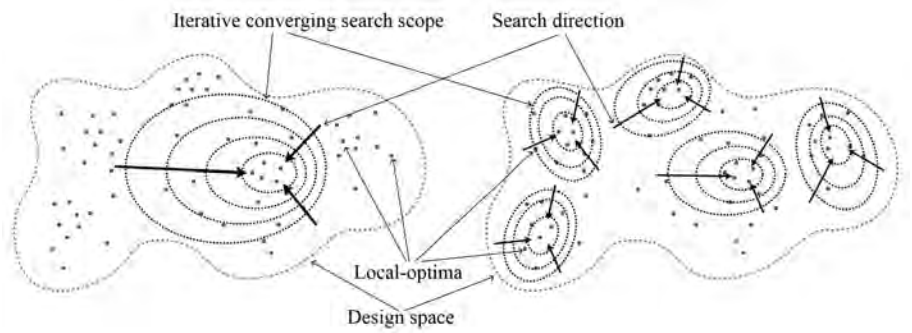


Figure 1. Diagrams of a standard (centralised population) search process (left) and a distributed parallel search process (right).

With regards to search efficiency, the generational replacement strategy applied by most evolutionary algorithms results in slow search processes because the design population can evolve only after all individuals in the current generation have been evaluated. Such a process does not proceed as the natural evolutionary process does, where elite individuals affect the population immediately and asynchronously once they come into being. For many studies or applications with a fast evaluation process, poor search efficiency may not draw much attention. However, most architectural design optimizations require evaluation processes based on detail and time-consuming performance simulations, which can prolong the overall search process. When constrained by tight design schedules, poor overall search efficiency will significantly degrade the utility of evolutionary algorithms for real-world architectural design tasks.

The two abovementioned challenges can be controlled, to some extent, by adjusting the selection pressure in order to achieve the desired intensity of design exploration or exploitation. Even so, these two challenges still act against one another. The pursuit of design exploration inevitably hinders search efficiency and vice versa. Thus, in order to reconcile the contradiction between these two challenges, the research proposes a new hybrid evolutionary algorithm integrating an island model approach (Alba & Troya, 1999) with a state-steady replacement strategy (Rasheed, 1998). The development of the algorithm is aimed

at accommodating the requirements of design diversity and search efficiency concurrently. Compared with standard evolutionary algorithms, the proposed hybrid algorithm meets the need for improving both design diversity and search efficiency through a series of parallel search processes focusing on different subspaces, while each of the search processes exploits the subspace more greedily (Figure 1 right).

2. Hybrid Evolutionary Algorithm

For the proposed hybrid evolutionary algorithm, the application of an island model approach and a state-steady replacement strategy will help maintain design diversity and speed up the search process. However, the combination of these two techniques is non-trivial, as overcoming both poor design diversity and poor search efficiency at the same time is challenging. First and foremost, the design space defined by the parametric model of architectural design is commonly multimodal, which means that there are many feasible design subspaces sparse within the design space (Wang et al, 2018). Multimodal design spaces are, in fact, in favour of designers' divergent design exploration, as design exploration does not strictly require the search process focus on finding the global optimum but can instead perform multiple parallel searches. With such parallel search processes, the evolutionary process can provide multiple design solutions, helping designers to uncover patterns or trade-offs within the design problem. In addition, focusing too much on speeding up the evolutionary process by emphasising design exploitation can result in premature convergence. Such risks can be offset if design diversity is maintained by parallel search processes.

With regards to these two facets, the combination of the island model and steady-state replacement strategy allows the hybrid algorithm to search the design space both exploratively and exploitatively: the island model approach enables the search process to focus on several feasible subspaces rather than one single subspace simultaneously, while the steady-state replacement strategy speeds up the search process in exploiting each of the design subspaces (Figure 1 right). In the remainder of this section, we describe these two techniques and the implementation of the proposed hybrid algorithm.

2.1. ISLAND MODEL

For maintaining design diversity, it is important to preserve the *accessibility* of different promising subspaces during the evolutionary search process. Accessibility implies that the search process can reach all locations in the design space with reasonable effort (Woodbury & Burrow, 2006), through recombining (crossover) or random shuffling (mutation) certain parameters (genes) of the already discovered individuals. From this point of view, a weakness of the standard evolutionary algorithm is that many subspaces with desirable design solutions are often lost when a local-optima with slightly better fitness is found. Such local-optima quickly start to overwhelm the rest of the population, and as a result, individuals carrying information that could guide the search process to locate other promising subspace are typically killed and replaced. For preserving

the accessibility of different subspaces, the island model can be used to reduce competition between individuals from different promising subspaces.

The island model uses a parallel distributed search approach that can overcome certain disadvantages inherent in the centralised population models, including prematurity and poor robustness (Alba & Troya, 1999). Such centralised models treat the entire population as a single breeding unit and execute evolutionary operations (crossover and mutation) on the whole population. In contrast, the island model splits the population into several 'niche' subpopulations that are then evolved relatively independently. This separation of the search process into subpopulations avoids the entrapment of local-optima at the outset of the evolutionary process.

While the initial incentive for developing the island model approach is mainly aimed at preventing prematurity, it also introduces other benefits. One such benefit is the ability to launch parallel searches from multiple points in the design space. This makes the island model a compelling approach for maintaining design diversity during design exploration. With the island model approach, the sub-optimal individuals found by each subpopulation are able to be preserved for a longer time and will not be immediately replaced when better individuals are found in other subpopulations. Thus, the accessibility of different subspaces can be preserved, which allows the evolutionary process to exploit multiple sub-optima inside each subspace.

2.2. STEADY-STATE REPLACEMENT STRATEGY

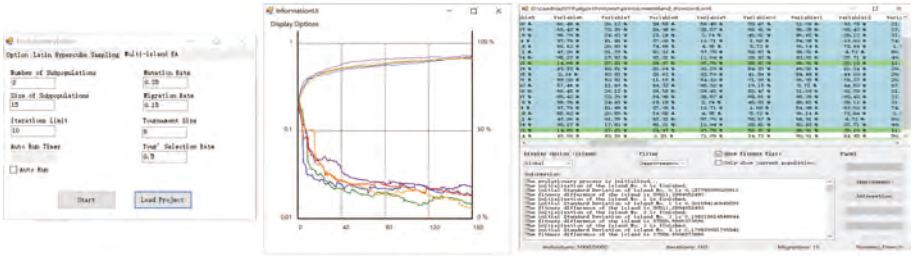
In order to improve search efficiency, the steady-state replacement strategy may have certain advantages (Janssen, 2015). Compared with the generational replacement strategy, the steady-state replacement strategy evaluates only a small number of individuals and immediately replaces inferior individuals in the population. Thus, the evolutionary process is more responsive to the discovery of new improving individuals, as it can react to feedback from performance evaluation more promptly.

In the proposed hybrid algorithm, a steady-state replacement strategy is used. All other evolutionary operations are still run sequentially, as in standard evolutionary algorithms. In each iteration, a fixed number of individuals in every subpopulation are randomly selected as parents to create offspring. The parents and offspring then all compete with one another. The higher ranking individuals (either parents or offsprings) are then inserted back into the subpopulation while the rest are discarded. The selective nature of the steady-state replacement strategy renders the evolutionary process exploitative. However, as mentioned above, the risk of over-exploitation or premature convergence can be compensated by the explorative nature of the island model.

2.3. IMPLEMENTATION

In order to facilitate ease of use for designers, the hybrid algorithm is implemented in the Rhino-Grasshopper environment as a built-in component. The component has several graphical user interfaces (GUI) for providing information

to assist designers to understand the search progress. The component provides visualizations at both the global population level or at the subpopulation level for enabling users to keep track of the evolutionary progress. These visualizations show progress trend lines and other basic information (Figure 2).



Setup Menu Information GUI Runtime Monitor GUI

Figure 2. GUIs of the component.

In addition to the island model approach and steady-state replacement strategy, there are two other important techniques implemented in the algorithm worth mentioning. The first technique focuses on the generation of the initial population. It is reported that the distribution of the initial population has a significant impact on the quality of the subsequent evolutionary process. An uneven initial population distribution can result in early entrapment of the evolutionary search process by poor local-optima (Maaranen et al, 2007). In this regards, we used Latin Hypercube Sampling to generate an initial population to ensure the population can spread more evenly in the design space.

The second technique relates to the exchange of individuals between subpopulations. Natural evolutionary processes often benefit from mating across the boundaries of the subgroups of different species (Chipperfield et al, 1994). Likewise, the exchange of genetic material among subpopulations is also encouraged when using the island model, and the exchange process is referred to as *migration*. The use of migration can help a subpopulation entrapped in a poor fitness subspace to escape to other subspaces by introducing genetic material from other subpopulations. The mixture of genetic material from two subpopulations allows the search process to reposition itself somewhere between the two associated subspaces.

For most algorithms based on an island model, the migration is triggered synchronously after a fixed number of iterations. When triggered, all subpopulations will simultaneously send and receive individuals with other subpopulations. However, such migration operations can be harmful if well-evolved individuals with better fitness are sent to a subpopulation still under evolution. In order to prevent this weakness, the proposed hybrid algorithm executes the migration in an asynchronous fashion. The approach is based on previous studies by Horii et al. (2002). With this approach, the exchange process will only be triggered when the evolution of a subpopulation falls into stagnation.

3. Demonstration

For demonstrating the utility of the hybrid algorithm, the paper uses a design problem from a previous study (Wang et al, 2018). The design generates high-rise buildings with an atrium and a series of vertical gardens. The objective is to search for design alternatives that optimise economic performance, taking into account various factors including rental profit, and facade and structural cost. With the economic performance evaluation, a simplified calculation is used that has the advantage of being fast to evaluate. Otherwise, running relevant simulations would be too time-consuming. We will not go into other implementation details of the design here, as they can be found in the above-mentioned study.

With regards to search efficiency, the design space defined by the parametric model is huge and multimodal. Searching such a design space, the evolutionary process can be easily misled by a local-optima, resulting in premature stagnation. In this regards, section 3.1 compares the proposed hybrid algorithm in terms of search efficiency with two other search techniques: a random search technique and a simple genetic algorithm (SGA).

With regards to the design diversity, section 3.2 presents the evolutionary result from the proposed hybrid algorithm. The result presents a rich diversity of design variation, giving designers a better understanding of the trade-off between economic performance and geometric features.

3.1. SEARCH EFFICIENCY

The three search techniques were all executed in Rhino-Grasshopper platform. In addition to the hybrid algorithm, the random search was executed by setting the parameter list to always be 100% random, while SGA was executed using the Grasshopper Galapagos genetic algorithm component (Rutten, 2013). The setup of each search technique is illustrated in Table 1. In order to reduce the impact of stochastic variation, the search process for each technique was repeated five times. During each search process, the best two solutions found at each point in time were recorded. The reason for recording the best two is that focusing only on the best solution can conceal the overall progress of the whole population. By recording the best two solutions, the improvement of the population is shown more clearly.

Table 1. The parameter setup for the three search techniques .

	Simple Genetic Algorithm	Random Search	Hybrid Algorithm
Mutation Rate	25% (*Inbreeding*)	-	35%
Selection Rate	25% (*Maintain*)	-	50%
Number of Subpopulation	-	-	5
Size of Population	100 (*Initial boost* x 2)	-	200
Size of Subpopulations	-	-	40
Stop Criteria	20 generation stagnation	5000 birds	5000 birds

For SGA, the number of stagnant generation was set to 20. In comparison, since there are no mechanisms for the hybrid algorithm and the random search to stop the search process, 5000 births were set as the limit of the search. The setting of 20 generations or 5000 births considered both the factors of search completeness

and of run-time limits.

Figure 3 shows the fitness progression trend lines of the search processes for the three alternative search techniques. In term of the improvement of the fitness, SGA is inferior to the other two other techniques. The result suggests that SGA is incapable of solving design problems with such large multimodal spaces. This is most likely due to the fact that the exploitative nature of SGA can easily mislead the search process towards current sub-optimal subspaces. In such cases, the search process can often spend a long time exploiting a subspace that does not include any acceptable designs. This is the case for the bottom trend line in Figure 3, that produced 12 thousand births but only made very limited progress.

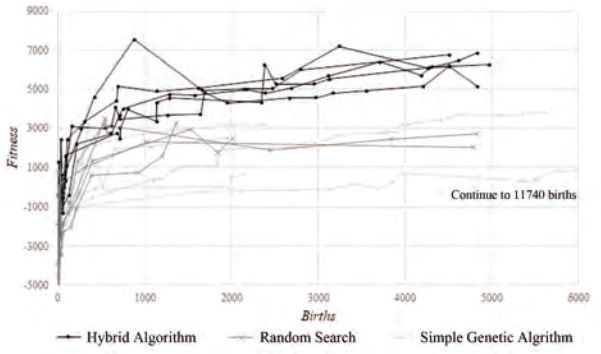


Figure 3. Fitness progress trend lines of the evolutionary runs.

Compared with SGA, the random search is little more efficient in solving the assigned design problem. Without exploitation, the search process randomly explores the design space in an unbiased way. As a result, overall search progress is generally better than SGA. However, without any search heuristic, the improvement achieved by the search process is limited.

In comparison, the proposed hybrid algorithm outperforms the other two search techniques in terms of search efficiency. The evolutionary process with the hybrid algorithm is able to identify promising subspaces faster than the other two approaches. Partly this is due to the use of Latin Hypercube Sampling, which ensures that the initial population evenly covers the design space. This gives the evolutionary process access to a wide range of design subspaces at the outset of the search. In addition, the steady-state replacement strategy enables the search process to discard inferior design variants faster. The evolutionary heuristics of the hybrid algorithm also prevent the search process from just wandering around the design space as the random search does.

In addition to the initial fast discovery of the feasible design alternatives, over the long term the hybrid algorithm is also able to find better designs than the other two techniques. This ability to deliver steady progress is due to the use of the island model. At the early search stage, the island model approach prevents the evolutionary process from being entrapped by a single local-optima. But this also divides the computational search effort into multiple parallel search processes.

However, as the search progresses, the parallel search process allows the hybrid algorithm to exploit each of the subspaces more efficiently. As a result, it is more likely to discover designs with better fitness among these subpopulations. Lastly, the migration of individuals among subpopulations can allow the search process to escape from the entrapment of poor local-optima. The island model approach contrasts with the centralised population model used by SGA, which must pay the price of putting "all the eggs in one basket".

3.2. DESIGN DIVERSITY

As a sign of search convergence, the genetic distribution displayed by parallel coordinates (Wortmann, 2018) can also be used as an indicator of the similarity among the individuals in the design population. With SGA, the genetic distribution will typically become reduced with the search progress (Figure 4), which means that most individuals in the final population will come from one particular subspace. Figure 4 and Figure 5 respectively show the genetic distribution of one of the conducted evolutionary runs based on SGA and the hybrid algorithm. The comparison shows that the hybrid algorithm can preserve richer diverse genotypes than SGA. Even so, the genotypes preserved with the use of the hybrid algorithm all have approximately the same fitness (the right-hand two columns of Figure 5 indicates the fitness of the genotype), which means that there is no significant trade-off on obtaining richer design diversity.

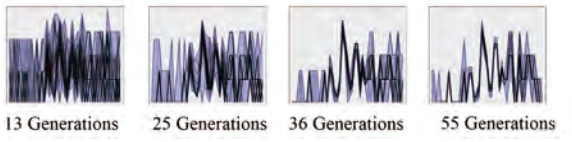


Figure 4. An example genetic distribution change process with Galapagos.

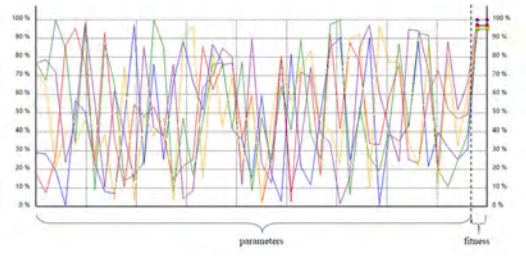


Figure 5. Genetic distribution of elite individuals from different subpopulations with the hybrid algorithm.

The diverse genetic distribution can help designers grasp the implication of design performance. It is clear from Figure 5 that these individuals share similar values for certain parameters while differing in others. The pattern of

genetic distribution indicates that the parameters with similar values are significant for creating satisficing solutions. By identifying these significant parameters, designers are able to modify the design in consideration of other objectives but avoid steering the modification into infeasible design solutions. The pattern of the genetic distribution also indicates that the found designs should share a certain geometric similarity, which can reveal certain relationships between design performance and geometric features.

Figure 6 shows a set of example design alternatives evolved using the hybrid algorithm. Each of the design alternatives comes from a different sub-population. On first sight, all design alternatives have a similar geometric feature, namely that vertical gardens are inserted on middle-to-upper floors. This result is aligned with the conclusion of the previous study that reveals how the insertion of vertical gardens can cause a smaller loss in economic performance. There are also noticeable geometric differences among these design alternatives. By comparing the geometric features and the fitness value, the designer can find the trade-off relationship of the fitness with geometrical features. Among the presented designs, the design alternatives with complex interlocking vertical gardens are typically poor in economic performance because the increase in the number and the size of vertical gardens raises the facade cost while reducing the rental profit.

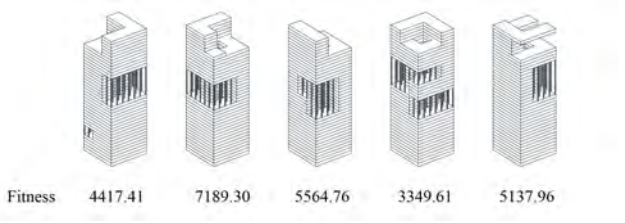


Figure 6. Optimal designs in different subpopulations.

4. Discussion

The conducted experiment compares the search efficiency of the hybrid algorithm with a random search and SGA while also investigating design diversity. The results of the experiment reveal that, by combining the island model and the steady-state replacement strategy, the hybrid algorithm can simultaneously overcome the challenges of poor search efficiency and poor design diversity. This is achieved by integrating these two techniques in a way that synergies their individual strengths. The analysis in Section 3.1 makes it clear that even if the SGA search was repeated numerous time, it is highly unlikely that it would ever reach the fitness levels achieved by the hybrid algorithm.

Compared with the other two search techniques, the use of the hybrid algorithm can also make the evolutionary design process more robust. In Figure 3, the pattern of the fitness trend lines demonstrates that the evolutionary processes based on the hybrid algorithm are more stable than the other search techniques in terms of the final fitness value and overall search progress. This will allow designers to develop

greater trust in the evolutionary result. In contrast, the trend lines for SGA are unstable, rendering it untrustworthy.

The experiment also highlights the weakness of SGA in searching multimodal design spaces. The poor design diversity and search efficiency of SGA make it unsuitable for use within the divergent-convergent design process. This also confirms what Wortmann (2018) has identified - the problematic integration of SGA within architectural design. In this regards, the research provides a potential solution for applying evolutionary search in architectural design. The proposed hybrid algorithm can allow the results from evolutionary search to act as catalysts in the divergent-convergent architectural design process.

The research has successfully demonstrated the proposed hybrid algorithm for a specific design problem. However, according to the No-free-lunch theorem (Wolpert & Macready, 1997), it is not possible for an algorithm to solve all problems effectively and efficiently. Hence, further systematic examinations are needed to identify the range of problems that the proposed hybrid algorithm is able to solve, which also points out the future research direction.

Acknowledgements

This paper was supported by the National Natural Science Foundation of China (51378248) and the China Scholarship Council (201706190203).

References

Alba, E. and Troya, J.M.: 1999, A survey of parallel distributed genetic algorithms, *Complexity*, **4**(4), 31-52.

Chipperfield, A.J. and Fleming, P.: 1994, "Parallel genetic algorithms: A survey" . Available from no URL given.

Janssen, P.: 2015, Dexen: A scalable and extensible platform for experimenting with population-based design exploration algorithms, *AI EDAM*, **29**(4), 443-455.

Likai, W., Patrick, J. and Guohua, J.: 2018, EFFICIENCY VERSUS EFFECTIVENESS, *In Proceedings of the 23rd International Conference on Computer-Aided Architectural Design Research in Asia*, Beijing, 163-172.

Liu, Y.C., Chakrabarti, A. and Bligh, T.: 2003, Towards an 'ideal'approach for concept generation, *Design Studies*, **24**(4), 341-355.

Maaranen, H., Miettinen, K. and Penttinen, A.: 2007, On initial populations of a genetic algorithm for continuous optimization problems, *Journal of Global Optimization*, **37**(3), 405.

Rasheed, K.M.: 1998, *GADO: A genetic algorithm for continuous design optimization*, Ph.D. Thesis, Ph. D. Thesis, utgers University New Brunswick, NJ.

Rutten, D.: 2013, Galapagos: On the logic and limitations of generic solvers, *Architectural Design*, **83**(2), 132-135.

Turrin, M., Von Buelow, P. and Stouffs, R.: 2011, Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms, *Advanced Engineering Informatics*, **25**(4), 656-675.

Wolpert, D.H. and Macready, W.G.: 1997, No free lunch theorems for optimization, *IEEE transactions on evolutionary computation*, **1**(1), 67-82.

Woodbury, R.F. and Burrow, A.L.: 2006, Whither design space?, *Ai Edam*, **20**(2), 63-82.

Wortmann, T.: 2018, *Efficient, Visual, and Interactive Architectural Design Optimization with Model-based Methods*, Ph.D. Thesis, Ph. D. Thesis, Singapore University of Technology and Design.

DESIGNING OUT URBAN HEAT ISLANDS

Optimisation of footpath materials with different albedo value through evolutionary algorithms to address urban heat island effect

STEPHEN GREEN[1], GEOFF KING[2], ALESSANDRA FABBRI[3], NICOLE GARDNER[4], M. HANK HAEUSLER[5] and YANNIS ZAVOLEAS[6]
[1,3,4,6]*UNSW*
[1,3,4,6]*{s.green|a.fabbri|n.gardner|y.zavoleas}@unsw.edu.au*
[2]*City of Parramatta*
[2]*GKing@cityofparramatta.nsw.gov.au*
[5]*UNSW & CAFA Visual Innovation Institute Beijing*
[5]*m.haeusler@unsw.edu.au*

Abstract. The Urban Heat Island (UHI) effect is pronounced in dense urban developments, and particular an issue in the case study city of Parramatta, where temperature increases are impacting use of public space, health, and economic productivity. To mitigate against elevated temperatures in built up areas, this research explores the optimisation of paving material layouts through using an evolutionary algorithm. High albedo (reflective) materials are objectively cooler than low albedo (absorbent) materials yet tend to be more expensive. To reduce the amount of heat absorbent pavement materials whilst keeping in mind material costs, a range of materials of different albedo levels (reflectivity) can be assigned on the same path using an evolutionary algorithm to optimise the coolest materials for the cheapest price. Over the course of this paper, this research aim will be approached using visual scripting software such as Grasshopper to simulate daylight analysis and to generate an optimisation algorithm. Previous research on the topics of UHI have revealed different methods for solving specific problems, all focusing on using software analysis to determine an informed decision on construction. The paper contributes via a computational approach of material selection to battle urban heat island effects.

Keywords. Urban heat island; albedo value; material properties; evolutionary algorithm; landscape architecture.

1. Introduction: Research Aims, Motivation, Context and Defining Problem

Since the advent of the twenty-first century there have been a significant surge in urbanisation. The United Nation (UN 2018) predict that by 2050 two-thirds of the world's population will live in cities. Owing to the built-up nature of cities they

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 603-612. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

can be significantly warmer than rural contexts. This is typically referred to as an Urban Heat Island (UHI). The Urban Heat Island effect has only been recently recognised as a major environmental issue in major global cites such as Sydney, Australia, (Irger 2014) as, as research by Irger demonstrates, temperatures of Sydney's western suburbs have elevated dramatically and have been endangering human health and economic productivity levels. In the past, city development was focused on practicality, aesthetics and cost, with little regard for the environmental impacts of the buildings and places. Parramatta city council is on the brink of developing 50% more infrastructure on their way to become the 2nd CBD of Greater Sydney, and have established a Future City program in an effort to become more environmentally conscious. To mitigate against elevated temperatures in built up areas, this research explores the optimisation of paving material layouts through developing an evolutionary algorithm. Pavement materials with high heat absorption are not only impacting cities microclimates, but they can also be uncomfortable to walk through, reducing the amount of pedestrian engagement and preventing social interaction (Santamouris 2013). High albedo (reflective) materials are objectively cooler than low albedo (absorbent) materials yet tend to be more expensive. To reduce the amount of heat absorbent pavement materials whilst keeping in mind material costs, a range of materials of different albedo levels (reflectivity) can be assigned on the same path using an evolutionary algorithm to optimise the coolest materials for the cheapest price. This research explores this problem by using one visual scripting software Grasshopper, to simulate daylight analysis and to generate the optimisation algorithm. Previous research on UHIs has revealed different methods for solving specific problems, focusing on using software analysis decision-support as a tool.

2. Research Question

Based on this motivation and observation the paper asks the core research question: *How can evolutionary algorithms which optimise pavement material layouts mitigate urban heat island effect?* Still, the core research question itself needs to be discussed with asking sub questions as: *What is an UHI effect?* and *What value have evolutionary algorithms to this enquiry?* This is relevant as apart from scripting algorithms for the evolutionary optimisation, and an understanding of their operation, environmental impacts and weather needs to be researched deeper to understand what variables and objectives need to be used in the algorithm, and why these are important in the efforts to mitigate UHI effect. Post answering these question an appropriate research methodology can be identified.

3. Research Aims and Observations

With this in mind this research project aims to explore how optimising pavement material layout through parametric simulation and analysis can mitigate the UHI effect. The overall goal for this case study is to provide City of Parramatta with an alternative method to measure material properties in pavement materials and an evolutionary algorithm which demonstrates an opportunity for computational

design to optimise the pavement material layout. This research project aims to explore how a script can be applied to the case study area in Parramatta, and if it can be applied to any given geometry or space to adapt to new contexts and shading. Another objective is to determine the estimated albedo of a range of materials through personally testing the infrared surface temperature during daylight hours, which can be used as an objective for optimising pavement material layout.

4. Background Research

To assess the impacts of the urban heat island (UHI) effect in a or any chosen location, one needs to understand firstly its context. Irger (2014) defines the UHI effect as *"the phenomena where urban areas experience higher temperatures than rural locations"*. Throughout Irger's research, he initially discusses topics such as climate change and UHI introducing their important history and upbringings, and what importance they still have in today's environment. By introducing schematic diagrams of past findings and their relevance, it allowed to visually understand the effects that UHI has on cities. There are a number of variables which influence UHI ranging from daylight material absorption, material composition, and urban planning. For example, a significant contributor to the urban heat island effect is the choice of materials and their formal composition.

In their paper on Modulating thermal mass behaviour through surface figuration, Cupkova and Promoppatum (2017) question if heat absorption radiation can be significantly delayed by changing the geometric surface pattern over the same amount of thermal. Their motivation is based on the lack of information and research on how the physical composition of materials effects heat absorption, and their aims are to develop a set of rules for designers to understand thermal lag behaviours of complex geometric systems. Coming from backgrounds of Architecture and Engineering, they used thermal simulation software on complex geometry to show heat reduction on different form with the same mass. From these simulations on iterative designs Cupkova and Promoppatum have come up with an ideal surface to mass ratio to optimise reduction in heat absorption in materials. This study on thermodynamic behaviour in architecture is a significant contribution in the field however also one that arguably requires further research. Yet, with these successful results, a framework could be designed where designers could understand how to use materials and composition better.The above mentioned work shows that study and research heat absorption does not have to be undertaken via 'traditional methods' - using coatings or reflective qualities to reduce the heat absorption, but to think outside the box about alternative methods. This new thinking could be implemented into more heat absorption studies, allowing others to experiment with other possible simulations to optimise materials in different ways. Nguyen Quang (2008) work on urban heat simulation discusses the absence of simulated urban heat software in architecture and aims to test if the same level of data can be achieved on AutoCAD compared to professional simulation software. The motivations for developing an easy to use urban heat simulation in AutoCAD is that the program is typically used in the architectural industry and having the choice to use simulation in the

same software makes it easier for beginners wanting to experiment with urban design tools. By running a basic simulation through an absorption coefficient of material tool in AutoCAD, then importing the image into photoshop to apply a gauss blur, a simulation was possible to a certain level. Nguyen Quang's argument was supported by several other projects as well, all using GIS instead of AutoCAD, (Nichol, J. 2004) (Mardaljevic and Rylatt. 2003) demonstrating that the simplicity of the AutoCAD simulation is ideal for the target audience of architecture students. This level of simplicity has its weaknesses including overlooked factors in simulation, which overall are affected by urban heat. Still the significance of Nguyen Quang's (2008) article is that it demonstrates it is possible to develop simulations inside AutoCAD as opposed to relying on GIS or external simulation software. This suggests it may be possible to use programs such as Rhino or Grasshopper to similarly create urban heat simulations.

This argument is supported by more comprehensive, current studies looking at how daylight can impact UHI have focussed on using computational decision support for a complex airport roof design. The project conducted by Ensari, Kobas, and Sucuolu (2017) have used evolutionary algorithms to analyse given zones of a built environment from an architecture team for an airport roof. Their objectives to accomplish with this evolutionary algorithm was to minimise energy consumption, provide enough natural daylight for the interior, and to take into consideration additional environmental elements such as rain wind. By undertaking solar radiation simulations of the base cases, they could use the results to grade zones based off their daylight coverage and use this information to optimise and manipulate the performance of the spaces. Utilising Grasshopper's Octopus plugin the team were able to develop the right algorithm for their desired tasks, showing how particular software can be used for specific problems such as these in architecture. This example can be applied to the research of heat island effect especially if study using daylight coverage was used for material absorption testing. Based on the above literature review the paper hypothesis to pose similar concepts and to define a methodology to study and research urban heat island effect using computational tools. Here the paper argues that the gathering of different perspectives on how work has been accomplished in the past on similar topics, a forthcoming research to be valued and considered.

5. Methodology

In order to developing an evolutionary algorithm in Grasshopper for optimising pavement material layouts the paper proposes the use of action research (O'Brien, R. 1998) in an iterative process as a chosen methodology due to its effective and practical uses. As Avison (1999) points out that Action research is unique in the fact that it combines the results and processes of theory and practice synergistically, and *"research informs practice and practice informs research."* As outlined in Action Research, the planning phase consisting of researching academic articles and performing literature reviews, has informed the research in three fields.

- First, understanding what the UHI effect is, and what it is impacting. From this understanding, a specific topic such as pavement materials was identified

as the case study for this research.
- Secondly, research has identified algorithms and tools that have been prior used to solve similar problems and translate this understanding to field of enquiry UHI. Here Grasshopper plugins Ladybug and Octopus were selected for the use in this research.
- Lastly, from understanding the use of albedo in the UHI field, surface temperature data were obtained on the five materials that were tested to compare each material albedo properties.

After completing this planning stage, an action phase of iterative testing began where the results can be observed, reflected, and revised.

By developing a simple first iteration with limited variables and objectives to understand if the algorithm works, knowledge can be drawn from the success to go back and collect more data, adding more complex conditions to the next iteration. By expanding the original range of the experiment, further understandings can be gained such as the extent of the process and what it could possibly be used for in the future if given enough research and iterations.

6. Case Study

As outlined earlier this research project aims to develop a GH workflow any firm or company can use for optimisation methods, using the site defined via the collaborating with Parramatta City Council as case study. Hence the project used a specific intersection in the heart of Parramatta (the intersection of Philip street and Church street) where the developed optimisation algorithm can be applied to geometry of that space. All with the objective to provide the Parramatta City Council with information about an alternative solution for pavement material layouts.

6.1. PARRAMATTA GEOMETRY

Over the course of several design iterations through the case study research a basic geometry was used to first gain an understanding of the algorithm being applied. This was followed by setting up the script to then be used for any alternate geometry which replaces the Parramatta precinct geometry. Hence the first iteration geometry was a very simple layout of a street which did not consider dimensions, curves, or orientation, as it was purely to see if the radiance analysis was working.

Upon reevaluating after the first iteration, the geometry was updated to fit the actual case study of Philip street and Church street, where official geometry of Parramatta City Council was used in this research project. However, the Parramatta City Council uses SketchUp to develop their precinct geometry, whereas this project uses Rhinoceros as the 3D modeling program, with Grasshopper as its visual scripting plugin.

Consequently, the geometry had to be exported into Rhino, as well as being scaled down and cropped to the appropriate street intersection. Further, the pavement footpaths were also not modelled into the SketchUp geometry as the

provided geometry was created by council for overall building structure. Thus for this research the pavements were modelled in as correctly as possible, however not using exact measurements or the same measurements that the building geometries were based on. When these footpaths were modelled in correctly, this would be the final geometry to be used for both second and third iterations of this project.

6.2. MATERIAL SURFACE TEMPERATURE

To be able to gather objectives for the evolutionary algorithm to run with to optimise cool materials, five materials were used for this research project:

- Standard pathing material used in council [Adelaide Granit Black]
- Standard decorative pathing material used in council [small orange]
- Standard decorative pathing material used in council [small grey]
- Albedo improved material [Tile cool]
- Albedo improved material [Tile dark]

For all five material albedo levels were identified for an accurate example for the algorithm. To try and evaluate the levels of reflectivity of the materials myself, each material was tested by recording their surface temperatures through a manual infrared surface temperature gun repeatedly and consistently over a sunny day. By tracking the surface temperature of each material over a full sunny day, a rise and decline of each material's temperature can be visualised to understand out of these five materials, which order they belong in when discussing the materials with the highest albedo level, and the material with the lowest albedo level. These results were then used as data for the lowest heat gain of each material using their albedo levels for the objectives of the evolutionary algorithm. The research team is aware that this might not be an accurate scientific way to provide exact data for UHI studies but the focus of this research was in complementing existing research in UHI through a computational method and this generating a workflow that allows to alter the input data with correct data at a later stage.

6.3. GRASSHOPPER MODEL

Grasshopper is the visual scripting program that is run through the 3D modeling platform Rhinoceros and is the basis of the algorithm in which will be produced. However, as this project deals more with an environmental analysis focus than 3D modelling, external plugins were downloaded to assist this research project in dealing with radiance analysis and evolutionary algorithms. Through researching academic literature and past research projects on similar topics, DIVA as a plugin which runs thermal daylight, solar radiation, and glare simulations appeared originally as a perfect fit for radiation analysis of the geometry. However, when installing this plugin, several complications arose, and consequently the research had to identify alternatives to simulate a radiation analysis.

6.3.1. Solar radiation using Ladybug

Ladybug is a weather analysis plugin for Grasshopper which can produce such diagrams of sun pathing and radiation analysis. The first step to setup the algorithm was to input a weather data file which is local to the proposed case study site

of Parramatta City Council. In this case we will be using one of the Parramatta weather files which will be used to simulate the geometries sun orientation and path over the year. Once the weather file is set up, a sun path tool can be run using Ladybug for use as an input for the radiation analysis. The radiation analysis will use the sun path results along with the hours, days, and months of study to produce an estimated simulation of the amount of kw/h in a tile like visualisation mesh. The areas of the pavement which are exposed to the most amount of sunlight over the daylight hours in the season of summer are indicated in red, where areas which have lower sunlight intake are indicated in blue. The radiation analysis results can then be multiplied with the amount of heat each material will absorb to produce results on what the heat gain of each area of the pavement would look like over the summer period when the five different materials are introduced.

To be able to select specific areas of the output mesh from the radiation analysis, the mesh threshold selector tool was used frequently to obtain areas based off their values and not their items. This tool however proved difficult when trying to select areas between specific values as they would overlap instead of stopping at the boundaries. The opposite values had to be selected to then be subtracted from the overall mesh to get the values in between, however this mesh difference also only worked once making a 3D mesh. In the end, the correct areas were able to be selected but only after a messy process.

Originally, manual parametric methods were used to produce three different layouts to then be exported into a spreadsheet to understand what the differences were in price and heat gain when assigning different amounts of each material to different layouts. This did produce results to show out of the selected arrangements which would be the most optimal solution, however this algorithm could be taken a step further to automatically produce the most optimal layout to begin with where manual analysis and parametric adjustments are not needed. To produce an evolutionary algorithm to compute these kinds of results, Octopus worked in conjunction with Ladybug. Honeybee was also attempted to be used in this project to gather more variables for the final algorithm to incorporate. However, when trying to understand how to use reflective material properties it was too difficult to get working and follow along and so was discontinued from the research project.

6.3.2. Evolutionary optimisation using Octopus

Octopus is a plugin for Grasshopper which applies evolutionary principles to parametric design and can be used to optimise multiple goals at once when also given multiple variables. Using this plugin in combination with Ladybug, Octopus can produce an evolutionary algorithm to optimise minimal cost and minimal heat gain, using the albedo data generated from infrared surface temperature testing, and the heat results from the radiation analysis and sun path.

With the goals of the algorithm to optimise cost and material heat gain, and the variables being the areas in which each material are assigned, the algorithm will run through several different area combinations for each material aiming to find the material layout with the lowest cost and lowest heat gain. The results from this analysis are the produced alternatives to what the pavement material layouts could

be, providing information on how much each alternative will cost in total and how much heat gain is in total as well.

With the full evolutionary script completed using the combination of Ladybug and Octopus, the results which become outputs in grasshopper can then be exported into Rhinoceros for visual images of the optimum pavement material layout, or into a spreadsheet such as Excel to produce graphs and tables of the numerical data.

7. Significance of Research

Evolutionary algorithms are incredibly effective optimisation algorithms used mainly in fields of evolution strategy and genetic programming as the algorithm itself derives itself from the process of biological evolution such as reproduction and mutation. In this research paper, evolutionary algorithms are used in the field of architecture in order to developed an intelligent and informed strategy to minimise the impact of Urban Heat Island in our cities. We argue that past projects as the ones discussed (Ensari, E; Kobas, B; Sucuolu, C. 2017) use evolutionary algorithms for optimising roof orientations changing the angle or size of the roof and keeping the amount of materials in the roof the same. Whereas, in this research, multiple variables are put in place to demonstrate how effective evolutionary algorithms can be at producing to multiple goals whilst altering multiple variables. This research demonstrates how the use of evolutionary algorithms can be significant in councils such as Parramatta when optimising pavement materials which would normally be handled by the urban design or planning department. While the algorithm as such does not provide any new knowledge or is as such significant its application is. Cities are becoming under increased pressure and as argued in the beginning of the chapter Urban Heat Island is not only a matter of discomfort but have been endangering human health and economic productivity levels (Irger 2012). Here we further argue that this research engages with the conference theme as it engages explicitly with the innovative, intelligent and informed exploitation of computational design and apply them on two of the grand challenges of the 21st century - rapid urbanisation and climate change.

8. Evaluation of research project

The aim of this research project was to develop an evolutionary algorithm using Grasshopper to optimise pavement materials layouts to mitigate urban heat island effect. From experimenting and analysing the results given from Ladybug and Octopus an optimisation algorithm was achieved with the goals of the optimisations being cost and heat gain. As successful as this research was, it is yet unclear if this algorithm alone would be the most optimal solution in pavement materials to mitigate urban heat island effect, as there were some limitations holding back the full potential of the evolutionary algorithm. Firstly, with the infrared surface temperature testing on the materials completed only manual and only on a very small pool of data, a point of criticism exists. Further most of

the thermal testing were conducted in Spring and during days with less optimum sun exposure. Thirdly, the manual testing required the entire day to constantly measure temperatures and needs to be automated. Consequently the temperature measurement should be conducted with a automatic surface temperature reader as this would provide a larger pool of data and a more accurate pool of data.Plugins of DIVA and Honeybee were discontinued from the course of this research as there were many issues with installation and tool management, Honeybee would have been able to provide more weather variables such as reflectivity from buildings which could have added another level of depth to the algorithm. Still, the GH workflow still achieves all the objectives it was set out to complete, even if it is a simple workflow it is possible to build upon this GH workflow to keep adding more variables and goals to be analysed.

9. Conclusion

What did this paper achieve? With the increasing importance on addressing climate change and the effects of UHI in our urban communities, research on ways to optimise the most beneficial solutions to mitigate this UHI effect become an important research focus. Yet at the point non of the UHI literature reviewed has considered the use of computational tools for optimising the material selection using an evolutionary solver. Throughout the research of this paper, by using evolutionary algorithms, our developed GH workflow was able to produce optimised results for configuring pavement material layouts, which can demonstrate in lower material heat gain in the lowest costs possible. If this research and algorithm are to be expanded upon, more variables and objectives can be applied for a more complex and accurate set of results, with the ability to substitute any amount of geometry possible for this algorithm to be assigned on pavements in other cities all over the world. As often the adoption of more sustainable materials come with cost consideration this tailor made approach uses expensive and albedo improved materials only at areas where they need to be used and leave the second grade materials for areas that are overshadowed anyway. We hope that this paper will open up an interest for computational designer to engage with the topic of UHI and make use of the vast amount data collected in the field for a computational urban heat island design.

References

Avison, D.: 1999, Action Research, *Communications of the ACM*, **42**(1), 94-97.

Cupkova, D. and Promoppatum, P.: 2017, Modulating Thermal Mass Behavior Through Surface Figuration, *ACADIA 2017*, Cambridge, MA.

Ensari, E., Kobas, B. and Sucuoglu, C.: 2017, Computational Decision Support for an Airport Complex Roof Design: A case study of evolutionary optimization for daylight provision and overheating prevention, *CAAD Futures 2017*, Istanbul.

Irger, M.: 2014, *The Effect of Urban Form on Urban Microclimate*, Ph.D. Thesis, Faculty of Built Environment / UNSW / Sydney, Australia.

Mardaljevic, J. and Rylatt, M.: 2003, Irradiation Mapping of Complex Urban Environment: An Image-Based Approach, *Energy and buildings*, **35**, 27-35.

Nichol, J. and Wong, M. S.: 2005, Modeling Urban Environmental Quality in a Tropical City, *Landscape and Urban Planning*, **73**, 49–58.

O'Brian, R.: 2001, "An Overview of the Methodological Approach of Action Research" . Available from Roberto Richardson (Ed.) Theory and Practice of Action Research, João Pessoa, Brazil: Universidade Federal da Paraíba. (English version)<http://www.web.ca/robrien/papers/arfinal.html> (accessed 1. December 2018).

Nguyen Quang, H.: 2008, A Simulation Image Of Urban Heat On Solar Absorption Cofficient by AutoCAD and GAUSS Matrix Blur Method, *CAADRIA 2008*, Chiang Mai, 647-653.

Santamouris, M.: 2013, *Energy and Climate in the Urban Built Environment*, Routledge.

USE OF UAV PHOTOGRAMMETRY TO ESTIMATE THE SOLAR ENERGY POTENTIAL OF RESIDENTIAL BUILDINGS IN SEVERE COLD REGION

YUNSONG HAN[1], YONGJIE PAN[2], TIANYU ZHAO[3], CHUNXING WANG[4] and CHENG SUN[5]
[1,2,3,4,5]*School of Architecture, Harbin Institute of Technology, Harbin 150001, China;Key Laboratory of Science and Technology of Urban and Rural Residential Environment in Cold Region of Ministry of Industry and Information Technology, Harbin 150001, China;*
[1,3,5]*{hanyunsong|zhaotianyu|suncheng}@hit.edu.cn*
[2]*pyj1203006843@hotmail.com* [4]*wang18712775817@gmail.com*

Abstract. In this paper, a method based on UAV photogrammetry is proposed to estimate the solar energy potential of the building surface. This methodology goes from the acquired aerial images captured by the camera mounted on UAV. 3D model of the urban context in study area was extracted from the aerial images using SFM and MVS algorithms, which could be directly applied to the Ladybug plugin as analysis objects. Estimates of solar radiation are expressed by means of data visualization. The results showed that the UAV photogrammetry could demonstrate the geometry and texture of residential buildings precisely and the solar radiation simulation results showed significant spatial and temporal variations in solar radiation on residential buildings.

Keywords. Residential buildings; UAV photogrammetry; 3D reconstruction; Solar energy potential; Severe cold region.

1. Introduction

Estimating the amount of solar radiation available on different building surfaces and assessing their solar potential has an important role in evaluating the feasibility of distributed photovoltaic energy in urban built-up environment, improving urban energy efficiency and optimizing energy structure.

The precise geometric information of existing building is the basis for evaluating the solar radiation on building facades (Theodoridou et al., 2012). Therefore, how to collect geometrical information of existing residential building efficiently to evaluate solar potential in the urban environment are the hot topics in the current research on urban solar utilization potential assessment.

In recent years, the technology of LiDAR (Light Detection and Ranging) has been rapidly developed. Carneiro et al. (2010) calculated and visualized the solar potential of buildings in combination with the DSM model derived from LiDAR data. Zhang et al. (2015) presents an approach for the assessment of solar energy potential at the building scale based on the model modeled by LiDAR point cloud

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 613-622. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

data and QuickBird imagery. Martinez-Rubio et al. (2016) calculated the solar irradiance of the building facade by sampling triangular faces at an interval of 0.5m and analyzing the occlusion between the triangular patches on the basis of 3d model reconstruction using LiDAR data. However, the utilization of LiDAR data in solar utilization potential assessment is based on DSM model, which is generated through point cloud data and limited to its 2.5D features. Meanwhile, the obtaining of LiDAR is high cost and large demand of professional operations, which is difficult to popularize and apply (Zhang et al., 2017).

With the popularization of small format multi-rotor UAV (Unmanned Aerial Vehicle) and the development of low-altitude photogrammetry technology, considerable attention has been paid to building information acquisition based on UAV photogrammetry (Ruzgienė et al., 2015). Image-based building information acquisition technology relies on images acquired by camera, which is much more convenient than the manual measurement and light detection and ranging. Zhang et al. (2017) proposed the method of geometrical information gathering in buildings based on the 3-dimensional (3D) geometrical reconstruction is suitable for the evaluation of existing building applied photovoltaic (BAPV) potential with high feasibility and accuracy. Szabó et al. (2016) assessed the opportunities available to exploit solar radiation on roofs with both LiDAR and photogrammetry techniques, and proved that both approaches can be applied because of the similarity of solar radiation values calculated.

To assess the solar potential on different building surfaces of the existing building in urban areas, the building information acquisition technologies mentioned previously such as original drawing and field measurement are both time consuming. LiDAR is a relatively fresh and fast way for data collection with high accuracy, while the large-scale application of this technique is still far due to the high cost and low operability. In recent years, image reconstruction technology has developed rapidly, and the accuracy of building geometry information obtained from UAV photogrammetry has also been significantly improved. The use of this method to build a three-dimensional model has many advantages, such as fast data processing, high precision of model results, and the ability to process large-scale model data.

The purpose of this paper is to develop a brand-new way to accomplish the annual solar radiation simulation and find potential locations for solar energy production by means of UAV photogrammetry coupled with solar radiation simulation tools, allowing for the assessment of solar potential not only on roofs but also on vertical facades.

2. Methodology

Fig. 1 showed the general workflow of the proposed method in a flowchart. A case study was conducted to demonstrate the applicability of the proposed method.

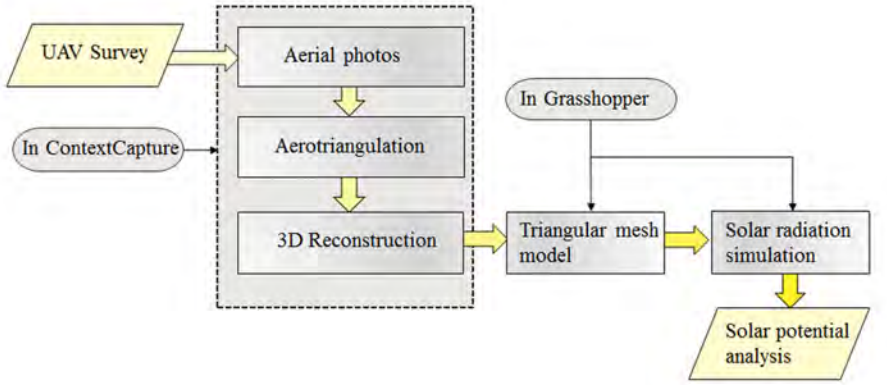


Figure 1. General workflow of the proposed method.

2.1. STUDY AREA

The selected area for the study corresponds to a residential district from Harbin downtown with relatively complex surroundings which covers approximately 8.1 ha (Latitude 45.7N, Longitude 126.6 E) (Fig. 2).



Figure 2. Location and building layout of the study area. a) Location of Harbin, b) Building layout of study area.

2.2. UAV IMAGE ACQUISITION

Prior to the UAV takeoff, route planning was done as shown in Fig. 3. Five flights were complete by the UAV, with the flying height of each flight being about 200 m and a duration of 20 min at the time of acquisition.

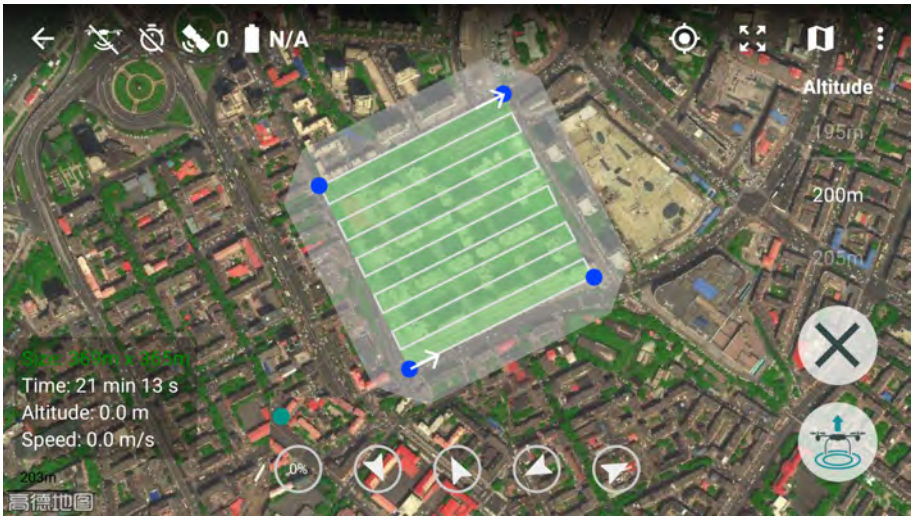


Figure 3. Route planning layout generated by Altizure.

2.3. IMAGE-BASED 3D RECONSTRUCTION

Three-dimensional reconstruction was created from the set of RGB images, using ContextCapture (Bentley, 2017) photogrammetric software, running on a Windows 7, with 64 GB of RAM and a six-core 4.0GHZ processer. The processing workflow of ContextCapture is illustrated in Fig. 4.

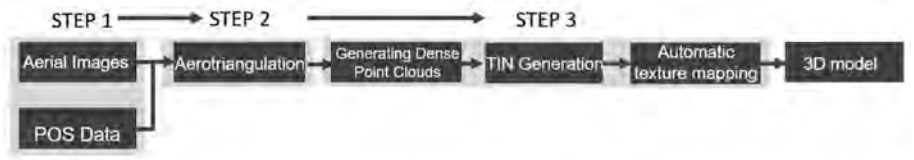


Figure 4. ContextCapture processing workflow.

In addition to the triangular mesh model produced from the total images set, a further 2 sets of point clouds were created for each plot, using subsets of 1/2 and 1/4 images from the full set. In order to ensure that the reduced image set has a complete description of the study area, when deleting the image, it is also necessary to uniformly filter the photos to ensure uniform distribution of the image capturing position. Take 1/4 images set as an example, the new data set was created by filtering one every four sheets.

2.4. SOLAR RADIATION SIMULATION

The solar modeling was run within the Rhino/Grasshopper environment with the Ladybug plugin. The solar radiation analysis implemented in Ladybug was based on the cumulative sky approach and meteorological data extracted from the

EnergyPlus Weather file (.epw) for a specific location.

3. Results and discussion

3.1. THE QUALITY OF IMAGE ACQUISITION

Table 1. Quality Overview.

Dataset	399 of 402 photos calibrated (99%)
Key points	Median of 35216 key points per image
Tie points:	51203 points, with a median of 530 points per photo.
Reprojection error (RMS):	1.06 pixels
Positioning / scaling:	Relative, not georeferenced

Through the collation and analysis of 402 collected pictures, the quality of image acquisition can be preliminarily seen in the Table 1. As can be seen from the above Fig. 5 (a), the captured photos coverd every corner of the sampling area.

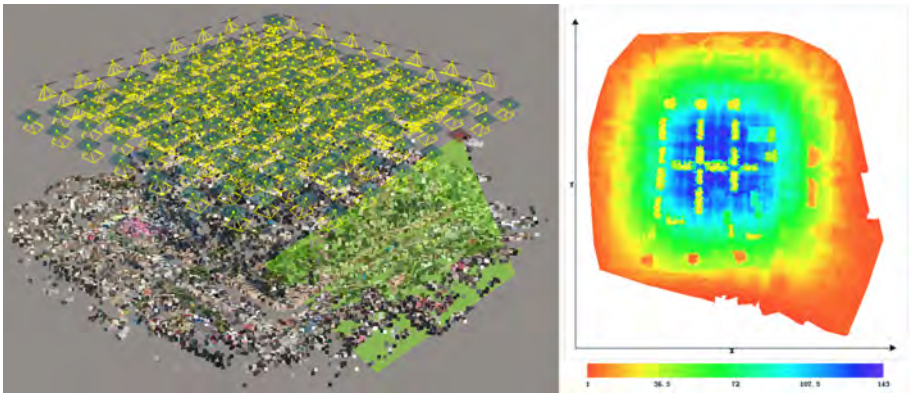


Figure 5. a) Photo positions b)Number of photos seeing the scene.

From the results, some strategies was obtained for subsequent image acquisition. It's not suggested to rotate the camera at a fixed point to take a separate set of images, but fly the UAV to take multiple sets of images at different positions. Image acquisition using route planning is the basis for obtaining high quality base image before reconstruction models. For later reconstruction effect, high overlap is required between images. Therefore, when setting the route planning, the longitudinal and side overlap of the image should be taken into account. 70% overlap is the basic, 80%~85% is of good balance, and more than 90% may be a waste of images and computing power.

3.2. RECONSTRUCTION EFFECT

Processing time and number of triangular meshes produced from each image set are shown in Table 2. Processing time includes aerotriangulation time and reconstruction time. The reconstruction time accounts for most of the processing

time as the dense point cloud generation is time-consuming. The aerotriangulation step only took approximately one tenth of the total processing time required. While it was possible to produce triangular mesh model using the sets of 100 images, the resulting model appeared to poorly representation of real environment on the visual (Fig. 6). Due to insufficient photo overlap rate, the details of some models were not reconstructed well with partial voids on the top. As the number of images increases, the effect of image reconstruction turn to get better. However, when the number of images reached a certain number, the effect of the reconstruction model did not change much, and more photos will only increase the processing time and not greatly improve the reconstruction effect.

Table 2. The processing time and number of triangular meshes for each image set processed.

Image Set	Aerotriangulation Time(min)	Reconstruction Time (min)	Number of triangular meshes
100	3	99	3872833
201	6	195	6104304
402	11	409	7887827



Figure 6. The side views of triangular mesh model processed using 100(a), 201 (b) and 402 (c) images.

To verify the geometric accuracy of the model of the photo reconstruction, 11 sets of data were selected in four different areas (Fig. 7). A comparison was given between actual measurement and data from UAV photogrammetry to acquire the difference and accuracy. Deviation is the difference between the measured data and acquisition of UAV photogrammetry, accuracy is the percentage precision magnitude. According to the Table 3, it could be observed that a mean accuracy of 95.69% >95%.



Figure 7. The measured position and serial number of the actual measurement marking on the reconstructed model.

Table 3. Comparison between actual measurement and UAV photogrammetry.

Number	Acquisition of actual measurement (m)	Acquisition of UAV photogrammetry (m)	Deviation (m)	Accuracy(%)
A1	14.25	13.35	0.90	93.69%
A2	4.63	4.99	0.36	92.14%
A3	1.00	0.87	0.13	86.63%
B1	5.30	5.35	0.05	99.04%
B2	13.95	13.61	0.34	97.54%
B3	3.60	3.47	0.13	96.26%
C1	4.18	4.03	0.15	96.31%
C2	4.18	4.03	0.15	96.31%
D1	6.45	6.47	0.02	99.66%
D2	3.32	3.26	0.06	98.24%
D3	3.16	3.06	0.10	96.76%

3.3. SOLAR UTILIZATION POTENTIAL ANALYSIS

It is evident from the Table 4 that the level of detail of the model has a significant impact on the simulation time. The simulation time is greatly increased as the level of detail of the model increases. As can be seen from the data relationship in the Table 4, the smaller the grid size, the longer the simulation time is consumed, but the amount of time influenced is relatively small.

Table 4. Simulation time consumption of triangular mesh models with different levels of detail.

Model detail level	Number of triangular mesh faces	Grid size（m）	Simulation time consumption(s)
L1	9211	0.5	2.8
		1	2.4
		2	2.3
		4	2.1
L2	82694	0.5	19.7
		1	20.7
		2	20.2
		4	18.6
L3	789005	0.5	306.8
		1	283.5
		2	170.7
		4	170.1
L4	7887827	0.5	Error
		1	Error
		2	Error
		4	610.5

The L3 model is selected as the model for solar radiation simulation and a value of 0.5m was selected as the final grid size of the case study.

Therefore, the intensity of radiation is computed for all surfaces of the study area with the L3 model. Solar radiation in the study area has been simulated for the whole year using Ladybug for Grasshopper, as shown in Fig. 8. The solar radiation rate is computed per square meter (kwh/m2).

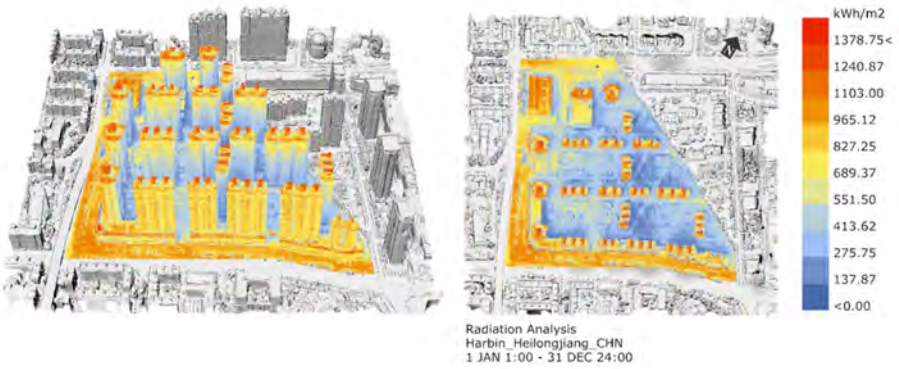


Figure 8. Annual solar radiation of study area.

The solar potential of the building roof in the study area is superior to that of the vertical facades. Facades generally receive solar radiation in the range of 100 ˜ 900 kWh/m2 per year, depending on their orientation and shadowing from the neighboring buildings and trees. The annual radiation level of the south façade is higher than that of the east and west side, and the north is the lowest (Fig. 9).

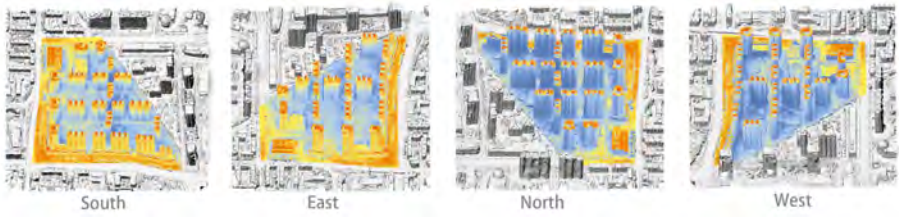


Figure 9. Annual solar radiation differences in different orientations.

The proposed method can also be applied to the analysis of solar radiation over specific periods. To take the study area for example, the seasonal maximum solar radiation reaches 312.76 kWh/m2 in spring, 439.53 kWh/m2 in summer, 406.49 kWh/m2 in autumn and 275.62 kWh/m2 in winter (Fig. 10). In summer, the building surface receives more solar radiation as the higher sun altitudes and more building surfaces that receive direct solar radiation. On the contrary, in winter, areas of receiving direct solar radiation decrease due to smaller altitudes. In addition, the winter sunshine duration is shorter, which also affects the solar radiation on the surface of building.

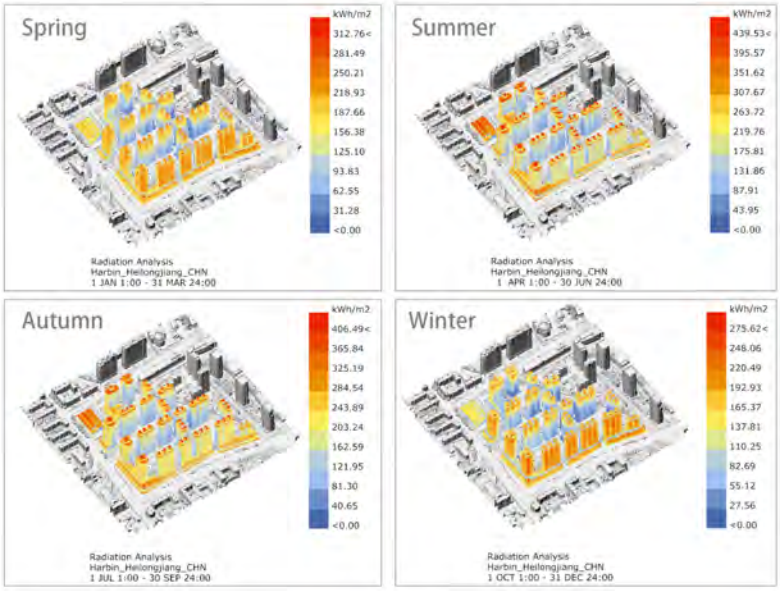


Figure 10. Seasonal radiation simulation results .

The solar utilization potential of the residential buildings is also influenced by the compactness of the urban layout and the surrounding buildings. For high-density residential areas with dense high-rise buildings, the vertical facade area is much larger than the roof area, and its solar potential should not be ignored. Under these circumstances, the influence on solar radiation acquisition mainly comes from the mutual shielding of high-rise buildings within the study area, and the influence is obvious. Surrounding buildings shows less impact.

4. Conclusion

This paper realized rapid and automatic modeling from “aerial images” to “solar radiation simulation model”. The results showed that modeling accuracy based on UAV photogrammetry can reach more than 95%. The visualized annual solar radiation can be used for guided installing different types of solar collectors, making it easy to select the location that is most likely to get the maximum amount, while discovering other locations that also have solar potential but are not visually predictable.

The method presented in this paper can be applied to solar radiation assessment measures by government agencies and energy investors, and the results can be used in energy saving to raise awareness of the use of renewable energy. In addition, the proposed method can be easily extended to solar potential assessments of different scales and different building types by images acquired from different environments.

Acknowledgments

The authors would like to acknowledge that this paper was financially supported by the National Natural Science Foundation of China (Grant No. 51708149), and the China Postdoctoral Science Foundation (Grant No. 2017M621276).Project funded by Heilongjiang Postdoctoral Science Foundation (Grant No. LBH-Z17076) and the Fundamental Research Funds for the Central Universities (Grant No. HIT.NSRIF.201838).

References

Carneiro, C., Morello, E., Desthieux, G. and Golay, F.: 2010, Urban environment quality indicators: application to solar radiation and morphological analysis on built area, *Proceedings of the 3rd WSEAS international conference on Visualization, imaging and simulation*.

Martínez-Rubio, A., Sanz-Adan, F., Santamaría-Peña, J. and Martínez, A.: 2016, Evaluating solar irradiance over facades in high building cities, based on LiDAR technology, *Applied energy*, **183**, 133-147.

Ruzgienė, B., Berteška, T., Gečyte, S., Jakubauskienė, E. and Aksamitauskas, V. Č: 2015, The surface modelling based on UAV Photogrammetry and qualitative estimation, *Measurement*, **73**, 619-627.

Szabó, S., Enyedi, P., Horváth, M., Kovács, Z., Burai, P., Csoknyai, T. and Szabó, G.: 2016, Automated registration of potential locations for solar energy production with Light Detection And Ranging (LiDAR) and small format photogrammetry, *Journal Of Cleaner Production*, **112**, 3820-3829.

Theodoridou, I., Karteris, M., Mallinis, G., Papadopoulos, A. M. and Hegger, M.: 2012, Assessment of retrofitting measures and solar systems' potential in urban areas using Geographical Information Systems: Application to a Mediterranean city, *Renewable and sustainable energy reviews*, **16(8)**, 6239-6261.

Zhang, X., Lv, Y., Tian, J. and Pan, Y.: 2015, An integrative approach for solar energy potential estimation through 3D modeling of buildings and trees, *Canadian Journal of Remote Sensing*, **41(2)**, 126-134.

Zhang, W., Zhang, Y., Li, Z., Zheng, Z., Zhang, R. and Chen, J.: 2017, A rapid evaluation method of existing building applied photovoltaic (BAPV) potential, *Energy and Buildings*, **135**, 39-49.

QUANTIFYING VISUAL ENVIRONMENT BY SEMANTIC SEGMENTATION USING DEEP LEARNING

A Prototype for Sky View Factor

RUI CAO[1], TOMOHIRO FUKUDA[2] and NOBUYOSHI YABUKI[3]
[1,2,3]*Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University*
[1]*caorui11022@gmail.com* [2,3]*{fukuda|yabuki}@see.eng.osaka-u.ac.jp*

Abstract. Sky view factor (SVF) is the ratio of radiation received by a planar surface from the sky to that received from the entire hemispheric radiating environment, in the past 20 years, it was more applied to urban-climatic areas such as urban air temperature analysis. With the urbanization and the development of cities, SVF has been paid more and more attention on as the important parameter in urban construction and city planning area because of increasing building coverage ratio to promote urban forms and help creating a more comfortable and sustainable urban residential building environment to citizens. Therefore, efficient, low cost, high precision, easy to operate, rapid building-wide SVF estimation method is necessary. In the field of image processing, semantic segmentation based on deep learning have attracted considerable research attention. This study presents a new method to estimate the SVF of residential environment by constructing a deep learning network for segmenting the sky areas from 360-degree camera images. As the result of this research, an easy-to-operate estimation system for SVF based on high efficiency sky label mask images database was developed.

Keywords. Visual environment; Sky view factor; Semantic segmentation; Deep learning; Landscape simulation.

1. Introduction

The 21st century has witnessed tremendous changes in architectural design, city planning, rapid urbanization process, and urban space environment management. There are still several issues that are urgently needed to be solved such as complicated spatial structure, large spatial density, and chaotic spatial order. Visual urban environmental management has become an inevitable approach to solve such issues. Thus, sky view factor (SVF) has been receiving great attention as an important parameter of a visual environment that can help to promote urban forms and create a more comfortable and sustainable urban residential building environment for the citizens (Ha et al., 2016). For example, in Japan, since 2003,

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 623-632. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

any new building to be erected must be designed and built in line with the legal items relating to SVF as stated in the Building Standards Act (Watanabe et al., 2017). Therefore, an efficient, low cost, high precision, easy to operate, and rapid building-wide SVF estimation method is necessary.

SVF is the ratio of radiation received by a planar surface from the sky to that received by the entire hemispheric radiating environment (Johnson et al., 1984). In the past 20 years, SVF was widely employed in erecting residential buildings in the urban-climatic areas as shown in Figure 1. A linear relationship at a local scale between SVF and urban heat island had been found (Unger J., 2004). After that, SVF started to be an important parameter in solar radiation modeling (Corripio et al., 2003). With SVF at the center, many kinds of research have been carried out such as urban air temperature analysis based on SVF (Svensson M., 2014). In summary, SVF is mostly used for modeling analysis at the macro level in an urban-climatic area.

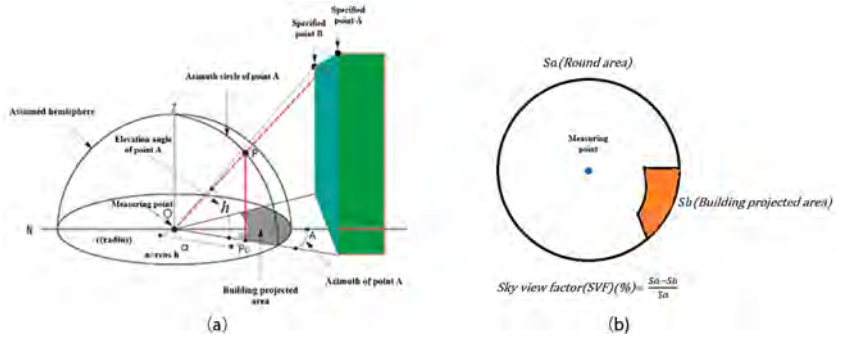


Figure 1. (a) Application of SVF in architectural design. (b) Definition of sky view factor.

Several methods have been proposed to estimate a building-wide SVF.

One of the conventional estimation techniques that have been put into practical use in estimating a building-wide SVF is by analyzing fisheye images taken in specific viewpoints (hereinafter called “practical estimation technique”); it means that the sky areas in the photographs would be masked after taking photographs in an eligible measuring point to estimate the SVF using an image processing software. This method is easy to understand and operate; it gives an intuitive SVF estimation result with high precision. However, when using this method, a worker needs to make a masking of the sky areas manually. Therefore, it takes a lot of preprocessing time and high labor costs in actual production and construction.

Honma et al. (2009) proposed a new algorithm to estimate the SVF by calculating the solid angles of urban landscapes based on computational geometry. On the basis of this algorithm, several engineering measurement design software programs can be used to estimate the SVF from 2.5D building models, which can extrude from building footprints with additional height information. This method of estimating the SVF is very accurate; thus, it is widely used in current architectural designs. However, it requires detailed CAD (Computer Aided Design) drawings and parameters; in addition, the prices of these software or

services from the software provider are usually very expensive. Therefore, it is not easy to implement and to generalize.

In contrast, several automatic methods of estimating SVF have been reported.

A sky region detection system based on OpenCV has been employed to scan down each column of the image to obtain different boundaries by constantly adjusting the gradient threshold. The optimal boundary is obtained by calculating the energy functions of all the boundaries and finally performing optimization on the estimated result of SVF (Shen et al., 2013). However, in this system, the sky area is not recognized when it is directly above the picture. On the other hand, when the picture starts from the first line and there are many areas where the gray value is larger than the sky, it is easy to misrecognize it because it is not clear what the sky is.

Furthermore, in the field of image processing, semantic segmentation describes the process of associating each pixel of an image with a class label. In recent years, image semantic segmentation systems based on deep learning with a focus on autonomous driving, industrial inspection, classification of terrain visible in satellite imagery, and medical imaging analysis have attracted considerable research attention (Long et al., 2015). The systems can also be used in other areas such as SVF estimation.

Lukasczyk et al. (2018) developed a convolutional neural network to estimate the SVF that depends on the analysis of landscape images obtained using Google street view (GSV). However, this system cannot accurately detect and segment gray windows and white walls. It incorrectly identifies dark clouds as obstacles. In other words, the accuracy of the system is not high.

In the past, researchers mainly used GSV and GIS (geometric information system) to collect and create 180° images as a database to estimate SVF. With the development of camera technology in recent times, fisheye camera and panoramic technology are gradually maturing, and the 180° fisheye image is widely being used in the research relating to SVF. However, the dataset based on high precision pixel-level label masked fisheye images is not very many.

This study presents a new SVF estimation method developed by constructing and training a deep learning network for semantic segmentation of sky pixels in landscape images.This research led to the development of an automatic SVF estimation system that has similar estimation accuracy as the solution proposed in previous researches. Herein, we provide a default model of the system and there are no detailed preprocessing and parameters to adjust; therefore, it can be easily generalized. Furthermore, considering the difference in architectural style between various countries, the default model (based on Japanese urban architectural style) may not achieve the same accuracy as the model that is proposed in this paper. We also provide a method to enable users to train their own model to achieve the same accuracy in simple steps.

2. Methodology

According to the definition of SVF, in a standard 180° image, the formula for calculating SVF is as follows in Figure 2. At this point, we need to segment the

sky area accurately.

Deep learning is part of a broader family of machine learning algorithms that are based on learning data representations. It creates a more abstract high level representation of attribute categories or features by combining low level features to discover distributed features within data. Semantic segmentation that is essential in image analysis tasks describes the process of associating each pixel of an image with a class label such as road, person, and trees. In recent years, significant progress has been made in the field of deep learning to improve the accuracy of image semantic segmentation. In this research, we will introduce a new system for estimating SVF based on 360° or 180° images by constructing and training a deep learning network.

The proposed system that mainly consists of five steps as shown in Figure 3 is described in the following sections.



$$SVF = \frac{Pixel_{sky}}{Pixel_{Total}} \times \frac{4}{\pi}$$

Figure 2. Formula for calculating SVF.

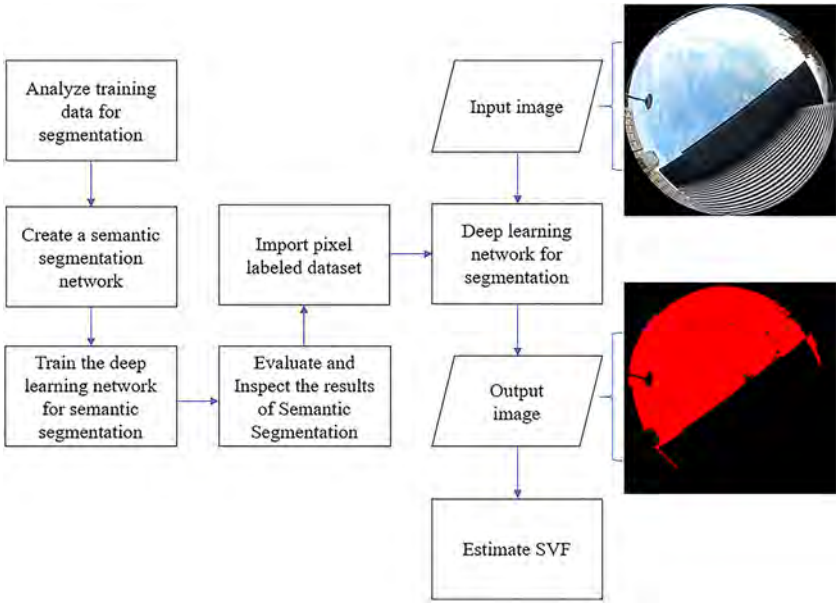


Figure 3. Flowchart of the proposed system.

2.1. IMAGE COLLECTION AND ANALYSES OF THE TRAINING DATA FOR IMAGE SEGMENTATION

To train a semantic segmentation network, a collection of images and the corresponding collection of pixel-labeled images are necessary.

A pixel-labeled image is an image in which every pixel value represents the categorical label of that pixel. In this research, we used a 360° camera to collect and prepare 300 original images including sky and buildings after which, we used a label software to segment the images manually into two parts: sky area and the others to get the label mask images. In addition, the original images were in three channels and the label mask images were 8-bit gray scale in a single channel. At the last step, both 300 original images and their 300 label mask images were prepared.

2.2. CREATION OF A SEMANTIC SEGMENTATION NETWORK

Various frameworks were developed to make deep learning easier to use.

Olaf et al. (2015) designed a deep learning network called U-Net. U-Net is a convolutional neural network that was developed for biomedical image segmentation. The network is based on a fully convolutional network. Its architecture was modified and extended to work with fewer training images and to yield more precise segmentation.

In summary, it is very suitable for segmentation of a single type of pixels, hence the reason we chose it as our base. Considering the characteristics of 180° images, we edited the input and output layers of U-Net to make it suitable for the training data. In addition, we adjusted the parameter of the convolution layer to fit our mask method. An instance is the location information represented by different color regions.

2.3. TRAINING OF DEEP LEARNING NETWORK FOR SEMANTIC SEGMENTATION

This step involves the creation of a database for loading the original images and a label database for loading label mask images. The training can then be started.

2.4. EVALUATION AND INSPECTION OF THE RESULTS OF SEMANTIC SEGMENTATION

As shown in Figure 4, during the training process, after 30 epochs, the accuracy and current loss of our model appeared to be smooth. We noticed that at the 19th epoch, abnormal fluctuations occurred in the accuracy curve; we filtered the training pictures that caused the fluctuations and continued the training. The accuracy curve started to converge at a high level. In contrast, the average loss curve started to converge at a low level.

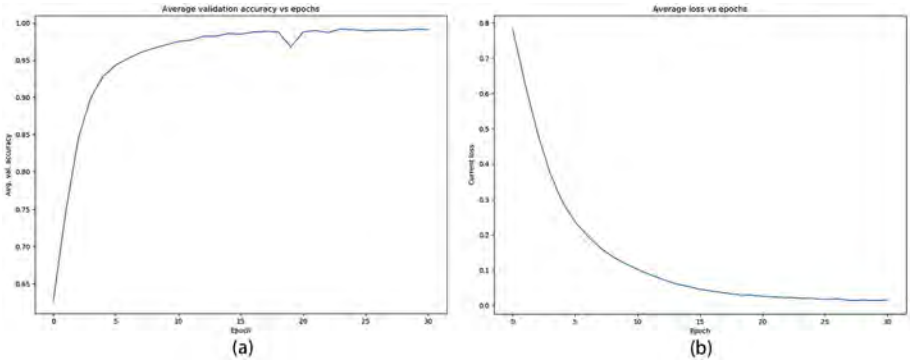


Figure 4. (a)Average validation accuracy vs epochs. (b)Average loss vs epochs.

2.5. IMPORTING PIXEL-LABELED DATASET INTO SEMANTIC SEGMENTATION NETWORK

In this step, after training 300 pairs of images for SVF, a pixel-labeled dataset for semantic segmentation network was created and saved in a text file. This file contains the result of the training we performed and the class-weight used for segmenting the sky area of the images.

At this point, our network construction and training are complete and we can use the model to segment the images for SVF estimation.

3. Verification Experiment

Although our system has a self-evaluation function as shown in Figure 5 that puts its accuracy at 99.37% as discussed in Chapter 2, we still want to evaluate its actual performance in segmenting the sky area from a fisheye photograph.

```
class0 = 0.991018
class1 = 0.996547
Average precision =  0.9937520491312676
Average recall =  0.9937059614393446
Average F1 score =  0.9936989790733245
Average mean IoU score =  0.9859709851085127
Average run time =  0.13674623436397976
```

Figure 5. Self-evaluation function of our system.

To verify the actual performance of our estimation system for SVF as discussed in Chapter 2, experiments were performed as follows.

First, we recorded landscape images including sky and buildings and uploaded them to the server. Then, the server started processing the segments of the transferred images into the sky area part and other parts with the estimation result of SVF. Here are some details about the experiment:

Date: 29th November, 1st December, 3rd December, 2018

Weather: Clear sky weather, sunny and cloudy

Location: Osaka University, Suita campus

Camera equipment: RICOH THETA V

Photograph parameter: 1920p

Amount of photographs: 100

Vertical distance of lens:1.6 m from the ground

In this case, we took 100 fisheye photographs as the original images and the output images generated by the proposed method to explain. In addition, considering the difference in sky color distribution under different weather conditions, these 100 fisheye photograph contains 3 types of sky: clear weather sky, sunny sky and cloudy sky. The verification experiment is as follows:

1. We created correct images for SVF by processing the original images. We used Photoshop to mask every pixel belonging to the sky area part and then painted them into green color; the other area was painted into black color. At last, we calculated the ratio of pixels belonging to the green region; it signifies the accurate SVF.
2. We calculated the ratio of pixels belonging to the red region in the images that were outputted by the proposed method; it means the estimation result of SVF by the proposed method.
3. Finally, we combined the two images into one as shown in Figure 6.

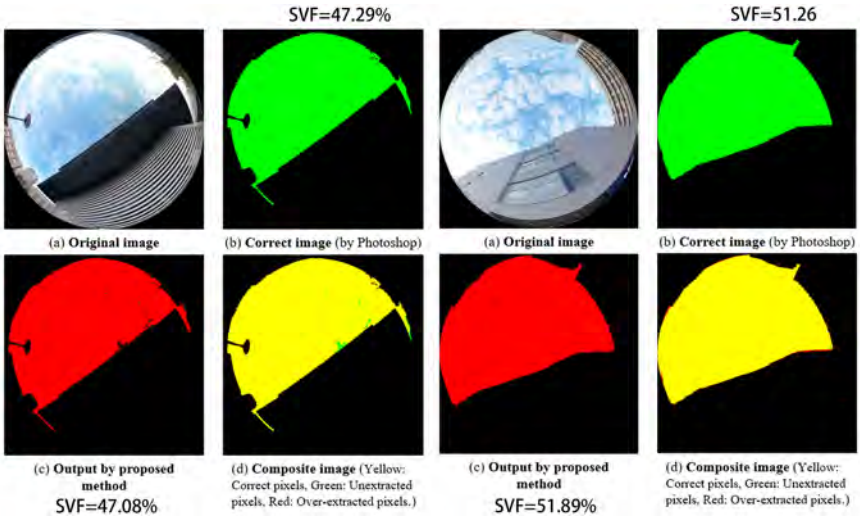


Figure 6. Comparison between correct image and the output image generated using the proposed method.

The region where the green color of an ideal image output overlaps with the red color of the segmented image (correct region) is yellow. In the composite images, the definition of different color regions is shown in Table 1.

Table 1. Definition of each color in the composite image in Figure 6.

	Definition
Yellow	Accurate extracted pixel.
Black	Accurate unextracted pixel.
Red	Over-extracted pixel.
Green	Unextracted area pixel

To calculate the number of pixels in each color region separately, we used Y to represent the number of pixels in the yellow region, B for black, R for red, G for green, and X for the total pixels in the images.

We then calculated the rate of pixels of each part in the combined image to perform verification analysis. Table 2 explains the formulas used in the calculations. According to Table 2, the average accuracy and inaccuracy rates of the 100 images are shown in Table 3.

In this verification experiment, the accuracy rate of the proposed system is about 98.9%, and we can also see the unextracted inaccuracy rate is at a very low level. Furthermore, we can also see that whether it is clear weather, sunny or cloudy, our system performed well in segmenting the sky area from the images. From the composite images, it is obvious that the inaccuracy rate is mainly from the over- extracted area; we believe it is because the training data needed more style containing various architectural shapes to increase the accuracy of the system in determining the boundaries of buildings and sky.

Table 2. The calculation formula for accuracy and inaccuracy rates.

	Calculation formula
Extracted accuracy rate [%]	$\frac{Y}{X} \times 100$
Unextracted accuracy rate [%]	$\frac{B}{X} \times 100$
Accuracy rate [%]	$\left(\frac{Y}{X} + \frac{B}{X}\right) \times 100$
Over extracted rate [%]	$\frac{R}{X} \times 100$
Unextracted inaccuracy rate [%]	$\frac{G}{X} \times 100$
Inaccuracy rate [%]	$\left(\frac{R}{X} + \frac{G}{X}\right) \times 100$

Table 3. Accuracy and inaccuracy rates of the SVF estimation (N=100).

Extracted accuracy rate [%]	45.7
Unextracted accuracy rate [%]	53.2
Accuracy rate [%]	98.9
Over-extracted rate [%]	0.9
Unextracted inaccuracy rate [%]	0.2
Inaccuracy rate [%]	1.1

We also estimated the SVF of these 100 images by using their correct images and output by the proposed method for comparative analysis as shown in Table 4. We believe that the accuracy of this system has a good reference value in practical applications.

Table 4. Comparative anylysis of SVF estimation result.

SVF [%]	1	2	3	...	99	100	Mean [%]	Standard deviation [%]
Correct images	47.29	67.27	14.47	...	40.82	26.12	44.67	15.82
Output by the proposed method	47.08	67.17	14.92	...	41.44	26.95	45.08	15.75
Difference	0.21	0.07	0.15	...	0.58	0.83	0.41	0.37

4. Conclusion and Future Work

In this research, we developed a visual environmental estimation system for SVF using image segmentation. The proposed system is based on deep learning. After constructing and training the proposed network for sky area segmentation, we inputted an image into the system to automatically segment them into sky area and the other area parts using the result of the SVF estimation; the accuracy rate of the system is about 99%, whereas the inaccuracy rate is about 1%. A simple fisheye web camera can also be used to take photographs remotely and transfer the data to a server that can automatically estimate the SVF about the scene in real time.

Because of the use of deep learning techniques, the versatility of this system is very high. It is not only limited to SVF estimation but also can be applied in estimating other environmental elements such as green view index by performing systematic deep learning training for it.

However, there are still some problems to be addressed. They are as follows:

- In a building environment with a large number of reflective materials, some details such as glass material on the outer wall of the building could be incorrectly detected as the sky. Thus, there is a need to expand our database with more architectural images in the future.
- Until this moment, the system can only estimate the SVF from a still image; if the data source is from a video, it will not work well.
- In the beginning, we wanted to develop a real-time system to estimate the SVF remotely and transer the segmented images using a statistical numerical display to a mobile client. However, there is a delay of about tens of seconds

between data transfer and segmentation. This is because, until this moment, we have not completed the server setup so as to implement both data transfer and segmentation at the same time. Hence, our future work would be to make data transfer and segmentation happen simultaneously.

Acknowledgments

This research has been partly supported by JSPS KAKENHI Grant Number JP16K00707.

References

Corripio, J.G.: 2003, Vectorial algebra algorithms for calculating terrain parameters from DEMs and solar radiation modelling in mountainous terrain, *International Journal of Geographical Information Science*, **17(1)**, 1-23.

Ha, J., Lee, S. and Par, C.: 2016, Temporal Effects of Environmental Characteristics on Urban Air Temperature: The Influence of the Sky View Factor, *Sustainability*, **8**, 895.

Honma, Y., Kurita, O. and suzuki, A.: 2009, An Analysis of Urban Landscapes with Respect to Solid Angles based on Computational Geometry Algorithms, *Journal of the City Planning Institute of Japan*, **74 Issue 643**, 2035-2042.

Johnson, R.T., Bjorklan, R. and Krotee, M.L.: 1984, The Effects of Cooperative, Competitive and Individualistic Student Interaction Patterns on the Achievement and Attitudes of Students Learning the Golf Skill of Putting, *Research Quarterly for Exercise and Sport*, **55 issue 2**, 129-134.

Long, J., Shelhamer, E. and Darrell, T.: 2015, Fully Convolutional Networks for Semantic Segmentation, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition 2015*.

Lukasczyk, J., Maciejewski, R. and Garth, C.: 2015, Understanding hotspots: A topological visual analytics approach, *Proceedings of the 23rd SIGSPATIAL International Conference on Advances in Geographic Information Systems*, 36.

Ronneberger, O., Fischer, P. and Brox, T.: 2015, U-net: Convolutional networks for biomedical image segmentation, *International Conference on Medical image computing and computer-assisted intervention*, Springer, Cham., 234-241.

Shen, Y. and Wang, Q.: 2013, Sky Region Detection in a Single Image for Autonomous Ground Robot Navigation, *International Journal of Advanced Robotic Systems*, **10** , 362.

Svensson, M.: 2004, Sky View Factor Analysis-implications for Urban Air Temperature Differences, *Meteorological Applications*, **11 Issue 3**, 201-211.

Unger, J.: 2004, Intra-urban relationship between surface geometry and urban heat island: review and new approach., *Climate research*, **27(3)**, 253-264.

Watanabe, H., Honma, Y., Honma, K. and Imai, K.: 2009, Effects of Height Restriction and Relaxation by Sky Factor Focusing on Digestion Floor Area Ratio and Building Height, *Journal of the City Planning Institute of Japan*, **52 Issue 3**, 682-688.

THE FUTURE OF ENVIRONMENTAL PERFORMANCE ARCHITECTURAL DESIGN BASED ON HUMAN-COMPUTER INTERACTION

Prediction Generation Based on Physical Wind Tunnel and Neural Network Algorithms

YUQIONG LIN[1], JIAWEI YAO[2], CHENYU HUANG[3] and PHILIP F. YUAN[4]
[1,2,3,4]*Tongji University*
[1,2,3,4]*{1630237|jiawei.yao|1830234|philipyuan007}@tongji.edu.cn*

Abstract. As the medium of the environment, a building's environment performance-based generative design cannot be separated from intelligent data processing. Sustainable building design should seek an optimized form of environmental performance through a complete set of intelligent induction, autonomous analysis and feedback systems. This paper analyzed the trends in architectural design development in the era of algorithms and data and the status quo of building generative design based on environmental performance, as well as highlighting the importance of physical experiments. Furthermore, a design method for self-generating environmental performance of urban high-rise buildings by applying artificial intelligence neural network algorithms to a customized physical wind tunnel is proposed, which mainly includes a morphology parameter control and environmental data acquisition system, code translation of environmental evaluation rules and architecture of a neural network algorithm model. The design-oriented intelligent prediction can be generated directly from the target environmental requirements to the architectural forms.

Keywords. Physical wind tunnel; neural network algorithms; dynamic model; environmental performance; building morphology self-generation.

1. Introduction

Today, the Internet and computer hardware have greatly enhanced information storage and social computing power, which endows the concept of "man-machine collaboration" proposed by Joseph Licklider (1960) in the mid-last century and the "Ulm philosophy", which advocates scientific and technological rationality as the design idea and principle (Lindinger, 1991), with prophetic meaning. As a measure of civilization, the interaction between human and machine, physical reality and cyberspace has gradually become the core of digital culture (Yuan and

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 633-642. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Chai, 2018). With this digital technology, design media have been transformed while design thinking has changed. From the birth and application of CAD equipment and CAAD technology in the 1950s to the integration of design and performance-based design in the conceptual design stage by Andrew Marshall in the early 21st century, performance simulation has been integrated into architectural form design (Morris, 2013).

Digital technology can assist architects to take form, function, climate, environment, energy and other elements as initial parameters of performance-based design, carry out sustainable design, and determine the design parameters of buildings by means of environmental performance simulation. According to Stefan Behling's and Inaki Abalos' triangular illustrations of the historical hierarchy of passive systems, active systems and architectural forms, the principle of form-first design is becoming a trend (Kubler, 1962 & Behling and Schindler, 2000). Machine learning, as an important area of artificial intelligence, can automatically improve from training data and learn from experience (Leach, 2015). Thus, the purpose of this paper is to explore the possibility of applying a neural network algorithm in machine learning, instead of human beings, to discover such internal rules and ultimately assist architects to make morphology design decisions conducive to the urban wind environment without knowing the specific mathematical logic.

2. Return of physical simulation tools

2.1. BOTTLENECK OF ENVIRONMENTAL PERFORMANCE GENERATION DESIGN

With the continuous development of performance-based simulation tools, the "blind test" passive design method has been gradually replaced by logical generation design. Fine decision-making at the initial stage of design will greatly affect future energy consumption. Therefore, environmental performance simulation should be a "leading and preparation" generation tool in addition to being employed as an analysis tool. However, at present, a large number of performance simulation tools require architects to constantly seek a balance between the level of model detail and simulation consumption time, which makes it very difficult to bring timely feedback to the early stage of design (Kaijima and et al., 2013). This "post-evaluation" paradigm finds it increasingly difficult to meet architects' pursuit of environmental performance-based design. This method is based on numerical simulation and is essentially an iterative heredity. It simulates the first generation of randomly generated form and then selects the optimal solution for next generation simulation. The calculation speed relies heavily on the performance of the computer's central processing unit.

2.2. REAL-TIME PERCEPTIBILITY OF PHYSICAL WIND TUNNEL

With the development of digital technology such as sensing, human-computer interaction, three-dimensional recognition and augmented reality, many pioneer researchers have begun to focus on physical experiments and develop various customized experimental platforms to explore the reality of physical phenomena.

Environmental performance such as daylight and air flow analysis can be carried out on the basis of physical simulation. Digital feedback of physical simulation results could be achieved through electronic components, which provides a novel approach for environmental simulation in the early stage of architectural design.

Wind tunnels based on an intelligent interactive platform (Fig. 1) have the advantages of simple operation, controllable cost, stable flow field and measurement accuracy to meet the initial building design requirements. The potential makes wind environment simulation, data measurement and performance feedback possible. On the one hand, smoke visualization and scouring experiments can visually describe wind acceleration, steering, turbulence and other phenomena, which help architects truly observe and perceive the wind environment performance around buildings. On the other hand, the pressure sensors installed on the building facade and the wind speed sensors set on the surrounding ground surface can convert the wind field information into data in real time and transmit it to the computer. Finally, the wind field diagrams can be generated synchronously by parametric design software to assist the design decision-making. This perception and real-time acquisition of environmental data make wind environment simulation shift from post-design verification to prepositive design exploration.

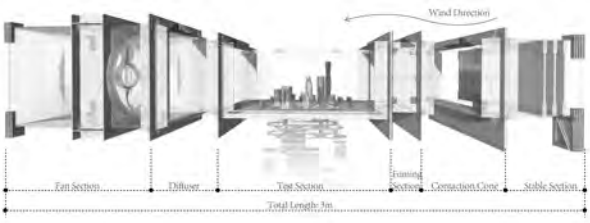


Figure 1. Mini customized physical wind tunnel.

2.3. A LARGE NUMBER OF SAMPLES FROM DYNAMIC MODELS

Although “model” is not a paradigm, it can be defined as just a design technology, but when it becomes a way of thinking, it becomes a “nonrepresentational machine” (Lohr, 2012). The gradual transformation from the structure of the static model is based on expectations of the design process, which are mainly according to code and calculation generation. Therefore, the dynamic model combined with mechanical transmission make up for the defect that the solid model is difficult to update in real time and enable the digital model to produce a large number of materialized body schemes instantaneously in the physical wind tunnel. In the process of continuous change, the environmental data corresponding to each architectural form are collected intelligently, and the data transmission bridge between virtual and reality is built up through the open source platform named Arduino, which integrates software and hardware to realize self-regulation.

In 2017, the building model movement mechanism of rotation, translation and elevation was realized. Based on high-rise building forms that are beneficial

to urban ventilation, such as distortion, concave-convex, hollowing and bottom lift-up, our team has carried out a preliminary study on the self-generating form of high-rise buildings in urban central areas, as shown in Fig. 2. To change the direction and trajectory of the horizontal force of the main building model, the main principle of the mechanical transmission design of the main building model in this study is to use the steering gear as the active part to drive the follower through meshing. The number of actuators in the whole model plays a role in increasing the diversity of motion, helping to produce more abundant building model changes (Fig. 3).



Figure 2. A preliminary study of urban autogenesis in CAADRIA WORKSHOP 2018 Group 7.

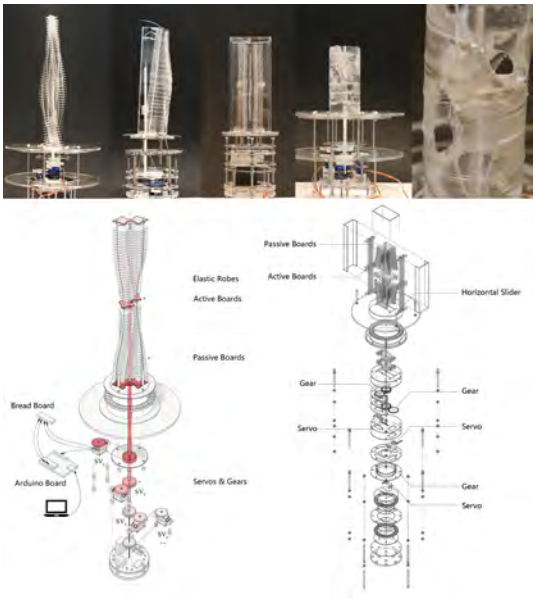


Figure 3. Dynamic model with twisting, concave-convex, hollowing and bottom lift-up (up) & twiseted form model's structural schematic diagram (down).

3. Design-oriented performance-based building generation method

3.1. WIND ENVIRONMENT-BASED MORPHOLOGY DESIGN STRATEGY

This study mainly selects the twisting dynamic model to predict the morphology of the building from the urban wind environment performance to the building unit. At the same time, four categories of the basic shape strategy were divided in the experiment of the twisting form: (1) rectangular plane; (2) cleavage plane; (3) crest angle; and (4) top contraction.

3.2. DESIGN WILL-BASED WIND ENVIRONMENT EVALUATION METHOD

The influence of the building on the surrounding environment is different at a specific site. Therefore, the position of the sensor measuring point in the wind tunnel experiment needs the designer's independent consideration, and the social attributes such as the functional elements and crowd objects around the building and the wind environment are controlled. The degree of importance is judged comprehensively. The effective data generated in the experiment can be evaluated by the deviation values, Ec, of the three standard comfort temperatures commonly used in the wind environment evaluation, the discrete value Ed of the measured wind speed, and the probability Eu of the uncomfortable wind speed value. The weight of the overall environmental performance score E(X)=aEc+bEd+cEu of the scheme X and the weight of the different environmental evaluation indicators, such as the difference of the importance degree of each measurement point and the weight of the environmental data evaluation is a=70%, b=15%, c=15%; for the homogeneity of the main ambient airflow, the evaluation weights are a = 60%, b = 30%, c = 10%.

3.3. NEURAL NETWORK-BASED MORPHOLOGY GENERATION LOGIC

To make full use of the "big data" of the "information ear", what currently needs to be designed is not a novel architectural form but a new information-based working method for architecture (Morfidis and Kostinakis, 2018). The process of environmental performance-driven generative design consists of three elements: performance simulation data, shape change rules, and evaluation criteria. The basic system combined with the neural network on this basis consists of four parts: design strategy, mechanical dynamic system, simulation evaluation system and intelligent prediction system, wherein the parameter logic can be described as the data cycle flow of "geometric parameter group-mechanical parameter group-environmental parameter group".

First, according to the selected twisting strategy, the mechanical system is set to a random model to freely twist the shape, generate a large number of physical schemes, and use the wind speed sensor to measure the speed in the wind tunnel. After that, the corresponding physical and environmental data are recorded through the Arduino platform. Entering the evaluation system, the program will automatically obtain the average wind speed value and the wind speed discrete value of the plurality of sensor measuring points, and the wind evaluation program automatically calculates the environmental performance score according to the designer-defined weight, performs a large amount of sample training, and obtains

the physical and environmental database as Experimental sample data. Then, the neural network learns these sample data, and repeatedly adjusts the algorithm parameters until the verification set has the smallest mean square error and the best performance and ends the sample training. Finally, the algorithm model obtained by the sample training can be directly predicted. The optimal building morphology parameters under the target environmental parameters and the site conditions, that is, the steering gear parameter group that controls the dynamic model, are again transmitted to the mechanical model device through the Arduino platform, which means the final predicted optimized morphology results are presented.

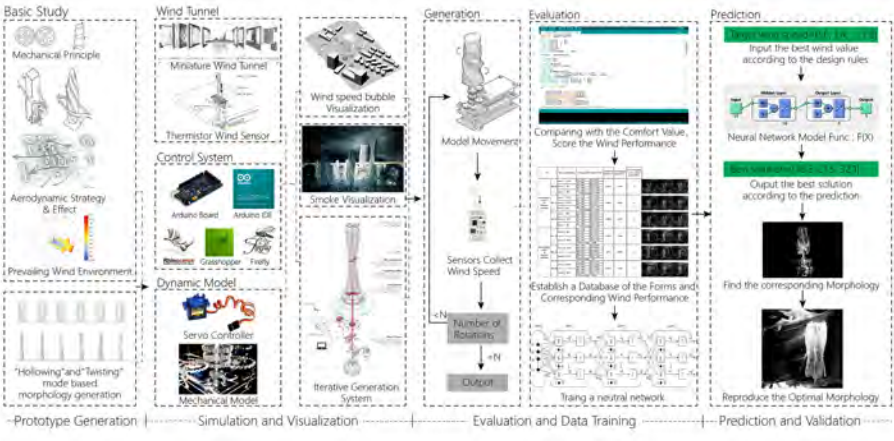


Figure 4. Workflow diagram based on physical wind tunnel and neural network algorithm.

4. Building monomer morphology experiment

To control the performance of the urban wind environment, this study uses the dynamic model of distorted form to carry out wind tunnel experiments under different plane and elevation strategies and takes the mechanical parameters of each physical scheme, while the corresponding environmental data obtained by experiments are the sample data. The architecture of the neural network regression model is implemented, which can independently predict the optimal architectural unit form in a given target wind environment.

4.1. B-P NEURAL NETWORK

An Artificial Neural Network is a complex nonlinear dynamic system that is widely connected by a large number of simple processing units (Maxwell and Pigram, 2012). The network consists of an input layer, an output layer and several hidden layers. The layers are unidirectionally connected by neurons in sequence. It is especially suitable for processing nonlinear data with complex input and output relationships such as wind environment and architectural form, which demonstrates an effective means of summarizing the law in the data. Supervised neural networks are suitable for modeling and controlling

dynamic systems, classifying noise data, and predicting future events. The B-P (back propagation) algorithm is one of the most effective multilayer neural network learning methods. Its main features are signal forward transmission and error backward propagation (Morfidis and Kostinakis, 2018). By continuously adjusting the network weight value, the final output and expectation of the network are made (Maxwell and Piggram, 2012). The output is as close as possible to achieve the purpose of training. It can learn and store a large number of input-output mode mapping relationships without revealing the mathematical equations describing the mapping relationship, and the fault tolerance is good. Therefore, the experiment uses the B-P neural network to experiment with small physical wind tunnels. The multidimensional matrix of the wind environmental evaluation values of each sensor obtained as an input is used as an output of the steering angle matrix of the steering gear.

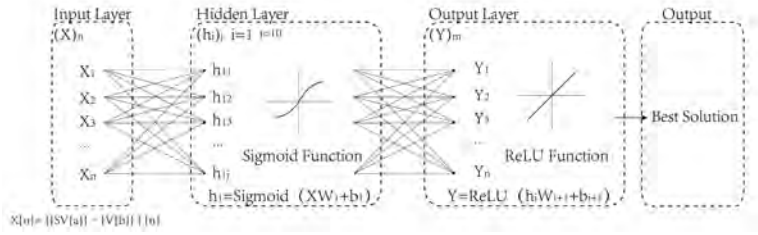


Figure 5. Schematic diagram of double-layer feedforward network with S-shaped hidden neurons and linear output neurons.

The training and learning capabilities of neural networks are based on the ability to automatically adjust grid weights and biases. The training function specifies global algorithms that affect the weight and bias of a given network. The neural network will use the Scaled Conjugate Gradient to train the neural network for the training function. The workflow of the neural network framework is as follows: First, the wind tunnel experimental data are preprocessed and converted into tensor input; second, the structure of the neural network is configured; then, the weights and deviations between the neurons connected to each layer are initialized; after that, the neural network regression model verifies the network effect and adjusts the parameters repeatedly; and finally, the neural network is used for prediction. Among them, the structure of the neural network is a standard network fitted with a supervised double-layer feedforward network as a function, a sigmoid transfer function in the hidden layer, and a linear transfer function in the output layer. The number of hidden neurons is initially set to the number of sensors in this wind tunnel test. If the network training performance is poor, the number of neurons can be adjusted after the training is completed, and the training is performed again until the verification set has the smallest mean square error and the best performance, when sample training is ended. To date, the research framework has completed the neural network model (Figure 5).

4.2. WIND TUNNEL EXPERIMENTAL DATA PREPROCESSING

At present, most artificial intelligence applications rely on a large number of artificial data annotations. The wind environment evaluation algorithm in the wind tunnel experiment performs performance scoring for each architectural form and completes automatic data annotation through the establishment of the database. Therefore, the experiment can use the database of the shape and environmental performance obtained by the wind environment evaluation algorithm as a training sample for the machine learning algorithm.

Since the determination of the twisted morphology is according to the linkage of the active rotating boards, which is the total of a and the multilayer passive rotating plate by the a servo. A building form can be simplified to a steering degree (indicated by SVa). For the morphological parameter set {SV1, SV2, SV3...SVa} (represented by {SV[a]}), when a steering gear is rotated simultaneously to produce an architectural form, the program automatically acquires the building corresponding to the current form. For the surrounding wind environment data, taking b wind speed measurement points as an example, an architectural form corresponds to wind environment data sets {V1, V2, V3...Vb} composed of b wind speed values (represented by {V[b]}). During the wind tunnel experiment, a rudder changes n times, that is, n building forms are generated, and multiple sets of {SV[a]} and {V[b]} can be obtained, and the two arrays correspond respectively, the nth twisting scheme can be recorded as X[n]= {{SV[a]}·{V[b]} } [n]. When the evaluation rule is set to the wind speed average value Vm at the pedestrian height of 1.5 m above the building, which is closest to the set comfort value Vs, the program is processed from {V[b]} to Vm. Then, the deviation calculation of Vm, the comfort value Vs and the screening of the minimum deviation are performed. Therefore, the minimum deviation corresponds to the morphological parameter group {SV[a]}; that is, the steering gear parameter group corresponding to the optimal architectural form is found, and finally the rudder is driven. The machine returns to this parameter group to reproduce the optimal building form.

4.3. RESULTS

The Scaled Conjugate Gradient Algorithm is applied to train the network. The optimal verification performance of the steering angles of the three steering gears is shown in Fig. 6. The mean square error (MSE) is 20.9995, which indicates that the prediction effect of the model on the steering angle of the steering gear is relatively stable. It can be seen that the mean square error of the training set gradually decreases with the number of iterations, and the mean square error of the verification set and the test set begins to decrease several times and then gradually stabilizes. In theory, if the sample is large enough that there are enough verification sets and test sets to test the trained network, the mean square error of the verification set while the test set should be reduced. The results of neural network training show that the neural network can better fit the wind environment parameters and predict the steering angle of the steering gear.

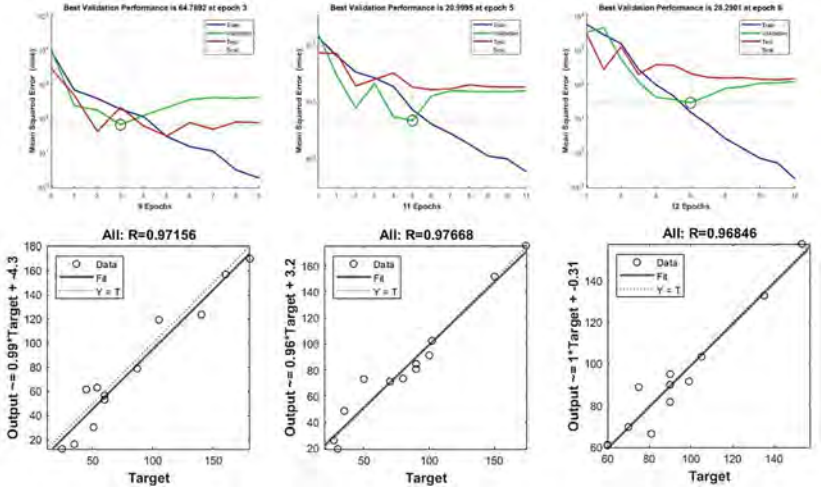


Figure 6. Neural network effect and corresponding regression (left: Servo 1; middle: Servo2; right: Servo3).

4.4. CLASSIFICATION MACHINE LEARNING ALGORITHMS INTEGRATED TO PREDICT DIFFERENT DESIGN STRATEGIES

The value of artificial intelligence in design is not only the solution obtained, but it also creates "uncertainty" to inspire designers to generate new ideas. This experiment uses a small physical wind tunnel, for which the experimental data in the morphology train the shallow neural network regression model to predict the steering gear parameters corresponding to the target wind speed value. The selection of the basic morphology generation strategy of the building also needs to be integrated with the classification machine learning algorithm, which will be able to judge the most likely target wind environment so that the basic form strategy corresponds to the architectural form.

Future work can be based on the neural network principle adopted in this study, based on a larger set of experimental sample data, combined with a high-speed camera to take pictures of wind tunnel smoke visualization experiment results, which increase the characteristics of sample data to more dimensions and makes for more accurate models. Training, in which the obtained experimental photo library can be learned by a deep learning convolutional neural network, is also a component. At the same time, combined with the CFD simulation software, a more comprehensive environmental simulation analysis and evaluation of the predicted building shape can be carried out, and the results are returned to the algorithm model for further parameter adjustment.

5. Conclusions

This paper introduces a design method and process framework based on urban wind environment performance as the entry point and motivation. The physical

experiment platform combining the physical wind tunnel and dynamic model is used to simulate the wind environment performance of a large number of physical schemes. Then, the results are taken as data, while the sample uses a neural network algorithm to self-summarize training rules between the morphology and the corresponding surrounding wind environment. Finally, the algorithm model obtained can predict the optimal morphology solution under the wind environment of the input target. On the other hand, the physical wind tunnel avoids the problems of time-consuming and complicated operation of the digital simulation method; that is, the CFD simulation software. The introduction of the dynamic model provides the possibility of acquiring a large number of entity model models in a short time, while the combination of neural network algorithms maximizes the wind tunnel test data used to realize the design-oriented reverse solution from the target environment performance to the scheme shape. Thus, at the beginning of the design, the optimal control of the urban wind environment-based morphology can be realized. The economic and resource losses brought about by the adjustment phase have further subverted the "post-evaluation" model of the performance of contemporary architectural design environments.

Acknowledgement

This research is funded by Science and Technology Commission of Shanghai Municipality (Grant No.16dz1206502) and China Postdoctoral Science Foundation Funded Project (Grant No.2018M632162).

References

Behling, S. and Schindler, S.: 2000, *Solar power: the evolution of sustainable architecture*, Prestel Munich, London.

Kaijima, s., Bouffanais, R., Willcox, K. and Naidu, S.: 2013, Computational Fluid Dynamics for Architectural Design, *Architectural Design*, **83 (2)**, 118-123.

Kubler, G.: 1962, *The shape of time: Remarks on the history of things*, Yale University Press.

Leach, N.: 2015, The Informational City, *Next Generation Building*, **2 (1)**.

Licklider, J. C.: 1960, Man-computer symbiosis, *IRE transactions on human factors in electronics*, **1**, 4-11.

Lin, Y. Q., Yao, J. W., Zheng, J. Y. and Yuan, P. F.: 2018, Environmental-Performance Morphology Generation: Combining Physical Wind Tunnel and Dynamic Building Model, *Advances in Architectural Geometry 2018*, Gothenburg, 174-194.

Lin, Y. Q., Zheng, J. Y., Yao, J. W. and Yuan, P. F.: 2018, Research On Physical Wind Tunnel And Dynamic Model Based Building Morphology Generation Method, *CAADRIA 2018*, Beijing, 165-174.

Lindinger, H.: 1991, *Ulm design: the morality of objects: Hochschule für Gestaltung Ulm*, MIT Press.

Lohr, G.: 2012, The age of big data, *New York Times*, **11**.

Maxwell, I. and Pigram, D.: 2012, *Algorithmic Typology: Towards an Operational Model. Scripting the Futures*, Tongji University Press, Shanghai.

Morfidis, K. and Kostinakis, K.: 2018, Approaches to the rapid seismic damage prediction of r/c buildings using artificial neural networks, *Engineering Structures*, **165**, 120-141.

Morris, I.: 2013, *The measure of civilization: how social development decides the fate of nations*, Princeton University Press.

Yuan, P. F. and Chai, H.: 2018, Digital twin on visualization and materialization of DigitalFUTURE Shanghai 2017, *Time + Architecture*, **1**, 17-23.

FACE-TO-FACE WITH PEOPLE IN SPACES

A method to identify face-to-face interactions using an indoor positioning system.

TIARA DOBBS
[1] *UNSW, Sydney, Australia*
[1] *Tiara.dobbs@unsw.edu.au*

Abstract. Recent developments in indoor positioning technology means gathering personal interaction data is possible however, the process of analysing this data to determine where and when interactions occur indoors is not yet standardised.This paper proposes a method to gather and examine indoor positioning data to infer face-to-face interactions indoors. The case study looks specifically at indoor office environment however the principles shown can be applied to other indoor spaces. This paper explores a high-level technological methodology that gathers indoor positioning data from users. A formula is used to calculate if, when and where interactions occur over a floor-plan, as well as visualising these interactions to highlight high and low interaction areas. The system considers the proximity between the individuals, the angle between their forward physical orientation, and any obstructions that might divide individuals from each other. The information presented in this paper can be used as a theoretical baseline to inform future post-occupancy evaluation methods. Additionally, this paper demonstrates the merit of using indoor positioning systems to test the effectiveness of design principles in encouraging face-to-face interactions of the users.

Keywords. Post-occupancy evaluations; Face-to-face interac-tions; Indoor positioning system; Data driven design.

1. Introduction

1.1. THE IMPORTANCE OF DATA-DRIVEN DESIGN

Data directs design flow and aids in decision making. Deutsch (2015) comments that "data allows [you] to back up [your] decisions, create confidence...[it] serves as a learning tool and improves intuition". Without data, designers are left to make assumptions about the influence of design on how people collaborate (Sailer et al. 2009). Decisions made using assumptions leaves room for criticism as to the validity of that decision.

Open-plan workspaces, unassigned seating arrangements, and collective amenities are thought to encourage more impromptu collaboration between workers (Peponis, et al., 2007). The assumption is, that if one can make

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 643-652. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

interactions more convenient, more interactions will occur. Critics argue, however, that there is little evidence to support these assumptions and that open plan offices may lead to sound and climate control issues ultimately affecting productivity (Hoendervanger, 2015; Telsyte, 2015). Without data-gathering methods, it is hard to determine which argument is stronger.

1.2. THE ASSUMED EFFECT OF SPATIAL DESIGN ON COLLABORATION

Many organisations invest heavily in finding ways to differentiate themselves through ideas, concepts, and strategies (Allen, 2016). One way of doing this is through encouraging more face-to-face interactions amongst workers. Studies show that face-to-face interactions are reported to increase the collective intelligence of an organisation (Pentland, 2014) reduce sick leave (Berg's, 2003) and improve physical and psychological recovery when compared with organisations where employees communicated heavily via digital modes (Lacovelli & Johnson's, 2012). Other studies show that higher levels of face-to-face interaction builds worker rapport and organisational commitment (Alnaqbi, 2011) and training and learning effectiveness (Rashid, et al., 2015). Therefore, a method to test where and when interactions occur within an indoor space would be highly useful because it offers feedback as to how effective design strategies are in encouraging face-to-face interactions.

1.3. DEFINING FACE-TO-FACE INTERACTIONS

There is not an accepted baseline definition for what constitutes a face-to-face interaction; therefore, definitions need to be made concerning what a face-to-face interaction is. A theory developed by Hall (1969) categorized four types of interaction: intimate, personal, social-consulted and public, requiring at least one of the human sensorial experiences. Hall describes a face-to-face interaction as a engagement of at least two people communicating using at least one of the five human senses without the aid of any mediating technology.

Hall (1969)'s research indicates that face-to-face interactions require at least two people to be 'near enough' to each other so that their senses can receive information. The heading and direction of a person can also be extracted from path data alone, however knowing that individuals may walk backwards while engaging in a interaction makes it important to know the real time heading of a individual. In this scenario, path data would register the two individuals away from one another, therefore failing to recognise a interaction at that moment in time.

1.4. FAILURE TO MEASURE INTERACTION INDOORS

Technology advancements have allowed the development of indoor positioning systems (IPS) to track users indoors (Khoury & Kamat, 2008). The global positioning system has allowed users to be located accurately outdoors (Martz, 2008). GPS, however, is inappropriate for indoor use due to satellite attenuation from physical objects like walls and furniture. Past research has used human movement data with sound data to infer face-to-face interactions (Williams, et

al., 2015). This practice assumes that face-to-face interactions require some form of verbal dialogue, however, this is not always the case. The methods did not consider the forward physical orientation of a person to affect the probability of an interaction. This is because face-to-face interactions can happen on multi-sensory levels as explored by Hall (1969). Field-of-view (FOV) is important in this case because of the subtle social cues that can be transferred between cultures (Pan, 2000) and between those that have speech and hearing and blindness (Legal Aid New South Wales, 2014) and those that are immobile or paralysed (Wu, 2016). These social cues are generally transferred when the involved members are facing each other and do not necessarily require sight for their meaning to be understood (Legal Aid New South Wales, 2014). For example, a person may hear better when their FOV is oriented towards the sound, or something can be felt or smelled, can be done so easier when the person is facing what is being smelled, or what is to be touched. Therefore, currently, a method of identifying face-to-face interactions using FOV is needed.

1.5. RESEARCH QUESTION

How can one infer face-to-face interactions within an office environment using an indoor positioning system?

1.6. RESEARCH OBJECTIVES

1. Design and deploy an indoor positioning system to gather movement data from participants from a real-world field experiment.
2. Use positioning data to determine field of view and positioning of participants in field experiment.
3. Create an algorithm to determine the number and location of potential face-to-face interactions.

2. METHODOLOGY

2.1. THE DESIGN & DEPLOYMENT OF THE INDOOR POSITIONING SYSTEM

Advancements in technology have lead to the development of indoor positioning systems. Systematic reviews of indoor tracking technologies were conducted (Martz, 2012; Scheerens, 2012; Rizal 2016) which found Bluetooth Low Energy (BLE) technology to be the most desirable for workplaces. As a result, an indoor positioning system was designed to recognise the signals emanating from the BLE device and translate that into tracking data.

2.2. DETERMINING FIELD OF VIEW FROM POSITIONING DATA

For this research project, the FOV was defined as a person's facing forward direction and extends to a 60-degree range on either side of the person's peripherals (Karlene K. Ball, et al 1988).To identify a individuals FOV based on the data of the indoor positioning system, an experiment was conducted. A participant wore a beacon and stood at the centre point of a room. Four receiver base stations were placed at one meter increments away from the centre location of the participant.

The participant, whilst wearing a beacon, rotated 15 degrees every ten seconds. The hypothesis was made that when a person is facing directly towards the base station, the signal strength will be at its highest point and the beacon was at its closest point. When the participant faces away from the base-station, naturally the participant's body would block the signals and therefore the signals received would drop to a lower value. The results from the experiment were plotted using a polar graph.

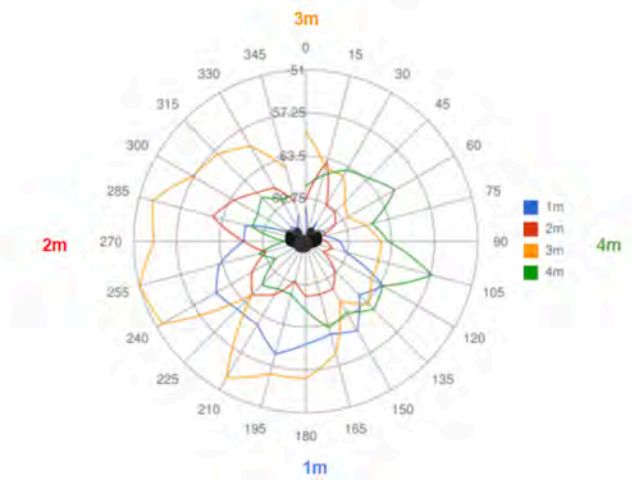


Figure 1. It was concluded that the highest density of signal clustering happened at the center of the participant's FOV as hypothesised. Therefore, the FOV can be identified as being where the highest received density of signal occurs.

2.3. DEPLOYMENT OF THE INDOOR POSITIONING SYSTEM

The indoor positioning system was deployed within the BVN & ARUP offices Sydney. The field data was gathered from 80 participants over a period of 30 days.



Figure 2. Beacon (left image) and reciever base station (right image).

2.4. FIELD EXPERIMENT RESULTS

A number of errors presented themselves during the collection of data. Methods employed to identify path data from the field exercise failed to accommodate several environmental factors. Space and geometry interference confused the normal database collection methods as the signals appeared to reverberate off hard surfaces like walls and floors unexpectedly. Earlier experiments showed these errors, however, the issue was negligible. In the larger field experiment, the reverberation multiplied when a greater number of users all had reverberation errors in their signal transmission. Sample size and participation was also an issue some participants did not engage in the experiment diligently. Constant movement was also an issue as it was difficult to detect the difference between when a participant stops, starts and if they are changing their direction or movements frequently. This is because the participant was detected only when in range of the receiver. The receiver assumes the participant is constantly moving, so any erratic behavior of users might be wrongly recorded. Only when the user was stationary was it possible to gather legible positioning data however this was hardly the case in the experiment.

In an attempt to overcome some of the issues found during the field exercise, a machine-learning algorithm was trialed. While the machine-learning algorithm was being developed, a simulation data set was created so the face-to-face interaction identification method could be developed simultaneously. It was intended that later the field experiment data would replace the simulated data set.

2.5. CREATING SIMULATION DATA

Simulation data was created as a placeholder to continue developing method of identifying face-to-face interactions while the field data path information was

unavailable, due to the challenges of using the field data,. The Simulation data was made using a Markov chain. Weighted values were placed at specific adjacencies to create simulated probable human path data.

As one state progresses to another, the shortest path algorithm tested to see which direction around an obstruction was the shortest. This method assumes that everyone takes the shortest path to avoid obstructions. Obstacles in the floor plan were given a boundary. A virtual mesh was placed over the floor plan using a Voronoi grasshopper algorithm. Each line of the mesh represents a potential path a person might take as they move through space. A boundary was drawn around the obstacles such as tables and walls which culled the lines that it intersected.

Once a path is determined, speed and duration of stay of an individual can be determined by cutting all individuals path data into even number of segments. These segments represent moments in time and can be compared with other individual.

2.6. FACE-TO-FACE INTERACTION PROBABILITY FORMULA EXPLAINED

Face-to-face interactions are associated with a target probability value. This target value represents the minimum requirement for a probability to reach before it will be plotted over a floor plan. The calculation process uses the FOV of the individuals and their proximity to one another, and considers their physical surroundings. These factors work together, each with an associated weighting. For this research project, assumptions were made about the weighted values an environmental stimulation played on the probability a face-to-face interaction occurred. For this research project, the factors were given an equal weighting in the overall probability value are 1 because the actual weighting values are unknown.

Combining the relationship that FOV, distance, and consideration to physical context work together to formulate a face-to-face interaction probability value, the relationship can be summarized in the following equation:

$$B = \left((a \cdot W^a) + \left(d \cdot W^d\right) + (m \cdot W^m)\right) \cdot G \tag{1}$$

$$B = \left[\frac{B}{B^{\max}}\right] \tag{2}$$

a = angle between the focal point of a person compared with another person's focal point.

Wˆa = the weighted probability value associated with angle.

d = distance between two particpants.

Wˆd = the weight to modify probability based on distance.

m = represents the value added to the probability if the scenario is within a meeting room.

Wˆm= the weight to modify the influence this term has on the result.

G = (absolute obstructions e.g. walls) the weighted probability value associated with if there is an obstruction for a clear line of sight).

All probable values are collected; however, the interaction is not plotted unless it achieves a minimum value. Figure 3 is an example of how probable

interactions can be visualised through a gradient map using the simulation data.This relationship can be used to calculate the probability of face-to-faces, where and when they occur. When a probable interaction reaches a value equal to or above the target value, a point is placed at the midpoint of the alleged interaction position between the two individuals. Over time, these points form a gradience of probable interaction locations which can be visualised with a colored map.



Figure 3. Gradient map of the various levels of identified face-to-face interactions scattered over a floorplan. The probability percentage value represents a colour given to cell representing a 'state'. The higher the number of interactions in relation to the total number of interactions, the higher the percentage.

2.7. USING MACHINE LEARNING TO IDENTIFY PATH DATA

Due to the overwhelming errors in the test data from the field experiment, a machine-learning algorithm was trialed to assist in identifying the path of a user during the field experiment. The algorithm uses an unsupervised clustering technique modeled off similar work by Wagstaff & Cardie (2000) and Marroquin & Girosi (1993). Clusters represent the signals received from a nearby beacon by the base station and represent an individual located in space. A K-means clustering technique receives a maximum number of clusters it is to identify (representing individuals within space) and then compares this to a dataset. Each point within that dataset is tested against every other data point in the set. Target groups of data points are partitioned to form groups of data. These groups represent the greatest probability that a cluster exists within that areas. When a grouping of signals exist and that grouping is not yet larger than the known number of individuals wearing beacons, then a mean position within the identified groupings is placed. This mean position represents the best estimate of a location known by the system. The position represents a 'state' of a person as they were located in time. These states can be joined to form paths. These paths can be optimised using the same "shortest path" grasshopper algorithm used during the development of the simulation data

set.

2.8. GATHERING TRAINING DATA TO SUPPORT MACHINE LEARNING

Training data was gathered to assist the machine learning algorithm to determine the parameters that constitute a K-means 'cluster' parameterized by a target signal distance range. To gather this data, a second field experiment was conducted using the same apparatus as the first experiment. This second experiment, however, used participants that were given a set path to be walked in a specified amount of time. QR codes were placed in a matrix of specified locations over a floor plan. The participants scanned these QR codes using their smartphone and transmitted this information to an online database. these QR scans indicated where and when the participant arrived at the 'state'. As readings from their BLE beacons were recorded, changes in the readings of signal strength and density of readings were recorded for each user.

The training data was used to find the machine-learning target test distances. This target distance formed the test parameter between two points in a dataset. When a distance between two points dropped below the target distance, the two points were identified as being part of a cluster. The figure below shows four participants standing in the same 'state' at different times. It was possible to reject data that fell outside of these parameters as it indicated when an individual left the location where the samples were taken from.

The user's 'state' registered as being present at the center where that cluster was identified, when data gathered from a user reached the target parameters, based on the training data fed to it. Due to time restrictions, only a small data set could be gathered to train the algorithm, therefore it is difficult to evaluate the reasonability of the parameters set by the training data at identifying when a subject entered a location or when they exited. The algorithm itself also suffers from various limitations. The algorithm does not deal with when a person might leave the experimental state completely and therefore does not adjust the number of target clusters it is to identify. The efficiency of the algorithm also needed to be evaluated, as each point was tested individually with every other data point. Although the location of the person can be inferred, the FOV of the person is still not yet clear and requires further work. The clustering of the signals received indicates a person's location, however, from which way they are facing, the data may be confused with obstructions in signals received, making it impossible to determine to head (head?). If a previous location is known, the heading of a person can be inferred, as long as the assumption is that the person is always facing forward, however, this is unrealistic to the human experience and therefore less than ideal.

3. Evaluation

3.1. EVALUATION OF RESEARCH OBJECTIVES

The research presented in this thesis has achieved many aspects of the aims and objectives. The deployment of an indoor positioning system within an office environment was successful to the extent that the theoretical work was

completed; however, the practical implementation was not. Technical issues such as the interferences with data received made it difficult to gather accurate path information to test the face-to-face interaction algorithm. Despite these difficulties, the simulation data was successfully created to act in place of the field data so that the face-to-face interaction algorithm could be developed and successfully tested. Further work is required in refining the mechanism to decipher the indoor positioning systems field data, as it is not yet clear whether the machine learning algorithm is a suitable solution to its problem.

Although the field exercise for gathering face-to-face interactions was less than successful, earlier experimentation in the research process proved that successfully determining the FOV and positioning of participants in the field experiment with a single user is possible. One possible solution for improving the success of the field exercise is to use a different method of indoor positioning than what is used in this research - for example, a WIFI-based indoor positioning system which has the ability to measure individuals' movements through objects and is less affected by object attenuation and reverberation. This research does not aim to test the quality and success of the research from its users as this will be explored in further work.

3.2. RESEARCH SIGNIFICANCE

This research paper lays down theoretical foundations for using an indoor positioning system to infer face-to-face interactions. These interactions can be identified and visualised to offer designers quantitative information about the number and location of interactions within a space, therefore, informing the designer about the validity of a design choice in encouraging interactions within a space. The research presented in this thesis revolved around simulated data. Further work is required to replace the simulated data with real-world data. This will allow designers to gain a realistic understanding of how individuals move within the workplace.

Acknowledgements

I would like to thank BVN and ARUP for allowing field studies to be conducted in their facilities. I would like to also thank Matthias Hank Haeusler for his continuous support in pursuing this body of work and his suggestions for continuous improvement and future work. I would like to thank my team members Alex Lee and Annisa Rizal for assisting in the building of the indoor positioning system. I would like to thank my family and especially my sister Ellesha Dobbs for supporting me through the creation of this research project. Finally, I would like to thank my supervisor Ben Doherty for going on and beyond his call of duty, I would not have done this without your amazing advice and support.

References

Allen, D.J.: 2016, "Drive productivity through innovation" . Available from <http://ipacutredtape.org.au/opinion-pieces/475/> (accessed 16th November 2016).

Alnaqbi, W.: 2011, The relationship between human resource practices and employee retention in public organisations, *Edith Cowan University Research Online*, **1**, 9-15.

Ball, K.K., Beard, B.L., Roenker, D.L., Miller, R.L. and Griggs, D.S.: 1988, Age and visual search: expanding the useful field of view, *OSA Publishing*, **5**, 2210-2219.

Berg, P., Kallerberg, A.L. and Appelbaum, E.: 2003, Balancing Work and Family: The Role of High□Commitment Environments, *Industrial relations: A Journal of industry and society*, **1**, 12-15.

Deutsch, R.: 2015, Data□Driven Design and Construction: 25 Strategies for Capturing, Analyzing, and Applying Building Data, *Wiley online Library*, **1**, 0-20.

E.T. Hall (ed.): 1966, *The hidden dimensions*, Doubleday.

Hoendervanger, J.G., Noble, V.L., Mobach, M. and Van Yperen, N.W.: 2015, Tool development for measuring and optimizing workplace utilization in activity-based work environments, *In 14th EuroFM Research Symposium*, Glasgow, 1-10.

Khoury, H.M. and Kamat, V.R.: 2008, Evaluation of position tracking technologies for user localization in indoor construction environments, *Automation in construction*, **18**, 444-457.

Liu, Z. and Zhang, Z.: 2011, Face geometry and appearance modeling, *Cambridge University Press*, **1**, 1-10.

Marroquin, J.L. and Girosi, F.: 2000, Some Extensions of the K-means Algorithm for Image segmentation and pattern Classification, *Massachusetts Institute of technology artificial intelligence Laboratory*, **1**, 1-2.

Mautz, R.: 2012, *Indoor positioning technologies*, Master's Thesis, ETH Zurich, Department of Civil, Environmental and Geomatic Engineering, Institute of Geodesy and Photogrammetry.

Pan, Y.: 2000, *Politness in chinese face-to-face interactions*, Ablex Publishing corporation.

Pentland, A.: 2014, Social physics : how good ideas spread-the lessons from a new science, *The Penguin Press*, **1**, 1-10.

Rashid, H., Piper, D.J.W., Martin, C. and Polyak, L.: 2015, Reply to the comment on "The timing of the Gold Cove glacial event:A comment on "Signature of the Gold Cove event (10.20 ka) in theLabrador Sea"by Pearce, C.", *Elsevier*, **1**, 1-10.

Rizal, A., Doherty, B. and Haeslier, M.H.: 2016, ENABELING LOW COST HUMAN PRESENCE TRACKING, *Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA*, **1**, 45-54.

Sailer, K., Budgen, A., Londsdale, N.a.t.h.a.n., Turner, A.l.a.s.d.a.i.r. and Penn, A.l.a.n.: 2009, Comparative Studies of Offices Pre and Post, *Proceedings of the 7th International Space Syntax Symposium*, **1**, 1-10.

Subedi, S. and Pyun, J.Y.: 2017, Practical Fingerprinting Localization for Indoor Positioning System by Using Beacons, *Journal of Sensors*, **1**, 1-16.

Wagstaff, K.: 2000, Clustering with Instance-Level Constraints, *Proceedings of the Seventeenth International Conference on Machine Learning*, **1**, 1103-1110.

Wineman, J.D., Kabo, F.W. and Davis, G.F.: 2009, Spatial and Social Networks in Organizational Innovation, *Environment and behavior*, **1**, 1-10.

Wu, S.: 2016, "How blind people interact with visual content on social networking sites" . Available from Open Source Repository<https://research.fb.com/how-blind-people-interact-with-visual-content-on-social-networking-sites/> (accessed 5th April 2016).

DISCOVERABLE DESKS

Finding location and orientation in a mobile workplace

SOPHIE SCOTT[1], BEN DOHERTY[2], ALESSANDRA FABBRI[3], NICOLE GARDNER[4] and M. HANK HAEUSLER[5]
[1,3,4]*UNSW*
[1,3,4]*{sophie.scott|a.fabbri|n.gardner}@unsw.edu.au*
[2]*BVN*
[2]*Ben_Doherty@bvn.com.au*
[5]*UNSW & CAFA Visual Innovation Institute Beijing*
[5]*m.haeusler@unsw.edu.au*

Abstract. The drive towards increasing productivity through collaborative ways of working has spurred a parallel trend in flexible and adaptable workplace environments. Mobile desks are one feasible solution to this but workplaces that adopt mobile desks risk creating spatial inefficiencies. These range from overcrowding or underutilization, to potential compliance issues in terms of fire egress requirements and health and safety regulations. While there is a need to understand mobile desking configurations there are currently no well-established ways to track the location and orientation of mobile desks within workplaces. Consequently, this paper describes a research project that adopts an action research methodology as an iterative and participatory framework to investigate and develop a unique method for capturing the location and orientation of freely moveable desks in an open workplace environment. This uses an ensemble of Bluetooth location beacons and computer vision techniques to provide a finer resolution than either method alone can currently provide. The demonstration of this ensemble method is the main contribution of this work. This paper demonstrates that combining these methods can enhance the advantages of each; computer vision gives higher resolution and beacons reduce the scope of the image search task

Keywords. Indoor Positioning Systems; Office Space Planning; Location Data; Computer vision; activity-based working.

1. Introduction

The drive towards increasing productivity through collaborative ways of working has spurred a parallel trend for flexible and adaptable workplace environments. In an Australian context the workplace organisational strategy known as activity-based working (ABW) has gained increasing popularity (Candido et al. 2018). In an ABW environment, users are encouraged to change locations within

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 653-662. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

a workplace as often as required to suit the tasks at hand, and to be near those users they need to collaborate with. While a key principle of ABW is 'desk-ownership removal' (ibid), that is achieved by allowing users to choose from a variety of spaces to support differents tasks, a variation on this approach allows users to reconfigure their own workspaces by being able to freely move their mobile desks. Gaming and hardware development company Valve Corporation were one of the first organisations to adopt mobile desking. For Valve (2012), mobile desks aligned with their corporate strategy that sought to reject hierarchical organisation as a way to promote collaboration and innovation. Consequently, mobile desks served as both a flexible workplace arrangement and "...a symbolic reminder that you should always be considering where you could move yourself to be more valuable" (p.6). As such, a mobile desk is a desk with wheels that can be moved to any location across a workplace, at any time by the user. Yet, while mobile desks can make workplaces easily reconfigurable, the corollary to this approach are issues of find-ability, spatial inefficiency, and regulatory compliance.

When desk arrangements are 'unknowable', this risks configurations that are overcrowded, underutilized, or that create potential compliance issues in terms of fire egress requirements and health and safety regulations. Presently, there are no established ways to 'know' the location of mobile desks. Consequently, this paper outlines a research project that explores the discoverability of mobile desks through a case study of the BVN workplace in Sydney. This investigates and develops a unique method for capturing the location and orientation of freely moveable desks in an open workplace environment, through an ensemble of Bluetooth location beacon technology and computer vision (CV) techniques to provide a finer resolution than either method alone can currently provide. By locating and orienting desks in space, such data can be used to locate individual users, analyse compliance against minimum space standards and fire egress regulations, and critically, provide empirical insight into how people choose to occupy their workplace. In short, this establishes a method for generating workplace environment intelligence. The following sections of this paper outline the overarching research methodology, the technical methods explored for developing mobile desk discoverability and the outcomes and significance of the research.

2. Methodology

This research adopts the overarching methodology of action research. Originating in the social sciences, action research is people-centred, oriented towards participation, and engages iterative cycles of planning, acting, observing and reflecting (Baldwin 2012; Foth, 2006; O'Brien, 1998). This research project adopts the case study of a section of the BVN Sydney studio to explore the development of methods to locate the position and orientation of mobile desks. Finding a specific mobile desk in a large workplace can be challenging. However, given the exposed and highly figured soffit in the case study office, CV techniques were deemed a suitable approach to explore. While CVing could potentially work alone as a method, it is limited by being computationally intensive and thus slow and prone to error. Similarly, blue tooth Estimate location beacons alone could

be used locate a desk within a tolerance of 1.5m (Estimote, 2018) however this is insufficient information to accurately guage spatial compliance. For these reasons, this research explores the combination of Bluetooth Estimate location beacons and CV techniques to provide a finer resolution than either method alone can achieve.

3. Background Research

In a contemporary context, mobile digital technologies, such as the smartphone, enable a user's location to be readily and accurately tracked. Significantly, the accuracy of a user's location in geographic space is determined through a combination of technical features within the device, such as the accelerometer, magnetic field, and orientation sensors, and communication with a global positioning system (GPS) (Gubi et al, 2006). Yet, while the technologies that support a smart device's locatability are reasonably accurate for outdoor environments, they are less reliable in terms of indoor environments, such as workplaces. As such, this research is situated within a larger field of indoor positioning systems (IPS) research that address the challenges of tracking and locating moveable objects indoors (Gu et al. 2009; Zafari et al. 2018).

As Rizal et al. (2016) note in their recent research on IPS for human presence tracking, in relation to GPS for outdoor environments there has been "no comparably ubiquitous positioning system that can be used to make device-driven position tracking that is specifically adapted to indoor environments" (p.46). Indeed IPS developed for indoor environments to date has explored a variety technologies such as Bluetooth, Infrared, wireless local area network, radio frequency identification (RFID) and Ultra-wideband to name a few. In their review of locating methods, Kim and Han (2018) reflect that commonly proposed solutions for indoor location tracking "have problems, such as multi-path, obstacle (shadow area), and signal loss" (2018, p.3). Consequently, cost effectiveness emerges as a key challenge across numerous IPS research projects to date with several studies exploring opportunities to leverage already-deployed technologies such as smart mobile devices and low-cost trackers (Dardari et al. 2015; Rizal et al. 2016; Zhao et al. 2008).

As an alternative to location tracking that relies on user's carrying smart devices, numerous IPS approaches have explored wearable location tracking devices. The Active Badge System requires end-users to "wear tags that broadcast their location to a centralised service through a network of sensors" (Dardari et al. 2015). Similarly, Rizal et al's (2016) human presence tracking project relied on users carrying a Bluetooth enabled device. This project documents a number of problems that faced when employing mobile beacons and sensors for location tracking including users carrying multiple detectable devices, the interference of human bodies within the line of sight between emitter to receiver, the accuracy of data, and processing issues associated with real-time data collection (Rizal et al. 2016). Collectively, these IPS studies point to a range of challenges that are faced when devising methods to track objects in indoor environments. Equally, they highlight the ways IPS engage multiple technologies in often bespoke configurations informed by issues of cost, context, tracking subjects, and data use intentions. The case example in this paper differs from these existing

research examples primarily as the object to be tracked is a desk rather than a human and the data to be collected intends to inform, not only locatability, but also spatial regulation analysis. Given the case example necessitates a high degree of data veracity, this research explores the novel combination of low-cost Bluetooth location beacons in conjunction with CV techniques to achieve higher spatial tracking accuracy.

4. Case Study

This research explores the development of a system to identify the location and orientation of mobile desks in a workplace. Given the exposed and highly figured soffit in the case study office, this research employs a combination of CV techniques in conjunction with Estimote location beacons. This aims to create a data collection method that mobile desk users could easily follow by using their own mobile device to capture high resolution images of the workplace ceiling as a reference point to locate mobile desks. The end user would place the phone in a known position on their own desk to record its position. The Estimote location beacons complement this approach by narrowing down the search area of the workplace ceiling to within a tolerance of approximately 1.5m (Figure 1), while CV techniques then work to achieve enhanced position and orientation accuracy. Consequently, the research commenced with iterative cycles of developing and testing a method for capturing a high resolution ceiling image, developing and testing a method to merge the captured images and testing data interoperability with the OpenCV algorithms. Secondly, the location beacons were tested to establish a satisficing quantity and position for beacons in the case study workplace.

The method taken distinguishes between location-the coordinates of the origin point of the desk, relative to a local coordinate system-and orientation-rotation around the z axis of the local coordinate system, in degrees. The term ‘position’ in this case denotes the combination of location and rotation.

To locate a desk in space we assume that the mobile device is in a known position on the desk’s top. If we assume that the desk’s wheels are on the floor then, to remove additional degrees of freedom, we need to know either the position and rotation from a single datum, or two positions. In this cas study we have chosen to work with the former.

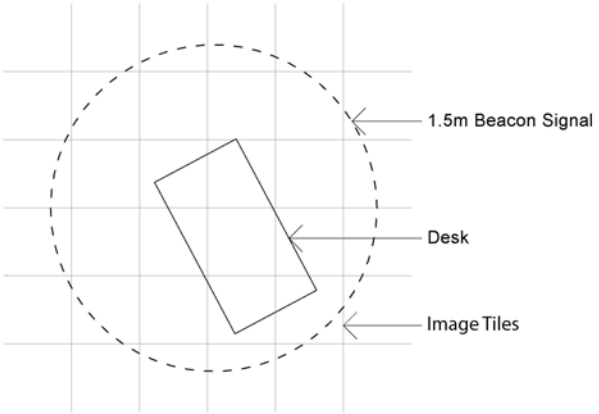


Figure 1. The desk could be located anywhere within the 1.5m tolerance of the beacon signal. Tiles explained further in Figure 3. .

4.1. CREATING A CEILING IMAGE

To test methods for capturing a high resolution ceiling image, the research began by exploring CV algorithms such as homography that can effectively position similar objects and patterns in pairs of images. This process however is computationally intensive meaning the growth of time complexity can be above linear with respect to pixel count. Equally, the case study ceiling presented a further challenge as it comprises many similar elements, meaning the possibility for false-positive matches returned was high. Using the beacons provided a coarse location, and helped narrowed the scope of the image search task. The ceiling was photographed, merged into a single image, then tiled into a collection of images that can be retrieved beacon's coordinates. These images were processed with a CV algorithm that identifies the centre of the sample image, and ultimately returns the centre coordinate and rotation angle (Figure 2).

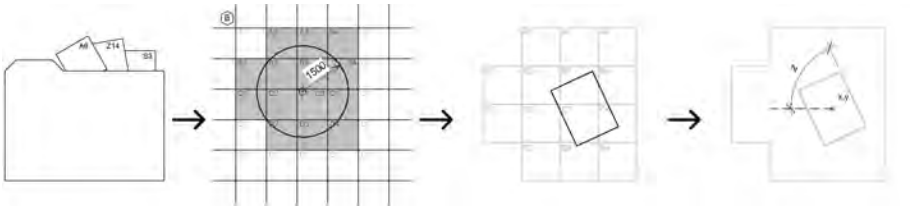


Figure 2. From left to right: Collection of ceiling image tiles. Beacon location to 1.5m radius. Location of the image within those specific ceiling tiles. Accurate data location of the image.

While the ideal image for searching would be perfectly parallel this was impossible and therefore multiple photos were taken of the ceiling from desk height. These were combined into one overall ceiling image (super image). To create and stitch together an image from many photographs necessitates

significant overlap, and only the central portion of the image is useful due to image distortion created at the perimeter by the larger angle deviation from the normal. Experimentation here showed that care and precision was needed to ensure complete coverage. However the most successful technique was to take a very large number images without any prior planning.

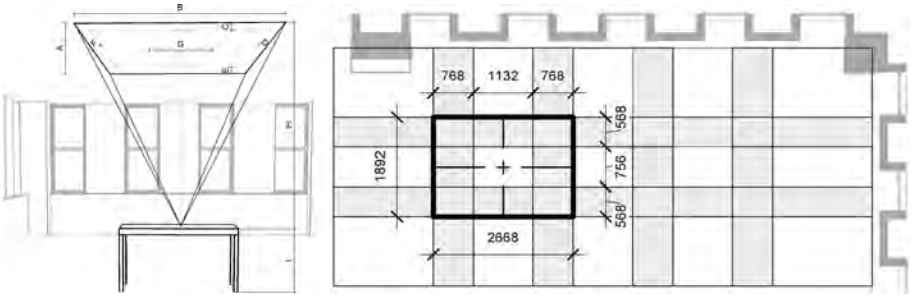


Figure 3. How the camera will locate an image on the ceiling, and the dimensions required (LHS) and 40% overlaps between images shown in grey (RHS).



Figure 4. Resulting photo merge.

4.2. COMPUTER VISION

With a method established to create a super-image (comprised of 4 individual ceiling images merged together) (Figure 4), the next part of the process sought to find an efficient and successful way to locate a search-image (the fifth photo within the bounds of the first four and rotated) within the super-image.

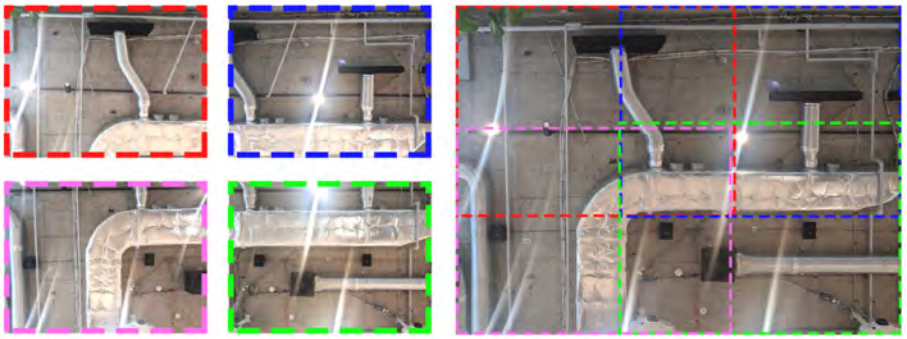


Figure 5. Four photos that were taken and merged together to create the super-image. A separate photo taken within the super-image in a different orientation and scale, described as the Search Image.

A number of image capture techniques were tested from the OpenCV library (OpenCV Dev Team, 2014). Template Matching failed because the search-image wasn't an exact subset of the super-image. OnlyMatches showed more promise, as did RANSAC, Shi-Tomasi and ORB, but were unable to complete the task of positioning. Ultimately SIFT and FLANN provided reliable positioning results.

Bobade and Jagtap (2014), explain the SIFT (Scale-Invariant Feature Transform) algorithm as "The first stage of computation searches over all scales and image locations". It also has an orientation assignment where each key point is assigned one or more orientations based on image data that has been transformed. This was used in conjunction with FLANN (Fast Library for Approximate Nearest Neighbours), "which contains a collection of algorithms optimised for fast nearest neighbour search in large datasets and for high dimensional features", as it is a faster process than the Brute-Force Matcher (Mordvintesv and Rahman 2013).

The algorithm retrieves the SIFT features of the images, puts these through the FLANN algorithm, before applying homography and a perspective transform to get the quadrilateral. The results (Figure 6) show the features identified in each image, with a boundary and centre point which correctly identify matched features to the super-image. It also returns a rotation angle of 31 degrees. SIFT and FLANN based matchers also returned a successful match of the super and search images. This resulted in two different images with a change in scale and rotation, something that is likely in the context of this application. This was especially significant in this research phase as it allowed the desk's position to be determined using this method.

4.3. TOLERANCE TESTING

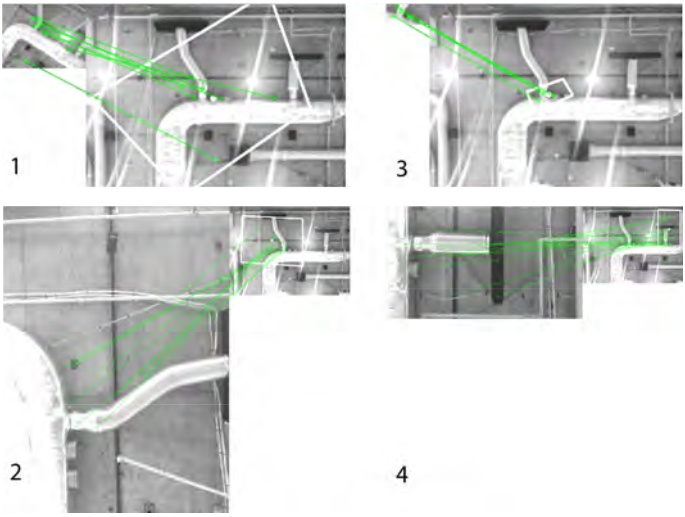


Figure 6. Four repeated results from the SIFT and FLANN Matcher.

To validate the system, and to give a sense of the possible tolerances within the system this paper outlines four examples (Figure 6, Table 1.0). The resulting difference between the exact angle and the returned angle was similar, showing an average difference of 1.8 degrees across the four tests. Distances are rounded up to the next 10mm as confidence in the centroid reporting led the research to be conservative.

Table 1. Results of the location & orientation testing, showing reported Δ from actual position.

Image	Actual Angle	Returned Angle	Difference	Distance
Test 01	31°	32.03°	1.03°	50mm
Test 02	90°	86.73°	3.27°	30mm
Test 03	24°	21.74°	2.26°	30mm
Test 04	90°	89.30°	0.7°	70mm

4.4. BEACONS

This research adopted Estimote location beacons to provide coarse grain location. Based on Rizal's (2016) research its was assumed that bluetooth signals are analogous to light. To establish a location, a mobile device must be able to 'see' at least three beacons. A count of overlapping isovists established an acceptable arrangement and quantity (6) of beacons to cover the case study area. A differentiation to Rizal's (2016) research where data was being tracked in real time, was in this research the data output from the beacons and the CV was on-demand to avoid the challenge of continually processing high volumes of data.

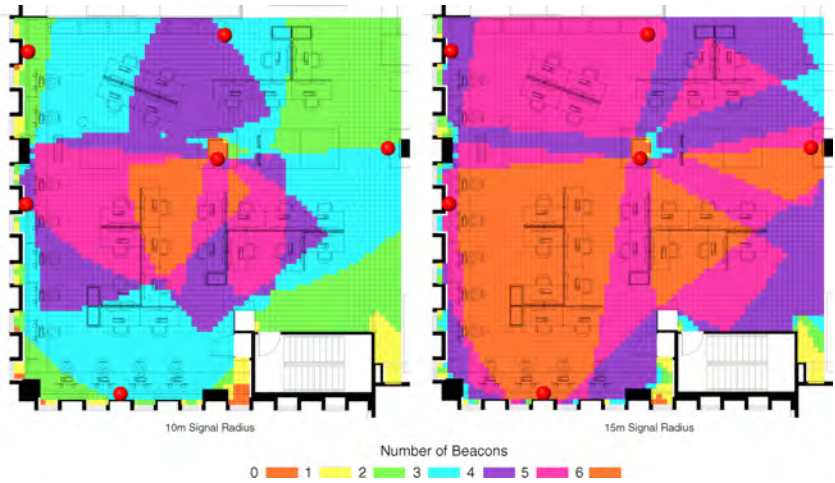


Figure 7. The left plan shows the beacon signal radius of 10m². The right plan image shows the beacon signal radius of 15m², and how many beacons can cover each part of the space. The beacons are placed where the red dots are, along walls or on columns.

5. Significance of research

This research builds on existing IPS research by proposing a method to locate the position and orientation of mobile desks in a workplace through a combination of CV and location beacons to improve the accuracy of locational data results. Capturing the ceiling image in a busily occupied workplace proved to be the first challenge of this process. Secondly, while the image capture enabled the identification of unique elements of the ceiling for the CV process, having an exposed soffit also meant that with many repeated elements there was potential for false positives. To resolve this, the research used location beacons to reduce scope of the task of searching a large image as it can be computationally intensive. The beacons operated to provide a coarse resolution to significantly reduce the size of the image to search. The location beacons alone were able to identify the location (but not rotation) of a desk with limited accuracy (±1.5m). Coupled with CV techniques this ensemble method allowed the positioning of mobile desks to <0.25m and <5° (ave: 1.8°). These initial results indicate that this application is productive, and can be built upon in future studies. The development of a mobile phone application to visualise the spatial data collection, while out of the scope of this project, is a logical next step for this research. Furthermore, future work could aim to develop a higher density ceiling map, and explore the use of the accelerometer in a mobile phone to ensure parallel images, while other sensors could add further to the ensemble.

6. Conclusion

Mobile desks are part of a current workplace trend that aims to promote collaborative and innovative ways of working by allowing users to freely

reconfigure their environments on an as-needs basis, yet this risks not knowing where people are located and creating fire egress and health and safety spatial compliance issues. This research has sought to address this problem by developing an IPS location method that combines CV and location beacons to enable mobile desk discoverability. This demonstrates that combining these methods enhances the advantages of each; CV gives higher resolution and beacons reduce the scope of the image search task.

This paper contributes to knowledge on IPS methods and outlines extended uses for image recognition and CV systems in indoor environments. Developing intelligent and informed systems to collect data and evaluate spatial compliance with health and safety regulations and fire egress regulations such as proposed here has extensibility well beyond this case example, from the health sector and construction industry to building management to name a few (Zafari et al. 2018). This research establishes a firm foundation for future work wherein more meticulous measurements are required to develop systems for enhanced spatial intelligence towards promoting safe and functional workplaces.

References

"Estimote" : 2018. Available from <https://community.estimote.com/hc/en-us/articles/201302836-What-is-the-accuracy-of-Indoor-Location-> (accessed 5th November 2018).

Baldwin, M. 2012, Participatory Action Research., *in* M. Gray, J. Midgley and W.e.b.b. S A (eds.), *The SAGE Handbook of Social Work*, Sage Publications, London, 467.

Bobade, K.B. and Jagtap, S.V.: 2014, Automatic Image Annotation by classification using SIFT features, *International Journal of Scientific Research Engineering & Technology*, **3**, 713-720.

Candido, C., Thomas, L., Haddad, S., Zhang, F., Mackey, M. and Ye, W.: 2018, Designing activity-based workspaces: satisfaction, productivity and physical activity, *Building Research & Information*, **X**, 1-15.

Valve Corporation, L.t.d.: 2012, *Valve handbook for new employees: A fearless adventure in knowing what to do when no one's there telling you what to do*, Valve Press, Washington, USA.

Dardari, D., Closas, P. and Dujuric, P.: 2015, Indoor Tracking: Theory, Methods, and Technologies, *IEEE Transactions on Vehicular Technology*, **64**, 1263-1278.

Foth, M.: 2006, Network Action Research, *Action Research*, **4**, 205-226.

Gu, Y., Lo, A. and Niemegeers, I.: 2009, A Survey of Indoor Positioning Systems for Wireless Personal Networks, *IEEE Communications Surveys & Tutorials*, **11**, 12-32.

Gubi, K.B., Wasinger, R., Fry, M., Jay, K., Kuflik, T. and Kummerfeld, B.: 2006, Towards a Generic Platform for Indoor Positioning using Existing Infrastructure and Symbolic Maps, *CEUR Workshop Proceedings*, 31-36.

Kim, H. and Han, S.: 2018, Accuracy improvement of real-time location tracking for construction workers, *Sustainability (Switzerland)*, **10**, 1488.

O'Brien, R.: 1998, "An Overview of the Methodological Approach of Action Research" . Available from <http://www.web.net/robrien/papers/arfinal.html> (accessed 10th August 2018).

Rizal, A. R., Doherty, B. and Haeusler, M. H.: 2016, Enabeling Low Cost Human Presence Tracking, *CAADRIA 20016*, Melbourne, 45-54.

Zafari, F., Gkelias, A. and Leung, K.K.: 2018, "A Survey of Indoor Localization Systems and Technologies" . Available from <arXiv.org> (accessed 1st November 2018).

Computational Design Education/Conversation

VISUAL PROGRAMMING FOR GEO-COMPUTATION

Towards Tools for Tool Makers

PATRICK JANSSEN[1], DEREK PUNG[2] and KIAN WEE CHEN[3]
[1,2]*National University of Singapore*
[1]*patrick@janssen.name* [2]*derek.pung@u.nus.edu*
[3]*Andlinger Center for Energy and the Environment, Princeton University*
[3]*chenkianwee@gmail.com*

Abstract. The paper presents the Möbius Geospatial Modeller, a web-based visual programming tool developed by the authors for creating interactive 3D geospatial datasets. As an evaluation of the modeller, the results of a five-day workshop are presented. The paper ends with a discussion, proposing the creation of customised visual programming environments that provide users with the ability to create their own customised high-level domain-specific functions, as opposed to trying to creating hundreds of functions to cater for all possible used case.

Keywords. Visual programming; geo-computation; geospatial visualization; dataflow and control flow.

1. Introduction

Geospatial data is abundant. Currently, interrogating and visualising such data is still the domain of experts. However, current technologies are making it possible for citizens from varying backgrounds to build interactive 3d geospatial web mashups to suit their own needs, creating visualisations that others can explore and interrogate. When the curiosity and ingenuity of vast numbers of citizens are unleashed on these datasets, important new discoveries may be able to influence the long-term evolution of cities in novel and unexpected directions.

A number of existing platforms provide support for end users to build geospatial narratives, consisting of web mashups that integrate various geospatial dataset (Baker 2015). An example is Esri's Story Maps, which allow end users to combine 2D maps with narrative text, images, and multimedia content to tell your story (Strachan 2014). However, a key downside of these existing technologies is that they do not support any type of advanced data generation through procedural geo-computation. Users are limited to manually editing datasets with GIS modelling tools, which makes it difficult to make novel discoveries. Such discoveries would require scripting or software programming skills that are beyond the reach of most citizens (Murgante et al. 2009). In this paper, we explore the use of visual programming as a possible solution.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 665-674. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

In computer-aided architectural design, a parametric model is a user-defined algorithm that generates 3D model instances by varying input parameters. Parametric modelling requires the designer to define this algorithm, possibly using some type of visual programming language. Parametric modelling is typically used either for quickly generating design options or for generating a single design with a high-level of complexity.

Despite numerous advantages, designers face difficulty in translating their design ideas into such an algorithm. In response, design schools have introduced computational thinking courses to provide students with the conceptual foundations for overcoming this difficulty. For design students, computational thinking involves idea formulation, algorithm development, and solution exploration, with a focus on the manipulation of geometric and semantic datasets. Through this process, students also become familiar with higher-level computational concepts, such as decomposition, encapsulation, and abstraction.

Visual programming is a useful method for learning and practising computational thinking. Visual programming is usually based on either of the two approaches: flow-based or blocks-based programming. Flow-based programming gives more importance to the state of data at each stage of the program. Blocks-based programming emphasises the order of operations in a program and is process-oriented. The former is usually visually represented as a network of nodes and wires, the latter as code blocks sequences stacked from top to bottom.

Parametric modelling can be categorised into four types: object-based modelling, associative modelling, dataflow modelling, and procedural modelling (Janssen & Stouffs, 2015). The latter are the more advanced, offering greater control and flexibility. Examples of such dataflow and procedural systems include *Bentley GenerativeComponents* (GC), *McNeel Grasshopper*, *Autodesk Dynamo*, and *Sidefx Houdini*. These systems all use a visual programming approach, where the designer defines algorithms by building networks of nodes and wires (Janssen & Chen 2011).

Numerous researchers have argued that the limited ability of flow-based visual programming to capture control-flow logic means that it is unable to fully support computational thinking (Celani & Vaz, 2012; Leitão, Santos, & Lopes, 2012). On the other hand, blocks-based visual programming has achieved considerable success in helping even elementary and high-school students do simple programming tasks (Brennan & Resnick, 2012; Weintrop & Wilensky, 2017). However, no existing parametric modelling tools have used the blocks-based approach.

We hypothesise that both flow-based and blocks-based approach can complement each other. We propose that the flow-based approach can be used at a higher level, to visually define the overall structure of the algorithm. At the lower level, inside each node, the algorithmic procedure is defined using the blocks-based approach. In this integrated approach, we disallow any control-flow logic at the flow-based level.

2. Möbius Modeller

A web-based parametric modelling platform called Möbius Modeller has been implemented that integrates these two visual programming approaches within a single language (Janssen, Li, & Mohanty 2016; Janssen, 2014). Previous research has presented broad benefits of this approach, the primary one being the significant reduction in the number of dataflow nodes required to achieve a particular modelling task (Janssen, Li, & Mohanty 2016). As a result, the complexity of the visual program can remain the commensurate with the complexity of the modelling task, even when highly complex models are created.

Our ongoing research aims to investigate to what extent the Möbius visual programming language can support computational thinking concepts required for constructing complex parametric models.

In Möbius, the flow-based approach is implemented as a flowchart of nodes with links. Inside each node in the flowchart, the blocks-based approach is then used to visually create a procedure. The user builds the procedure by inserting control-flow statement and functions from a library. The user interface is shown in Figure 1.

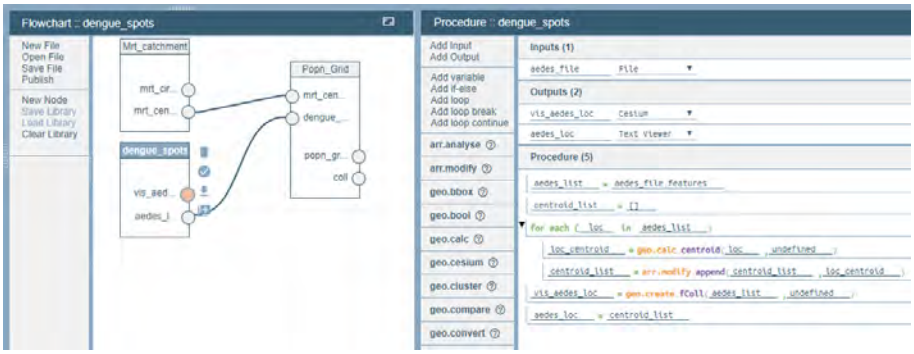


Figure 1. An example of a Möbius flowchart (left) and procedure (right).

Version 0.1 of Möbius was developed in 2015. After a year of further testing and evaluation, version 0.2 was developed in 2017, integrating a wide range of improvements. This second version was then used, between January and April 2018, for teaching a 12-week module called "Spatial Computational Thinking", for 135 second-year students in the undergraduate Architecture course at National University of Singapore. The module was designed to develop capabilities in spatial computational thinking, in order to help students translate their design ideas into executable algorithms.

Following the experience of teaching Möbius, version 0.3 was developed, this time focusing on geospatial modelling. This version allows users to code geo-computational procedures for manipulating and visualising geospatial data. It integrated *Cesiumjs* as a viewer, and the *turfjs* modelling library. One of the key features introduced in this third version was the ability to publish models as interactive web pages that others could visit and explore. The aim was to allow

students to develop specific data visualisations and narratives and to then share these with a wide audience.

This paper focuses on this third version of Möbius, called the Möbius Geospatial Modeller. Version 0.4 of Möbius, currently under development, is discussed in section 3 of this paper.

2.1. GEOSPATIAL WORKSHOP

Möbius Geospatial Modeller was used for a five-day workshop teaching students how to create and publish geospatial narratives and models on the web. The workshop was conducted in collaboration with the Beijing City Lab at Tsinghua University. Students did not have any prior scripting or programming knowledge. During the workshop, students were taught to build geo-computational procedures for generating interactive 3D narratives, consisting of web mashups built on top of diverse open data sets.

The modelling was all performed using the *geojson* file format, using 2D geometry consisting of three types of entities: points, polylines and polygons. The geometric entities were created as a way of representing and visualising data at particular geospatial locations. Various types of data were then added to the geometric entities by adding attributes. Such attributes consisted of key-value pairs, where the key was the name of the attribute and the value was any type of data. In many cases, student created simple grids of square polygons, with some data attributes capturing how certain types of data varied over a geospatial area.

Once the 2D geojson data had been generated, the visualisation of this data was then automatically mapped to 3D, using the *Cesiumjs* viewer. This visualisation could be performed interactively by anyone visiting the published website. A customised version of the *Cesiumjs* viewer was developed that allowed two attributes to visualise. One attribute would be visualised as an extrusion height while the other was visualised as a colour. For example, in the case of the 2D grid of square polygons, each polygon would first be extruded to represent the first attribute, and the colour of the extruded column would then be changed to represent the second attribute. For the colour, a blue-to-red false colour range was used. Attributes could be either discrete or continuous. For both extrusion height and colour, the attributes minimum and maximum values could be set.

This meant that a visitor to the website could play with the settings to explore the data in more depth. Initially, on opening the website, the default settings defined by the student would typically display two specific attributes. But the student could also have added other data sets to the geometric entities. The visitor to the website would then be able to change the data that was being visualised, and to play with the minimum and maximum data ranges to discover other data patterns and relationships.

For the workshop, everything was completed in only five days. The first day focused on learning basic programming skills, the second day on searching for and manipulating geospatial data, and the third day on learning a variety of geo-processing functions available in turf.js. Finally, during the last two days, the students developed geospatial narratives focusing on specific issues and then

collected a variety of geospatial data sets from open online sources.

In total 16 students attended the workshop. Students worked either individually or in small groups, developing 13 different geospatial narratives and associated data visualisations. The narratives engaged with a variety of different issues. In order to give a sense of the diversity of narratives and data visualisations, some typical topics were as follows:

- Tourist density versus rates of consumption.
- Air quality versus GDP.
- Building height versus open space ratio.
- Level of urbanisation versus mental health.
- Food rating versus food price.
- Subway versus bus accessibility.
- Salaries versus house prices.
- Urban demolition versus urban life.
- Land price versus population density.

In most cases, the process of manipulating the geospatial data was decoupled from the process of visualising that data. This was mainly done in order to make the visualisation process faster and more interactive. For the data manipulation, one or more Möbius models were created for analysing, mapping, and merging various existing geospatial datasets. The resulting data was then saved as a reduced geojson dataset optimised for visualisation. For the visualisation, a second Möbius model was then created, which was then used for publishing the interactive website.

2.2. SINGAPORE NARRATIVE

As an example of one of the narratives, an investigation focusing on Singapore and developed by the authors will be described in more detail. The model originally created for this narrative will then be analysed in more detail, and various alternative approaches and improvements to the workshop workflows and the process will then be discussed.

The Singapore narrative investigated the relationship between the population density around the island in relation to two factors: hotspots for dengue fever outbreaks, and distance to the Mass Rapid Transit (MRT) stations. The data for the visualisations were downloaded from a government data portal website, data.gov.sg.

For the data manipulation part, one Möbius model was created consisting of three nodes, as shown in Figure 1. First, two relatively simple nodes were created for extracting the centroids of the dengue hotspots and MRT station locations. Figure 1 shows the procedure for the dengue hotspots. In both cases, the original data was downloaded as geospatial data sets from the government portal. A third node was then used to perform the main processing of the data.

This third node creates an analysis grid, consisting of 50m x 50m square polygons covering the whole of Singapore. The population density was then read from another geojson data source and mapped onto the analysis grid. It then performs various distance calculations between points in the analysis grid and the

centroids of the dengue hotspots and MRT stations. All the resulting data is saved as attributes attached to the polygons in the analysis grid. A view of the developer version of the Möbius model showing the relationship between population density and dengue hotspots is shown in Figure 2.

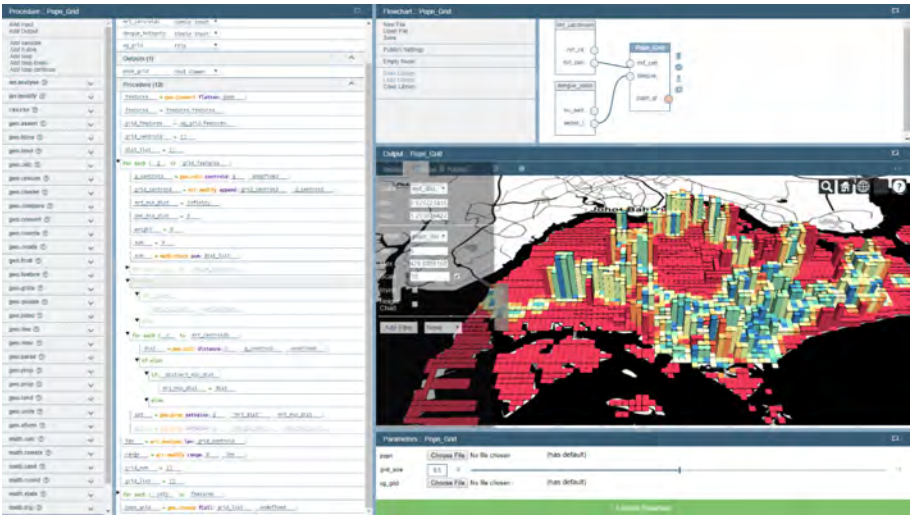


Figure 2. An example of a geospatial narrative being developed using Möbius Geospatial Modeller.

Finally, a second model is created for the data visualisation. As already mentioned, this visualisation could have been created directly in the first model. However, this would have made the visualisation very slow, and as a result, it was decided to split visualisation into its own model. The visualisation of the data as a published interactive website is shown in Figure 3. All the complexity of the of the flowchart and the procedures are hidden from the website visitor.

3. Critical Analysis

A critical analysis of the workshop results highlighted two issues. The first issue will only be briefly discussed as it is not the focus of this paper. It relates to the decoupling of the data manipulation models from the data visualisation models. This creates a significant problem, in that the data that is displayed in the published interactive web visualisation may quickly become outdated. A simple solution is being investigated for this, in which the data manipulation models are uploaded into the cloud and executed as a scheduled task (a 'cron' job). This can be achieved using an online cloud platform such as Travis CI.

This paper focuses on the second issue. Despite the effort to develop user-friendly visual programming tools, creating geo-computational procedures remained difficult for students with no programming experience. Two key challenges were identified. First, the number of functions provided to the students was found to be overwhelming and confusing. In total, the modeller included

160 functions, most of which were geoprocessing functions from the *turfjs* library. Second, the blocks-based procedures that the students created quickly became very long. These procedures became difficult to understand and maintain, especially when they included multiple nested loops.

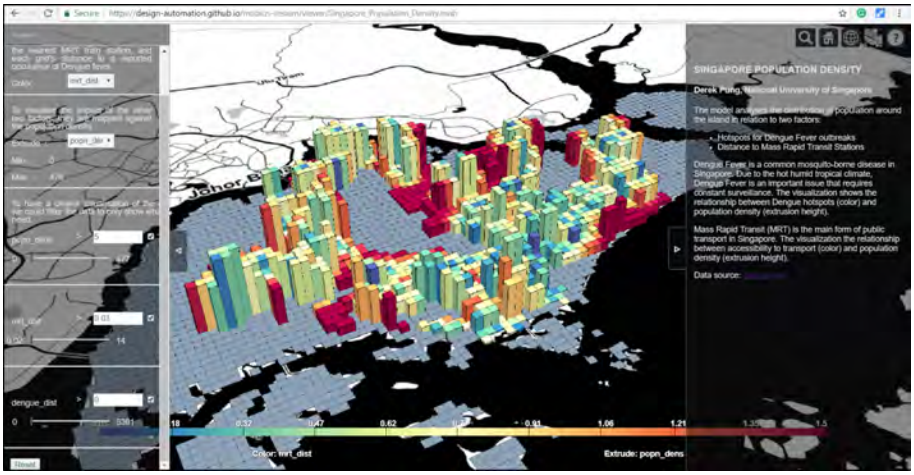


Figure 3. A geospatial narrative, published as an interactive web page.

An analysis of the models showed that in most cases, the models included only a small number of nodes but with long procedures. In addition, the procedures only used a very small subset of the geoprocessing functions available in the library. The third data manipulation model for the Singapore narrative was fairly typical. It consisted of just three nodes, with the third node creating the analysis grid and performing all the distance calculations. This node had a procedure 42 lines long, making use of 11 functions.

Further analysis of the student procedures revealed significant commonality in programming patterns. For example, out of the 13 models, 12 made use of an analysis grid. For all these models, significant parts of the code had similar patterns for distances between sets of features. Analysing these patterns in more detail then suggested that the procedures could have been created using just a few high-level functions.

In order to test this, a new set of high-level functions were implemented for the models that required analysis grids. In these high-level functions, the looping behaviour was built into the function itself, further reducing the code that needed to be written. Thus, students would not be required to write blocks-based code to explicitly loop over the collections of entities.

The required number of functions to implement all 12 analysis grid models was found to be just 8 functions. As an example, the Singapore narrative can be considered. For this narrative, just five high-level functions would be required. This would reduce the 42-line procedure to just 12 lines.

For the Singapore model, the five functions consisted of the following:

- *id()* - creates an id for each entity.
- *area()* - calculates the area of an entity and adds it as a new attribute.
- *attribTransfer()* - transfer an attribute from one entity to another.
- *attribMath()* - create a new attribute by performing mathematical calculations with one or more existing attributes.
- *many2manyDistance()* - calculate the distance from every entity in one collection to every entity in another collection, and stores the results in attribute arrays.

Although these functions are more high-level that the previous *turfjs* functions, they nevertheless remain fairly generic. These functions could be used in many different scenarios, even in models that did not necessarily require an analysis grid.

3.1. USER-DEFINED FUNCTIONS

It is clear that the number of functions required in order to perform a certain geo-processing task can be massively reduced by providing just a small set of higher-level functions. In the case of the Singapore model, the number of lines of code was reduced by over 71%, from 42 lines to just 12 lines. Such a reduction would make the task of visual programming much easier for a student, for two reasons. First, the number of functions they would have to become familiar with could be far fewer. Second, the blocks-based procedure itself would be much shorter and would require fewer loops, making it easier to understand.

However, all of this does, of course, come at a cost of reduced flexibility. If a visual programming system was created that provided only these 8 functions, then it could only be used for generating visualisations similar to the Singapore model, consisting of analysis grids and performing distance and area calculations. This would be highly limiting.

The ability for end users to define their own customised functions would offer a way out of this dilemma. We may imagine different types of end user. For example, in a scenario such as the workshop, two types of end-user are the teacher and the students. The teacher may be more experienced with visual programming, while the students may be complete novices. In such a case, the teacher can create a set of high-level functions for the students, while at the same time hiding many of the low-level functions. In this way, the students have an easier learning curve. If during the workshop, one of the students requires a different high-level function, then the teacher can implement that function on the spot and add it to Möbius for the students to use. For the students who are eager to explore the lower level functions, the teacher may also show them how those functions can be enabled again. This allows for a flexible approach, with different sets of functions being available to different types of users.

A key challenge with this approach is how to allow the high-level functions to be easily defined by the end users. This functionality is now being implemented in the latest version of Möbius. In the new version, the flowchart includes a *start* node, an *end* node, and zero or more *procedure* nodes. This flowchart can now be mapped to a single function, containing a set of nested functions for each of the *procedure* nodes. With the new functionality, a user is able to import any existing

Möbius file into their current model, and each file is then transformed into a single function. This allows any user to define their own higher-level functions, and to share these functions with others.

As an example, a flowchart could be defined for the *many2manyDistance* function that calculates the distances between all the entities in two collections. The *start* node is used to define a set of global variables which all the procedures can read. In this case, three global variables are defined. The first two variables define the names of the two collections to process. The third variable defines the name of the attribute to create. A number of procedure nodes could then be defined to calculate the distances and create the necessary attributes. When this flowchart is imported into another Möbius model, it will appear as an imported function, called *many2manyDistance()*, with three arguments. The function can then be inserted into any procedure, in exactly the same way as the built-in functions.

This functionality includes the ability to create a description of the model, together with descriptions of all the input parameters. When the model then gets used as a function, these descriptions automatically become the help of the function that other users are able to view. The ability to easily define the help for such user-defined functions is essential if they are to be used by a large number of other users. Eventually, the function may even be shared on online platforms.

Finally, the ability to hide selected low-level functions is being developed. This will be enabled through Möbius configuration settings that can be saved and also shared between users. When working inside Möbius, certain functions can be disabled through the user interface. Once the desired combination of functions has been set, the setup can then be saved as a configuration file which can later be imported into a different Möbius session. The configurations will be saved in the browsers' local storage, thereby allowing the changes to remain persistent.

4. Conclusions

The research project is developing a visual programming platform and language that combines flow-based and blocks-based visual programming approaches called the Möbius Modeller. The flow-based approach is used at a higher level, to visually define the overall structure of the algorithm. At the lower level, inside each node, the algorithmic procedure is defined using the blocks-based approach.

The paper focuses on the results of a workshop conducted using one version of this platform, the Möbius Geospatial Modeller. This version aims to support geo-computational modelling and visualisation. These models are typically dealing with large data sets, and the data processing requires nested looping and iteration. Through numerous iterations of software development and user testing, the research is trying to discover conceptual frameworks and constructs that will make it easier for end users to develop complex geo-computational models.

A critical analysis of the workshop results highlighted that, despite the visual programming tools, creating geo-computational procedures remained challenging for end-users with no programming experience. One of the key reasons forth was the fact that the modeller provided 160 low-level functions that were often confusing and overwhelming. An initial analysis of the student procedures

revealed significant commonality in programming patterns. Further investigation then revealed that the procedures could have been created with far fewer high-level domain-specific functions. Based on this analysis, the latest version of the Möbius is now being developed, incorporating the ability of end users to define their own high-level functions.

Acknowledgements

We thank Professor Long Ying from the Beijing City Lab at Tsinghua University for his support in running the Extruded Cities workshop. We also thank the workshop participants for their contributions: Fan Zekun, Feng Wenhan, Hou Luyao, Huang Zidong, Li Bayi, Li Xintian, Liao Hui, Liu Jiangde, Liu Shang, Tang Zixiao, Wang Pengyu, Wu Shuyun, Xu Bingjun, Yang Li and Zhang Xinrui. Finally, we thank our team members for helping to run the workshop: Akshata Mohanty, Sun Huiyao, Joie Lim and Wang Likai.

References

Baker, T.R. 2015, WebGIS in Education, *in* O. Muñiz Solari, A. Demirci and J. Schee (eds.), *Geospatial Technologies and Geography Education in a Changing World. Advances in Geographical and Environmental Sciences*, Springer, Tokyo, 105-115.

Brennan, K. and Resnick, M.: 2012)., New frameworks for studying and assessing the development of computational thinking, *Proceedings of the 2012 Annual Meeting of the American Educational Research Association.*, Vancouver, Canada.

Celani, G. and Vaz, C.: 2012)., CAD Scripting and Visual Programming Languages for Implementing Computational Design Concepts: A Comparison from a Pedagogical Point Of View, *International Journal of Architectural Computing*, **10**(1), 121–138.

Janssen, P.: 2014, Visual Dataflow Modelling: Some Thoughts on Complexity, *Proceedings of eCAADe 2014*, Newcastle, UK, 547–556.

Janssen, P., Li, R. and Mohanty, A.: 2016, A Parametric Modeller for the Web, *Proceedings of CAADRIA 2016*, Melbourne, Australia, 157-166.

Leitão, A., Santos, A. and Lopes, J.: 2012)., Programming Languages for Generative Design: A Comparative Study, *International Journal of Architectural Computing*, **10**(1), 139–162.

B. Murgante, G. Borruso and A. Lapucci (eds.): 2009, *Geocomputation and Urban Planning. Studies in Computational Intelligence, 176*, Springer-Verlag, Berlin Heidelberg.

Papert, S.e.y.m.o.u.r.: 1980), *Mindstorms: Children, computers, and powerful ideas*, Basic Books, Inc.

Strachan, C.: 2014, *Teacher's perceptions of Esri story maps as effective teaching tools*, Master's Thesis, University of South Carolina.

Weintrop, D. and Wilensky, U.: 2017, Comparing Block-Based and Text-Based Programming in High School Computer Science Classrooms, *ACM Trans. Comput. Educ.*, **18**(1), 3:1–3:25..

REDEFINING MIXED REALITY: USER-REALITY-VIRTUALITY AND VIRTUAL HERITAGE PERSPECTIVES

MAFKERESEB KASSAHUN BEKELE[1] and ERIK CHAMPION[2]
[1] *UNESCO Cultural Heritage and Visualisation, School of Media, Creative Arts and Social Inquiry (MCASI), Curtin University*
[1] *mafkereseb.bekele@postgrad.curtin.edu.au*
[2] *UNESCO Cultural Heritage and Visualisation, School of Media, Creative Arts and Social Inquiry (MCASI), Curtin University*
[2] *erik.champion@curtin.edu.au*

Abstract. The primary objective of this paper is to present a redefinition of Mixed Reality from a perspective emphasizing the relationship between users, virtuality and reality as a fundamental component. The redefinition is motivated by three primary reasons. Firstly, current literature in which Augmented Reality is the focus appears to approach Augmented Reality as an alternative to Mixed Reality. Secondly, Mixed Reality is often considered to encompass Augmented Reality and Virtual Reality rather than specifying it as a segment along the reality-virtuality continuum. Thirdly, most common definitions of Augmented Reality (AR), Augmented Virtuality (AV), Virtual Reality (VR) and Mixed Reality (MxR) in current literature are based on outdated display technologies, and a relationship between virtuality and reality, neglecting the importance of the users necessarily complicit sense of immersion from the relationship. The focus of existing definitions is thus currently technological, rather than experiential. We resolve this by redefining the continuum and MxR, taking into consideration the experiential symbiotic relationship and interaction between users, reality, and current immersive reality technologies. In addition, the paper will suggest some high-level overview of the redefinition's contextual applicability to the Virtual Heritage (VH) domain.

Keywords. Mixed Reality; Reality-Virtuality Continuum; Virtual Heritage.

1. Introduction

Over the last decade, the segments of the reality-virtuality continuum have witnessed fascinating technological advancements, yet their definitions have remained relatively untouched since they first appeared in the literature back in the 1990s. It is a natural process for definitions and scientific assertions, especially in the technology realm, to continuously align themselves towards current advances and even encode key conceptions that could highlight future developments in

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 675-684. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

the realm. Contrary to this natural development, however, the definitions of the reality-virtuality continuum have continued to appear unchanged, still being referred in their original forms. However, their market share keeps growing exponentially and a significant number of research labs dedicate their resources towards advancing immersive reality's applicability and technological bases across diverse domains ranging from medicine and engineering to education and cultural heritage. Hence, given recent developments, redefining the continuum, especially its most contesting segment (MxR), is warranted.

In this paper, therefore, we present a redefinition of the reality-virtuality continuum from a perspective emphasizing the relationship between users, virtuality and reality as a central basis. In addition, a zoomed-in view will be dedicated to MxR and its contextual applicability to Virtual Heritage (VH), a domain emerging in Cultural Heritage (CH) following the advances of immersive reality.

The motivation to redefine MxR is influenced by existing limitations observed in immersive reality and VH studies. This paper aggregates those limitations into three problem spaces: (1) AR and MxR are perceived as alternates, (2), MxR is perceived as a combination of AR and VR, and (3) users are excluded from the defining relationship between reality and virtuality.

Hence, our primary goals here in this paper are: (1) to delineate a boundary between AR and MxR rather than replacing their current definitions with new once, (2) to redefine MxR from a perspective that views the segment as a self-standing form of reality-virtuality instead of an approach that combines AR and VR settings, (3) to augment users' experience into the reality-virtuality relationship in order to redefine the continuum from a perspective that emphasises the relationship between users, reality and virtuality as a central point, and (4) suggest some contextual applicability of the redefined MxR to the VH domain, especially for future VH application that aim to exploit MxR to disseminate virtual reconstructions and simulations of cultural heritage.

To this end, we start by reviewing the current literature in immersive reality technology and exemplar case studies from different application areas to show trends in the uptake of AR, AV, VR and MxR. Moreover, we will compare this trend with the most common definitions of AR (Azuma et al., 2001; Azuma, 1997) and with the reality-virtuality continuum (Milgram & Colquhoun, 1999; Milgram & Kishino, 1994; Milgram et al., 1995) and discuss the interchangeable appearance of AR and MxR in the literature. Secondly, we argue that a relationship between users, reality and virtuality (User-Reality-Virtuality) resolves the issues discussed above and requires redefining MxR. Finally, we outline how the redefinition of MxR can be adopted into VH applications, especially when an application's primary aim is to ameliorate the relationship between users/visitors, cultural heritage sites and their virtual reconstructions or simulations.

2. Existing Definitions of the Reality-Virtuality Continuum

The reality-virtuality continuum (see Figure 1), first introduced by Milgram and Kishino (1994), classified the span between the physical and virtual environments

to Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV), and Mixed Reality (MxR). The continuum and its segments are briefly discussed below as per their appearance in the existing literature.

One of the most widely cited papers, also one of the first definitions of the segment, defines AR as a system that combines real and virtual content, provides a real-time interactive environment, and registers in 3D to enhance our understanding of the physical environment (Azuma, 1997). The sole purpose of AR is to enhance our perception and understanding of the real world by superimposing virtual information on top of our view to the real world.

VR is often referred as a segment of the reality-virtuality continuum that transports users into a computer-generated virtual world, where users are expected to experience a high level of presence in the environment (Carmigniani et al., 2011; Steuer, 1992). Virtual environments detach the users' sense of being here and now in the physical world and create artificial presence in a virtual one instead. To date, the advances in VR have enabled virtual environments to deceive our hearing, visual, and kinaesthetic senses. VR also has the potential to simulate imaginative and existing physical environments along with their processes and environmental parameters to engage and affect all of our senses including touch and smell.

While Augmented Virtuality (AV) augments virtual environments with live scenes from the real-world events, it is commonly understood as a variation of VR. This is problematic since the whole purpose of augmenting virtual environments with live scenes is to enhance our understanding of the underlying virtual environment, which diverts from VR's aim, transporting users to a completely virtual world. Essentially, AV is closely aligned to AR in terms of purpose, because both aim at enhancing the environment they are applied to. VR, on the other hand, has no direct implication on our perception of the real world. However, our interaction and presence in a virtual environment that simulates the real world might indirectly influence our perception of the physical reality.

Milgram and Kishino (1994) defined Mixed Reality (MxR) as "...a particular subclass of VR related technologies that involve the merging of real and virtual worlds." More specifically, they say that MR involves the blending of real and virtual worlds somewhere along the "reality-virtuality continuum" which connects completely real environments to completely virtual ones. However, there are instances where the terms AR and MxR are used interchangeably (Papagiannakis et al., 2018; Raptis et al., 2018). These immersive reality technologies, to some extent, share a common objective, that is enhancing our understanding of the physical environment. However, AR achieves this by overlaying digital content over our view of the physical world and this portion of the continuum is placed closer to reality, whereas MxR achieves a broader goal, enhancing our understanding of the real and virtual worlds, by blending elements from the real and virtual environments. Moreover, contrary to MxR, the academic literature has noted that AR has a limited visual and spatial immersion (Leach et al., 2018). MxR, on the other hand, combines interactivity and immersion from AR and VR, respectively, to bring immersive-interactive experience to our view of the real-virtual word. MxR is thus a broad portion combining different properties of the continuum into a single immersive reality technology. This puts AR in a

technically challenging position for consideration as a substitute to MxR.

In conclusion, the most widely known definitions of the reality-virtuality continuum and its segments are derived from a relationship between reality and virtuality and technological advances from their respective eras, most of which are already outdated. In addition, the definitions emphasise on displays rather than on users‘ experience. A redefinition of the continuum from a perspective that doesn't rely on technology and augments users' experiential aspect into the reality-virtuality relationship is crucial.

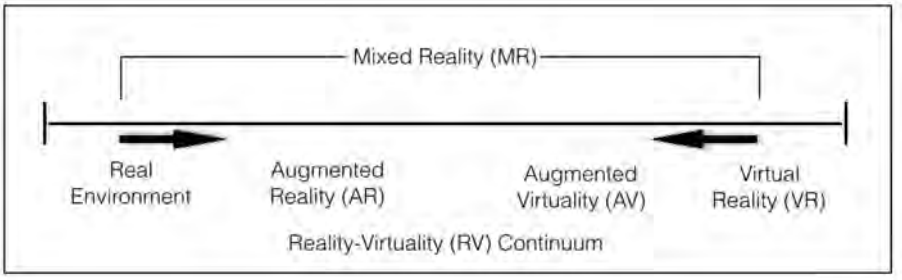


Figure 1. Reality-Virtuality (RV) Continuum (Milgram & Kishino, 1994). Existing definitions adopt this continuum.

3. Augmented, Virtual and Mixed Reality: Interchangeable, Collective, and Exclusive

This section discusses further the main gaps observed in existing definitions of the reality-virtuality continuum, particularly MxR. We would like to remind readers that the main objective of this paper is redefining the continuum, especially MxR, by redefining existing definitions rather than replacing them with new once.

3.1. AUGMENTED REALITY AND MIXED REALITY ARE PERCEIVED AS ALTERNATES

The term MxR is sometimes used for application that comprise AR characterises (Papagiannakis et al., 2018; Pollalis et al., 2017; Pollalis, Gilvin, et al., 2018). While it is technically challenging to create an immersive reality system or application that delivers AR and MxR experiences at the same time, it has become common to see the terms AR and MxR in the literature, especially since the last two years following the recent display technologies such as Microsoft HoloLens (Scott et al., 2018). However, most of these immersive reality applications demonstrate distinct AR characteristics. Hence, the terms AR and MxR appear in the literature representing identical experiential context. It is technically challenging for immersive systems to exhibit both AR and MxR functionalities because of the technological limitations related to displays. The technical challenge of developing a system that twines AR and MxR features rises mainly from the difficulty in blending dynamic content with dynamic lighting. As such, blending

elements from the real and virtual environments to the extent that the fusion appears as believable and immersive as virtual environments in VR is impossible. In addition, MxR application are rare due to lack of robust and real-time tracking and 3D registration, realistic virtual environments, natural interaction interfaces, and presentation devices for vivid experiences (Bekele et al., 2018).

3.2. MIXED REALITY IS PERCEIVED AS A COMBINATION OF AUGMENTED AND VIRTUAL REALITY

Mixed Reality (MxR) is sometimes considered as an umbrella term for systems that comprise both AR and VR characteristics rather than a specific segment of reality along the reality-virtuality continuum (Papagiannakis et al., 2018). These two segments are placed far apart along the continuum and often perceived as the end points of the continuum. AR is positioned close to physical reality whereas VR is the end point of the virtuality side. MxR combines some properties from both segments, interactivity and immersion from AR and VR, respectively. However, it is only VR that is one of the end points of the continuum, AR doesn't qualify as such since it enhances the real world (the other end point of the continuum).

3.3. USERS ARE EXCLUDED FROM THE REALITY-VIRTUALITY RELATIONSHIP

Incorporating users' experience needs to be treated as a fundamental part of any system or application design that somehow involves interaction between users and information. This relationship is a crucial factor that determines the efficiency of interaction interfaces. However, existing definitions of immersive reality and the reality-virtuality continuum haven't incorporated users' experience into the relationship between reality and virtuality that underlies the definitions of the continuum (Azuma, 1997; Milgram & Kishino, 1994). Akin to other Human-Computer-Interaction (HCI) studies in VH (Rahim et al., 2017; Slater & Sanchez-Vives, 2016), where users' experience is highlighted as a crucial aspect of the design and development processes, the interaction and experiential aspects of immersive reality systems need to establish a continuous relationship between users, reality and virtuality. Instead, they try to attract users towards the already established relationship between reality and virtuality. This has made users external observers of the relationship instead of active participants or collaborators in the relationship, influencing its forms and properties.

4. Redefining Mixed Reality: Integrating User's Experience into the Reality-Virtuality Continuum

The novelty of this paper is integrating a users' experiential aspect into the existing reality-virtuality continuum and establish a relationship between users, reality, and virtuality. The redefinitions presented in this paper are inferred from this relationship. The relationship is further discussed in terms of User-Reality-Virtuality Interaction and Relationship aspects in order to clarify the base for the redefinition.

4.1. USER-REALITY-VIRTUALITY INTERACTION AND RELATIONSHIP

Immersive reality technology's role is not just to enable interaction between users and information, it is more a continuous relationship between users, reality and virtuality that puts users at the centre, affects their senses, and allows users to be part of any change and process in the environment. This contradicts the conventional way we interact with virtual information and virtual environments presented via immersive reality systems. Figure 2 below demonstrates the contextual interaction between users, reality and virtuality. This interaction space can be considered as an extension of the original reality-virtuality continuum.

Arguably, MxR is a tread that connects elements form the real and virtual environments. The notions behind connecting elements form the two environments and connecting the two environments themselves differ. From a technological point of view, a complete fusion of the two environments is very challenging. Even if the two environments are blended completely, the fusion makes no sense as it provokes a fight between the two layers to win the user's attention. The logical approach is, therefore, to merge elements from both environments so that the fusion exhibits real-virtual characteristics. This enables the virtual environment to appear as real as the real. The real-virtual environment helps enhancing our understanding of both worlds, meaning the virtual elements enhance the real world and elements from the real world enhance the virtual one.

For instance, imagine a virtual simulation of a captain on a historic ship, our understanding of the significance of either the ship or the captain will be completed when the two are put together in a real-virtual environment. Alternatively, the captain's simulation can be experienced in a VR environment, but the historical significance may not be noticed or communicated as much as in the real-virtual environment, unless of course the virtual environment in the VR simulates both the captain and the ship. Such environments comprise a unique characteristic of MxR since this segment balances inputs from the real and virtual environments. Contrary to this, the other segments of the reality-virtuality continuum incline either to reality or virtuality. Hence, MxR needs to be positioned somewhere in the middle of the continuum.

Adding users' experiential and interactivity perspectives to the real-virtual environments allows to establish a relationship between users, reality and virtuality. This strengthens the redefinition of MxR, especially in terms of delineating a boundary between AR and MxR. This relationship takes into consideration four aspects: (1) the fusion of real and virtual environments or elements, (2) interaction between users and virtuality, (3) interaction between realty and virtuality, (4) immersion in a virtual environment. Figure 2 shows the interaction between users, different forms of immersive reality, and the real world. Figure 3 shows the relationship between users, fusion of real and virtual environments, immersion, and interaction between users, reality and virtuality. Considering a combination of these aspects, the different forms of immersive reality are redefined as follows.

- Virtual Reality (VR) occludes users' view to the real world and users' interaction is limited to the virtual environment. The sensorial effects on

users, users influence on the environment, and interaction with the virtual elements are constrained to the affordance of the underlying technology. The fundamental characteristic of VR is that a continuous two-way interaction and relationship could be established between users and virtuality. In addition, the virtual environment in VR is a completely computer-generated one. Hence, there is no direct relationship and interaction between reality and virtuality.

- Augmented Virtuality (AV) is a virtual environment supplemented by elements from the real world. Unlike VR, there is a relationship between reality and virtuality in AV, that is elements from the real word enhance the virtual one. Users primarily interact with the virtual environment but not with the elements from the real world that are augmented into the virtual environment. It is very rare to find AV applications because feeding live scenes from the real environment into a virtual environment is challenging, let alone interacting with and manipulating those elements. If fully exploited with the right enabling technologies, however, AV has the potential to: (1) generate 3D models, environmental parameters and spatial sound on the fly from live scenes and merging them with virtual environments, (2) allow users to interact and establish a relationship with both the virtual environment and the elements being streamed from the real world. In a broader sense, AV is comparable to AR since both try to enhance the primary environment they are based upon.
- Augmented Reality (AR) supplements the real word with virtual elements and enables users to interact with the virtual elements. Even if virtual elements are superimposed around the physical environment, the interaction in AR is always between users and virtual elements. More importantly, the real environment is dominant and benefits from the virtual elements in order to enhance users' perception of the real world.
- Mixed Reality (MxR) blends elements from both the real and virtual environments to create a real-virtual environment that enhances our perception of both environments. This environment enables interaction between users, virtual elements, and the real world, leading to a user-reality-virtuality interaction and relationship space. Unlike AR, where the real environment is dominant, MxR doesn't allow one environment to dominate the other, instead both environments benefit from each other's elements. This is perhaps one of the fundamental factors putting MxR ahead of AR or any form of reality-virtuality, because MxR targets at enhancing our understanding of both the real and virtual environments. One of the reasons why AR is confused with MxR is that they both seem to benefit from virtual elements. However, AR doesn't enhance virtual elements while MxR enables mutual or reciprocal benefits between the real and virtual elements. MxR is, therefore, an integration of elements from virtual and real environments that allows users to interact with the two worlds that benefit from each other's elements in order to enhance users' understanding of the two worlds.

5. Contextual Applicability of Mixed Reality to Virtual Heritage

Virtual Heritage (VH) is an emerging field that applies immersive reality technologies and digital tools to Cultural Heritage (CH) in order to simulate, preserve, and disseminate tangible and intangible cultural assets in a form of

diverse multimedia approaches. In general, MxR enables user-centred and personalised presentation of VH and makes cultural heritage digitally accessible in a form of virtual reconstruction or virtual museum/exhibitions. Such characteristics are viable for CH knowledge dissemination, especially when physical access to artefacts is limited.

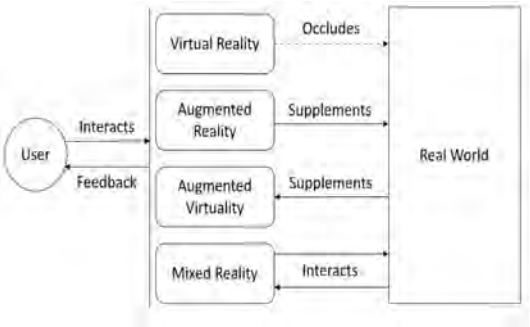


Figure 2. User-Reality-Virtuality (URV) Interaction: Interaction between users, display technologies and the real world.

MxR applications are very rare to find in any domain. Very recently, however, a few applications are emerging in the VH domain following recent advances in immersive reality technologies, such as the Microsoft HoloLens. For instance, Pollalis, Minor, et al. (2018) present an MxR application that utilises Microsoft HoloLens to allow object-based learning through mid-air gestural interaction with virtual representations of museum artefacts. Other examples of HoloLens based applications in the domain include (Baskaran, 2018; Bottino et al., 2017; Pollalis et al., 2017; Scott et al., 2018). Given the redefinition of MxR proposed in this paper, however, these recent studies are more exemplar cases of AR applications that can be tuned to attain the MxR characteristics as per the redefinition.

Following the recent advances and the redefinition presented in this paper, two contextual applications of MxR are proposed for the VH domain. These application areas are, namely, virtual reconstruction and virtual exhibition.

Virtual reconstruction aims at enabling users to visualise and interact with reconstructed historical views of tangible and intangible heritages. Such applications allow merges between historical views from the past with their current appearance. Especially, partially damaged or fully demolished architectural heritages can be virtually reconstructed at their historical location. Additional information beyond the virtual reconstruction itself can also be overlaid along with the virtual elements. MxR plays a great role in the restoration of lost heritages, starting from the reconstruction of statues and extending to reviving cultural practices in their original forms. Leach et al. (2018) present an outdoor AR application that partially achieves a virtual reconstruction of a historical building.

Virtual museums/exhibitions intend to improve visitors' experience at physical museums and heritage sites, typically through personalised virtual tour guidance. In general, such applications simulate or enhance physical museums and heritage

sites including their tangible and intangible assets. Such simulations are equipped with potential to enhance cultural presence, thereby bringing a sense of being there and then to visitors. MxR can extend the simulation by including virtual-human characters and cultural agents into the simulated virtual environment. In such cases, the simulation should consider environmental parameters, physical properties, and cultural/historical context of heritage sites. The redefined MxR allows interaction between users, heritages, and virtual simulations. Arguably, such interaction creates a perception of physical movement inside a real-virtual environment. This allows VH application designers to establish a relationship between users and their immediate heritage environment.

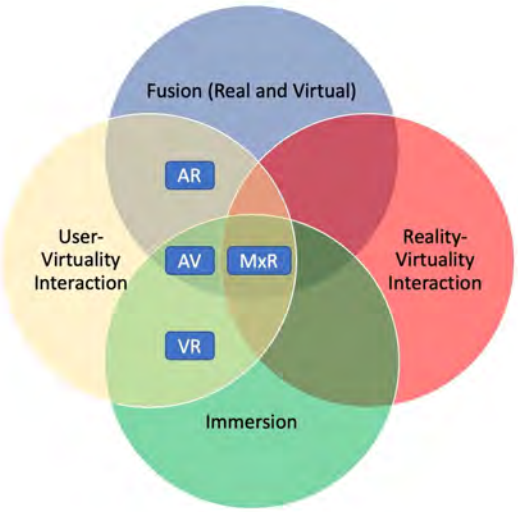


Figure 3. User-Reality-Virtuality (URV) Relationship Space: A relationship between users, fusion of real and virtual environments, immersion, and interaction between users, reality and virtuality. This relationship is the basis for redefining Mixed Reality.

6. Conclusion

In this paper, we have identified major gaps in existing definitions of the reality-virtuality continuum and its segments. Following this, we have presented a redefinition of the continuum from a perspective underlining the important relationship and interaction between users, reality and virtuality. Also, a special focus has been dedicated to MxR when redefining the reality-virtuality continuum. MxR is, therefore, redefined as an integration of elements from virtual and real environments that allows users to interact with the two worlds that benefit from each other's elements in order to enhance users' understanding of the two worlds. Following recent advances and the above redefinition of MxR, two contextual applications are proposed for the VH domain. These application areas are, namely, virtual reconstruction and virtual exhibition.

References

Azuma, R.T.: 1997, A survey of augmented reality, *Presence: Teleoperators \& Virtual Environments*, **6**(4), 355-385.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S. and MacIntyre, B.: 2001, Recent advances in augmented reality, *IEEE Computer Graphics and Applications*, **0**, 34-47.

Bekele, M.K., Pierdicca, R., Frontoni, E., Malinverni, E.S. and Gain, J.: 2018, A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage, *Journal on Computing and Cultural Heritage (JOCCH)*, **11**(2), 7.

Bottino, A.G., Garc\, A.M. and Occhipinti, E.: 2017, *Holomuseum: a prototype of interactive exhibition with Mixed Reality glasses HoloLens*, Master's Thesis, Politecnico di Torino.

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E. and Ivkovic, M.: 2011, Augmented reality technologies, systems and applications, *Multimedia tools and applications*, **51**(1), 341-377.

Leach, M., Maddock, S., Hadley, D., Butterworth, C., Moreland, J., Dean, G., Mackinder, R., Pach, K., Bax, N. and Mckone and others, M.: 2018, Recreating Sheffield, *International Conference on Virtual Reality and Augmented Reality*, 213-229.

Milgram, P. and Colquhoun, H.: 1999, A taxonomy of real and virtual world display integration, *Mixed reality: Merging real and virtual worlds*, **1**, 1-26.

Milgram, P. and Kishino, F.: 1994, A taxonomy of mixed reality visual displays, *IEICE TRANSACTIONS on Information and Systems*, **77**(12), 1321-1329.

Milgram, P., Takemura, H., Utsumi, A. and Kishino, F.: 1995, Augmented reality: A class of displays on the reality-virtuality continuum, *Telemanipulator and telepresence technologies*, 282-293.

Papagiannakis, G., Geronikolakis, E., Pateraki, M., L\, V.M., Tsioumas, M., Sylaiou, S., Liarokapis, F., Grammatikopoulou, A., Dimitropoulos, K. and Grammalidis, N.: 2018, Mixed Reality, Gamified Presence, and Storytelling for Virtual Museums, *Encyclopedia of Computer Graphics and Games*, **N/A**, 1-13.

Pollalis, C., Fahnbulleh, W., Tynes, J. and Shaer, O.: 2017, HoloMuse: Enhancing engagement with archaeological artifacts through gesture-based interaction with holograms, *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*, 565-570.

Pollalis, C., Gilvin, A., Westendorf, L., Futami, L., Virgilio, B., Hsiao, D. and Shaer, O.: 2018, ARtLens: Enhancing Museum Visitors' Engagement with African Art, *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility*, 195-200.

Pollalis, C., Minor, E.J., Westendorf, L., Fahnbulleh, W., Virgilio, I., Kun, A.L. and Shaer, O.: 2018, Evaluating Learning with Tangible and Virtual Representations of Archaeological Artifacts, *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, 626-637.

Rahim, N., Wook, T.S.M.T. and Zin, N.A.M.: 2017, Analysis on user Interaction in Virtual Heritage: Virtual Museum Environment, *Indian Journal of Science and Technology*, **10**(48), 1-10.

Raptis, G.E., Fidas, C. and Avouris, N.: 2018, Effects of mixed-reality on players' behaviour and immersion in a cultural tourism game: A cognitive processing perspective, *International Journal of Human-Computer Studies*, **114**, 69-79.

Scott, M.J., Parker, A., Powley, E., Saunders, R., Lee, J., Herring, P., Brown, D. and Krzywinska, T.: 2018, Towards an Interaction Blueprint for Mixed Reality Experiences in GLAM Spaces: The Augmented Telegrapher at Porthcurno Museum, *Proceedings of BHCI 2018*.

Slater, M. and Sanchez-Vives, M.V.: 2016, Enhancing our lives with immersive virtual reality, *Frontiers in Robotics and AI*, **3**, 74.

Steuer, J.: 1992, Defining virtual reality: Dimensions determining telepresence, *Journal of communication*, **42**(4), 73-93.

A CRITICAL FRAMEWORK OF SMART CITIES DEVELOPMENT

VICTOR CALIXTO[1], NING GU[2] and GABRIELA CELANI[3]
[1,2]*University of South Australia*
[1]*arq.victorcalixto@gmail.com* [2]*ning.gu@unisa.edu.au*
[3]*Universidade Estadual de Campinas*
[3]*celani@g.unicamp.br*

Abstract. This paper investigates through a review of the current literature on smart cities, reflecting different concepts across different political-social contexts, seeking to contribute to the establishment of a critical framework for smart cities development. The present work provides a review of the literature of 250 selected publications from four databases (Scielo, ScienceDirect, worldwide science, and Cumincad), covering the years from 2012 to 2018. Publications were categorised by the following steps: 3RC framework proposed by Kummitha and Crutzen (2017), the main political sectors of city planning, implementation strategies, computational techniques, and organisation rules. The information was analised graphically trying to identify tendencies along the time, and also, seeking to explore future possibilities for implementations in different political-social contexts. As a case of study, Australia and Brazil were compared using the proposed framework.

Keywords. Smart city; smart cities; literature review.

1. Introduction

By 2050, 68% of the world's population is projected to be living in urban areas, wherein 2.5 billion people will be relocated to urban areas, reaching 8.9 billion (DESA 2017). Cities share common challenges that must be addressed such as improving the management of urban growth, dealing with migratory movements, manage the urbanisation through a sustainable development approach, among other demands. However, besides the similarities between the cities, there are many specificities that are related to the singularity of each country, whereby is ruled by different political-social contexts. Policy governors, planners, researchers, and other stakeholders are addressing momentum to design new strategies to enhance performance and sustainability in the cities, and some of them are seeking to achieve these goals by a so called "smart city" approach.

According to Hollands (2008), the aim of a smart city consists of the improvement of economic and political efficiency to enable socio, cultural and urban development. However, approaches and methods to achieve those requirements through the concept of smart cities, are still under heated debate in academia. While some researchers tend to be biased by the technology-driven

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 685-694. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

method (TDM), others opt to the human-driven method (HDM) (Letaifa 2015). Kummintha and Crutzen propose on a literature review categorising smart city by 3RC Framework (Kummitha and Crutzen 2017). Despite differences between approaches on smart cities' development, there is no consensus about the concept or its actual benefits (Kummitha and Crutzen 2017). Moreover, smart cities could be addressed by methods and approaches under the diverse political-social contexts; for instance, almost 90% of the urban growth will happen in Asia and Africa (DESA 2018), in which there is a rich and diverse culture, wherein it is not reasonable to adopt the Euro-American smart city model without a critical revision or adaptation that suits the specificity of each country.

This paper aims to investigate the current literature on smart cities through a systematic review, reflecting different concepts across different political-social contexts, seeking to address the following research questions: (a) What are different approaches to smart cities in different regions across the world or is there a hegemonic view about the concept (b) What are the key design methodologies, intelligent systems, and computational techniques, identified in the development, creation, analysis, and management of smart cities? The investigation of these research questions will contribute to the establishment of a critical framework on smart cities development. The framework is an important tool for critically understanding current smart cities strategies and impact, as well as identifying, sourcing, and benchmarking future smart cities development. This work was based international studies; however, as a case study, it also aims to identify and compare trends and demands on the creation of future smart of cities in Australia and Brazil, seeking to demonstrate the usage and advantages of the framework proposed.

2. Methodology

This work provides a review of the literature selected from four databases (Scielo, ScienceDirect, worldwide science, and Cumincad), wherein cover the years from 2012 to 2018. The keyword used for the selection was 'smart city'. The search returned 367 results: Scielo 34, ScienceDirect 276, WordWideScience 39, and Cumincad 18. From these 367 publications were omitted 117, if they do not meet the proposal of this work or by the lack metadata or absence of other relevant information that could be extracted and organised by an automatised method. The final number for the selected publications was 250. The language of the selected publications was not restricted to English, and included works in Portuguese and Spanish, in order to increase the diversity of the authors. The review of the literature was divided into the following steps:

1. Publications were double-checked to certify if there was no replication
2. They were Categorised based on the framework proposed by Kummitha and Crutzen (2017)
3. The papers were categorised in the main political sectors of city planning: Energy, Mobility, Infrastructure, Sustainability, Economic, Communication, Housing, and Healthcare.
4. The papers were Identified and categorised in implementation strategies: development, creation, analysis, and management following by the computational techniques.

5. Publications were categorised based on their organisation rules as top-down approach or bottom-up.
6. Publications that discuss Brazil and Australia were separated into a subgroup.
7. Brazilian-Australian' s publications are compared in all the previous steps.

The second and final step was to analise the clustered works graphically to identifying tendencies along the time, seeking to explore future possibilities for implementations in different political-social contexts.

3. Kummitha and Crutzen 3RC Framework

The 3RC Framework was proposed by Kummitha and Crutzen (2017) with the objective to include questions related to the social dimension of the city, as well as the social aspects of sustainable development. The framework is articulated on three schools of thoughts: Restrictive, Reflective, and Rationalistic or pragmatic. In addition to these schools, there is also a critical school of thought. In this paper was decided to include a fourth category dedicated to literature reviews.

Kummitha and Crutzen (2017) define articles as Restrictive school of thought when the focus discussed paper's authors's are Information and Communication Technologies (ICTs) as the key component necessary to transform cities into smart cities, furthermore, in papers of this school of thought, are not mentioned social inclusion or social justice as an important factor on the implementation of smart city practices.

On the other hand, the Reflective school of thought questioning the objectives for which the Restrictive school adopts as a criterion for the implementation of smart cities, however, maintain "their core beliefs in the positive power of ICTs by integrating human elements within their construction"(Kummitha and Crutzen 2017). A key factor for this school of thought is that human capital and technology are jointly developed seeking to enhance and stimulate human capacity through technology, thereby helping to improve social order.

Authors from the Rationalistic school of thought argue that smart cities should focus on people and their capabilities instead of focusing all efforts on ICTs or technologies. They believe that an important aspect in the developing of a smart city might be empowering communities by promoting skills and capabilities, and as a result, technology emerges as a consequence of local context needs, in an appropriated political context. The main role for this school of thought is that the citizens should be able to invent and promote the use of technology addressing their own problems.

In contrast to all other schools of thought, the Critical school criticises the smartness of such cities that self-proclaiming itself as smart cities. This school argues that the implementation of smart cities by big corporations such as IBM and Cisco is a Neo-liberal strategy seeking to privatise urban space around the world (Kummitha and Crutzen 2017).

4. Categorisation

In order to understand the smart cities actual trend scenario, and try to add more layers of information to the previous works (Kummitha and Crutzen 2017;

Letaifa 2015; Thompson 2016; Andrade, E.A. de, Franceschini, M.C.T. 2017), this work pursued to categorise the literature in the main city planning sectors, smart cities implementation strategies, computational techniques, and organisation rules (top-down and bottom-up). This framework can contribute with new pieces of research that seek to implement future smart cities, as well as support the discussion on the establishment of a critical framework for smart cities' development.

The literature studied in this work were clustered by subjects, through similarities found in main political sectors of city planning: energy, mobility, Infrastructure, sustainability, economy, communication and social services, housing, and healthcare. The eight sub-domains of city planning political sectors were illustrated in Table 1. Also, the publications were divided into four implementation strategies: development, creation, analysis, and management focused on to understand the chosen period (2012-2018), that located the academic efforts on the smart cities' theme. Publications could be catalogued in one or more implementation strategies, for example, authors could develop pieces of research both in creation and analysis at the same time.

Table 1. Computational techniques.

Geographic Information System (GIS)	"A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present all types of geographical data." (Healey and Delve 2007)
Web-Scraping	"Web scraping is the practice of gathering data commonly accomplished by writing an automated program that queries a web server, requests data (usually in the form of HTML and other files that compose web pages), and then parses that data to extract needed information."(Mitchell 2018)
Internet of Things (IoT)	"A variety of "things" or "objects", such as RFID, sensors, actuators, mobile phones, which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbouring "smart" components to reach common goals."(Giusto 2010)
3D Modelling	Is the process of developing a graphic representation of an object in three dimensions via specialised software. A device used to measure pressure, position, temperature, acceleration, and other properties, responding with a feedback.
Sensors	A device used to measure pressure, position, temperature, acceleration, and other properties, responding with a feedback.
Virtual Reality (VR)	It is a technology that that provides an indirect experience by creating a virtual space that interacts with the human sensory systems and overcomes spatial and physical constraints of the real world.(Choi et al. 2015)
Augmented Reality (AR)	It is a technology that provides an experience integrating 3D virtual objects into a 3D real environment in real time.(Azuma and Malibu 2006)
City Information Modeling (CIM)	"A parametric model of an urban area with the data related with it providing simultaneously a design environment and an analytical environment where urban spaces can be measured, analysed and changed interactively along a design process."(Bilal et al. 2011)
Application (App)	Computer software designed to perform a group of coordinated functions, tasks, or activities in order to benefit the user.
Online Transaction Processing (OLTP)	"A method for executing a Secure online transaction between a vendor computer and a user computer, wherein the vendor computer and the user computer are interconnected to a computer network Such as the Internet for data communications there-between" (Sixtus 1999)
Internet of Agents (IoA)	"Internet of Agents (IoA) as an alternative to add an intelligence and autonomy component for IoT devices and networks."(Pico Valencia et al. 2018)
Web-Services	Electronic devices communicating with each other via the World Wide Web
Interactive Voice response (IVR)	"It is a technology that permit a computer to interact with humans through the use of voice and Dual-tone multi-frequency signaling (DTMF) tones input via a keypad."
Computational Fluid Dynamic (CFD)	"Computational fluid dynamics (CFD) is a science that, with the help of digital computers, produces quantitative predictions of fluid-flow phenomena based on the conservation laws (conservation of mass, momentum, and energy) governing fluid motion. "(Wu 2012)
Big data	"A new generation of technologies and architectures, designed to economically extract value from very large volumes of a wide variety of data, by enabling the high-velocity capture, discovery, and/or analysis."(Gantz and Reinsel 2011)
Blockchain	It is a growing list of records, called blocks, which are linked using cryptography. These blocks contain a cryptography hash of the previous block, a timestamp, and transaction data
Simulation	A simulation is an imitation of the operation of a real-world process or system by a developed abstract model.

This review found 17 different computational techniques related to smart cities: Geographic Information System (Gis), Web-Scraping, Internet of Things (IoT), 3D Modelling, Sensors, Virtual reality (VR), Augmented Reality (AR), City Information Modelling (CIM), Application (App), Online Transaction Processing (OLTP), Internet of Agents (IoA), Web-Services, Interactive Voice Response (IVR), Computational Fluid Dynamic (CFD), Big data, Blockchain, and Simulation. These computational techniques were briefly described in Table 2.

Table 2. City planning political sectors.

Energy	• Increase transparency and reliability of energy supply; systems by providing and facilitate information exchange; about providers and users; • Managing public lighting and natural resources; • Exploiting renewable resources such as heat, solar, cooling, water, and wind power.
Mobility	• Optimising logistics and transportation in urban areas; • Affording users with real-time and multi-modal information for traffic and transport efficiency; • Discussing sustainable public transportation seeking environmental-friendly fuels and new propulsion systems.
Infrastructure	• Improving city infrastructure systems by ICT.
Sustainability	• Using technology to protect and increase efficiency in managing environmental resources; • Adapting or retrofitting existing structures to gain energy and water efficiency.
Economy	• Integrating the city in national and global markets; • Encouraging innovation and entrepreneurship; • Discussing and deal with the economic aspects of the city by ICT.
Communication and Social Services	• Exchange of real-time information by citizens and governance; • Digitised public administration; • Promoting and communicate cultural events; • Communicate and managing entertainment, tourism, and hospitality; • Developing tools for social learning and participation, improving the quality of life; • Discussing and implementing Social policies by ICT.
Housing	• Building technologies to create living environments.
Healthcare	• ICT and remote assistance to diagnose and prevent diseases.

The hierarchical organisation of the smart city´s implementation was divided into two implementation strategies: top-down and bottom-up approach. A top-down approach is categorised as strategies where policies, steps, and implementations are defined by a governance or specialised company which will lead the process from the beginning to the end, where citizens have few opinions or none during the decision process, while the bottom-up approach is centred on the empowering of the community promoting skills and capabilities to deal and create with technology consequently these policies and strategies trying to make the city "smart" by the interaction of the citizenry.

The categorisation process was realised using Zotero and LibreOffice Calc (LOC). In Zotero the publications were organised and categorised, and the reports about each cluster were generated. LOC was used to import the reports in a spreadsheet format in order to control and generate graphs of the selected papers. This semi-automatised process increased productivity in the repetitive tasks that are common in literature reviews.

5. A publications' panorama on smart cities: 2012 - 2018

In this section, as the first attempt of this research, we will present and compare graphically the collected information in the 250 publications trying to expose, a quantitative analysis on trends in the academic discussion about the smart cities implementation.

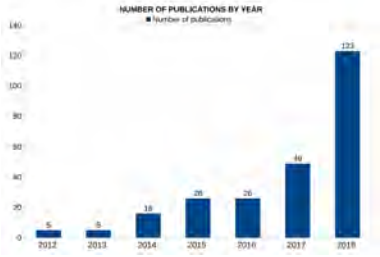


Figure 1. Number of publications by year .

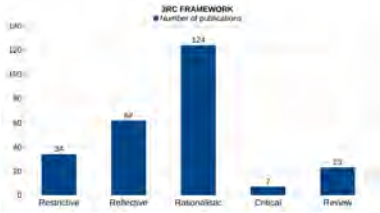


Figure 2. 3RC Framework.

As shown in Figure 1, publications on the smart cities are growing over time. Summing the publications during the years from 2012 to 2017 there are just five more publications along this period than the totality that was produced in the year 2018. Kummitha and Crutzen (2017) noticed an increase in publications with human-centred approaches on smart cities. Our work identifies and confirms this claim, which can be seen in our categorisation of 3RC framework in Figure 2 it shows 124 publications on the Rationalistic school of thought followed by the Reflective school with 62, for both schools the social dimension of the city is a relevant subject that may knew technology as a whole package solution of a smart city.

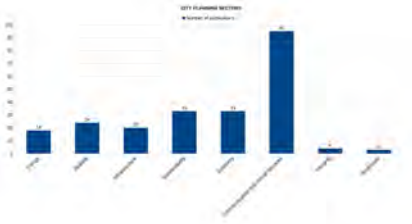


Figure 3. City Planning Sectors.

Our work reveals that “Communication and Social Services” is the major issue on smart cities discussed by scholars in the category of city planning sector. There are 95 publications on this category, followed by Sustainability and Economy at the second place both with 33.

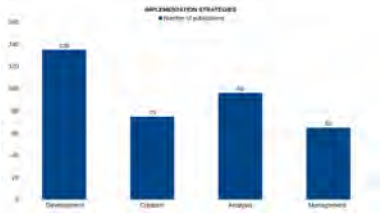


Figure 4. Implementation Strategies .

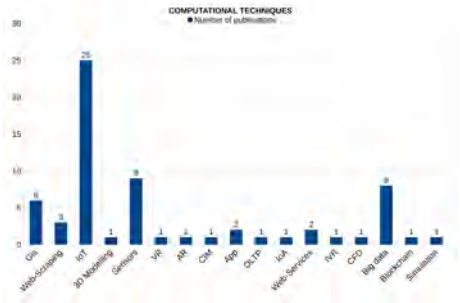


Figure 5. Computational Techniques.

Finally, this work noted that on this complete publications sample, the tendency for a smart city implementation is by a more human-centred approach, with communication and social services as the city planning sector with the major concerned about the implementation of smart cities. On the Implementation Strategies, developing ideas and concepts about the smart cities is the major issue. There are different computational techniques explored by the authors, with IoT as the most discussed, however, despite the fact that the smart cities human-centred approach were the most prominent among the publications, the main organisation rule found in the publications was the top-down approach.

6. "Developed" vs "Developing" Countries: The Australian and Brazilian case

The problems that have been emerging to the cities around the world have similar features, such as management of urban growth, dealing with migratory movements, the urbanisation management through a sustainable development approach. However, achieving a solution for such problem depends on the proper definition of the problem in the current political-social context that the problem is addressed, or the expected outcomes tend to fail along the time.

As an example of the implications and trends on the pieces of research produced in developed and in process of developing countries, this paper chooses Brazil and Australia as the case studies. Australia and Brazil share some common, both are located in the Southern Hemisphere, have continental sizes, had colonial past, and have an indigenous native population. However, there are more differences than similarities if we analyse the historical development of these

countries, as well as the current position on social well-being. For illustration, Brazil is the 79th in the list of Human Development Index (HDI), while Australia is the third country in the list. Brazil and Australia were chosen in order to try to understand and compare how countries with similar geographic conditions but different political-social context are dealing with the theme of smart city in the academy.

Without going beyond historical questions, which is out of the scope of this paper discuss and analyse the historical differences between Australia and Brazil at this time. However, this research is trying to understand where is possible to trace convergent lines between these two nations in the academic discussion on the implementation of smart cities. Furthermore, to identify main differences in the trends by analysing the produced graphs on the review.

7. Australia and Brazil in the publication scenery on the Smart City

In this section, we will present and compare graphically publications selected on the literature that presented a correlation with Brazil, Australia or both.

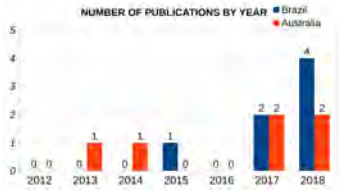


Figure 6. Number of publications Brazil/Australia by year.

We found in the literature 13 publications that deal with the theme Brazil/Australia, wherein discussing six about Brazil, five about Australia and one dealing with both countries. Figure 6 shows the publications from both countries distributed by the years.

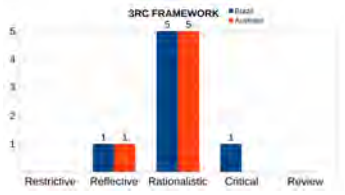


Figure 7. 3RC Framework Brazil/Australia .

Figure 7 shows the tendency of the whole sample among scholar of both countries are biased to address the implementation of smart cities by a human-centred thought, both countries have 5 publications categorised on the Rationalistic view, followed by one publication on the Reflective school of thought, and Brazil has an additional paper on the critical school. As shown in Figure 8 “Communication and Social Services” is the main topic discussed by

Brazilians with 3 publications, while the first position for Australian publications was occupied by both Infrastructure and Economy with 2 publications.



Figure 8. City Planning Sectors Brazil/Australia.

The analysis was the main topic discussed in Brazilian publications, while management was the most cited by Australians, as shown in Figure 9. The two computational techniques cited in the sample from Brazil/Australia were found in Brazilian publications, IoT and Simulation, with one publication by topic. All the publications on the sample Brazil/Australia were categorised by organisation rules as a top-down approach.

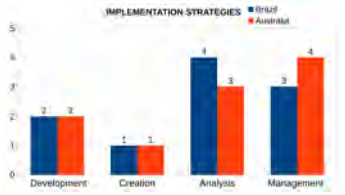


Figure 9. Implementation Strategies Brazil/Australia.

In a general overview, Brazilian and Australian publications, have similar outcomes in understanding of how a smart city should be, as well as on the understanding on how we should implement a smart city, this fact can be noticed by the utilisation of 3RC Framework developed by Kummitha and Crutzen (2017). Despite the differences in the focus of city planning sectors, results on the different subjects are similar and both follow the trends exposed by the other authors from the complete sample.

8. Further Research

This research is part of a work in progress, which forms a foundation for the PhD project of one author of this paper. We have been working on the literature review. It is known that these papers amount just reflects part of publications on the theme, as this research is just in the beginning, and this work was restricted to the keyword “smart city” during the process of searching and selecting publications. Furthermore, “smart cities” is an old concept that is limited in itself and mostly understood under a technological point of view. In further works, new keywords will be included in order to seek a more embracing and integrative perspective, also a more appropriate term, such as Future cities that focus more on the integration of the different agents, layers and systems that compose city space. We expect

to obtain a compiled discussion on the concept of the future cities, also, it could collaborate with future research in this field. In the next steps in this research, we focus on analysing the collecting of data beyond the quantitative analysis, seeking a more in-depth qualitative analysis.

Acknowledgments

This research is supported by Australian Government Research Training Program (RTP).

References

Andrade, E.A. and Franceschini, M.C.T.: 2017, O direito à cidade e as agendas urbanas internacionais: uma análise documental, *Ciência & Saúde Coletiva*, **22**(12), 3849-3858.

Beirão, J., Montenegro, N. and Arrobas, P.: 2012, City Information Modelling: Parametric Urban Models Including Design Support Data, *Conferência da Rede Lusófona de Morfologia Urbana. Anais*, **1**, 13.

Choi, S., Jung, K. and Noh, S.D.: 2015, Virtual Reality Applications in Manufacturing Industries: Past Research, Present Findings, and Future Directions, *Concurrent Engineering*, **23**(1), 40-63.

Department of Economic and Social Affairs, Population Division., D.E.S.A.: 2017, "World urbanization prospects: The 2018 revision, online edition." . Available from <https://esa.un.org/unpd/wup/> (accessed 1st December 2018).

Gantz, J. and Reinsel, D.: 2011, Extracting Value from Chaos, *IDC iview*, **v. 1142**, 12.

D. Giusto (ed.): 2010, *The Internet of Things: 20th Tyrrhenian Workshop on Digital Communications*, Springer.

Healey, R.G. and Delve, J.: 2007, Integrating GIS and Data Warehousing in a Web Environment: A Case Study of the US 1880 Census, *The internet of things: 20th Tyrrhenian workshop on digital communications*, **21**(6), 603-624.

Hollands, R.G.: 2008, Will the Real Smart City Please Stand up?: Intelligent, Progressive or Entrepreneurial?, *City*, **12**(3), 303-320.

Hu, H.H. 2012, Computational Fluid Dynamics, *in* E.L. Elsevier (ed.), *Fluid Mechanics*, Elsevier, 421-472.

Kummitha, R.K.R. and Crutzen, N.: 2017, How Do We Understand Smart Cities? An Evolutionary Perspective, *Cities*, **67**, 43-52.

Ben Letaifa, S.: 2015, How to Strategize Smart Cities: Revealing the SMART Model, *Journal of Business Research*, **68**(7), 1414-1419.

Mitchell, R.: 2018, *Web Scraping with Python: Collecting More Data from the Modern Web.*, O'Reilly Media, Inc..

Sixtus, T.: 1999, *Method and system for secure online transaction processing*, U.S. Patent No. 5,903,721.

Thompson, E.M.: 2016, Smart City: Adding to the Complexity of Cities, *34th eCAADe Conference*, **1**, 10.

THE SCHOLARLY REWARDS AND TRAGIC IRONY OF 3D MODELS IN VIRTUAL HERITAGE DISCOURSE

HAFIZUR RAHAMAN[1] and ERIK CHAMPION[2]
[1]*Research Fellow, Faculty of Humanities, Curtin University, Australia*
[1]*hafizur.rahaman@curtin.edu.au*
[2]*UNESCO Professorial Chair in Cultural Heritage & Visualisation, CIC and AAPI, Faculty of Humanities, Curtin University, Australia*
[2]*erik.champion@curtin.edu.au*

Abstract. To validate the hypothesis that virtual heritage papers are reliant on providing scholarly argumentation based on 3D models, and convenient access is provided to these models where relevant, this study reviewed 264 articles from the last three available proceedings of major digital heritage events and conferences (14 in total). The findings revealed this was not the case, few contain references to accessible 3D models. We discuss why this may be so, and we outline recommendations for ensuring that virtual heritage 3D models can be preserved and accessed.

Keywords. Virtual heritage; 3D model; repositories; publications; preservation.

1. Introduction

Various commentators and charters (London, Seville) have stated that the success of a virtual heritage (VH) project depends on 3D models and associated scholarly content (Tucci et al., 2017, Scopigno et al., 2017). Despite the importance of three-dimensional space to archaeology and heritage studies, 3D models seldom play a vital role in related scholarly argument and publications. In other fields, particularly in science, experimental data is made available for comparison and re-evaluation. Yet VH publications featuring 3D models are uncommon, with few examples of specific tools to aid scholarly arguments, even though many projects are funded from the public purse with the aim of disseminating cultural significance. However, 3D digital models are mostly inaccessible, their online existence and usage short-lived. Rome Reborn, Beyond Space and Time, and the VRML 2.0 showcase SGI Teotihuacán model, are famous but lost examples, *"... as digital heritage it [virtual heritage] has been remarkably unsuccessful at saving its own showcase projects"* (Champion, 2018).

To uncover why virtual heritage has so few accessible examplars, this paper attempted to record accessible 3D models (and related 3D assets) from the proceedings of the last three consecutive publications of major digital heritage events and conferences, namely, The *International Society for Virtual Systems and Multimedia (VSMM), Computer Applications and Quantitative Methods in*

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 695-704. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Archaeology (CAA), International Committee of Architectural Photogrammetry (CIPA), The European Mediterranean Conferences (EuroMed), and *The Digital Heritage International Congress*. 264 selected articles from 14 proceedings (containing 1483 papers) were studied, and the results are presented below (Table 1).

2. Rationale of the study

Due to their rapid increase (Niven and Richards, 2017), it has become increasingly challenging to retain 3d assets (Betts et al., 2011) although ensuring the continuation of accessibility and management and negating data loss has long been recommended by scholars like Niven and Richards (2017), Paquet and Viktor (2005), Clarke (2015), Haubt (2013), Pan et al. (2012), Doyle et al. (2009a), and Champion (2018). Nonetheless, long-term preservation and access to these collections can be overlooked (Paquet and Viktor, 2005). Kuzminsky and Gardiner (2012) suggested that the long-term storage of 3D datasets are hampered by the unreliability of storage, while Niven and Richards (2017) declared file formats and metadata are key issues. Koller (2008) instead recommended focusing on long-term objectives and argued for centralised, open repositories of 'scientifically authenticated virtual environments' developed specifically for cultural heritage sites. However, studies from Koller et al. (2008, 2009) on 3D archives (such as the Stanford Digital Michelangelo Project, Stanford Digital Forma Urbis Roman Project, UCLA Digital Roman Forum, CyArk and a few others); concluded projects typically lack a "peer-reviewed, searchable, and interoperable repository" and are often in an early stage of development.

In contrast, a study by Doyle et al. (2009a, 2009b) on long-term preservation of 3D data highlighted metadata and emulation issues. Paquet and Viktor (2005) also recommended an 'emulator' to run old programs or files on new platforms and standard file formats held in a central repository. To enhance accessibility and preservation of 3D digital heritage assets, Havemann and Fellner (2007) suggested considering '3D' models as a document; with features like full mark-up, indexing, and retrieval capabilities to allow for better integration with digital libraries. Clarke (2015), on the other hand, pointed out the 'obligations' of the concerned parties; and believed this 'digital dilemma' (the democratization of academic data versus legal obligations imposed by the heritage authority or the country where the data originated) directly impacts on the integrity of data preservation and frequently leads to the loss of 3D assets.

Many virtual heritage projects and associated 3D data may still exist on personal and corporate servers as their whereabouts are currently unknown. Some projects may require only a modicum of effort to ensure that they can work on today's platforms, browsers and computers while others may face potential legal issues, or have versioning issues. However, if the 3D assets are not being used by the public, to educate the public on the cultural significance of the heritage models that they are meant to examine and promote, and if they are not being used by scholars, IT specialists, curators or interpreters to improve, restore or develop heritage projects or the discourse around it, then they are not contributing to heritage.

3. Reviewing the publications

The primary aim of this paper is to raise awareness regards the protection and preservation of 3D heritage assets with and without dynamic data. There is an increase in the number of academic papers but a decreasing number of accessible 3D assets even in dedicated digital heritage conferences. The *Quality of Reporting of Meta-analysis (QUORUM)* statement presented by Moher et al. (2000) was chosen to select the papers, and a three-step procedure has been followed.

The **first step** included the selection of the source, retrieval and primary screening of the publications. Popular and renowned international events such as conferences and symposiums on digital heritage and allied domains were chosen, and their last three consecutive proceedings were selected, from 2012 to 2017. They include: *The International Society for Virtual Systems and Multimedia (VSMM), Computer Applications and Quantitative Methods in Archaeology (CAA), International Committee of Architectural Photogrammetry (CIPA), The European Mediterranean Conferences (EuroMed)*, and *The Digital Heritage International Congress*. A total of 1483 papers from 14 proceedings were collected from their respective digital repositories and publication databases. 296 articles that had contained representative images or references of 3D digital assets of heritage objects were selected for further study.

The **second step** continued with another screening process. The selected papers from the first step were reviewed in terms of their abstract, and rapid examination of structure and content in order to - *exclude irrelevant articles* (such as review papers and short survey papers), *eliminate duplicates* (or similar paper published in other proceedings with minimum changes), and *exclude articles on digitization of painting and artworks*. Thirty-two articles have been excluded at this stage.

Final sorting, review and analysis of the selected articles was done in the **third step**. The final articles selected for this study were 31 (out of 173) from *VSMM*, 38 (out of 240) from *CAA*, 79 (out of 305) from *CIPA*, 61 (out of 284) from *EuroMed*, and 55 (out of 481) from *Digital Heritage Congress*. The selected articles were studied to discern whether they provide any references citing external links or information to - *accessible 3D assets* (and the degree of their accessibility), *accessible video content*, *visual materials* (such as VR models, photographs, images of 3D reconstruction etc.), and *other external resources* (if any). Detailed descriptive data was inputted into MS Excel. For each article reviewed, required information about the criteria (mentioned above) was inserted into the database and presented in a tabular format.

4. Results of the Study

From a group of 1483 articles, 264 papers were selected, which accounts for 17.8% of the total publications published in *VSMM, CAA, CIPA, EuroMed and Digital Heritage Congress*, from 2012 to 2017. The results of the study, (Table 1), shows that a significant number of articles (i.e. 17.8%) refer and contain images of 3D assets or 3D digital models but accessible 3D assets or 3D models were found only in nine (9) articles, i.e. 3.4% of the selected publications.

Table 1. Articles contain references to 3D models and heritage assets.

Conference/event name		VSMM		CAA		CIPA		EUROMED		Digital Heritage	
Accessible articles & year of publication		Year	No.	Year	No.	Year	No.	Year	No.	Year	No.
		2017	55	2015	117	2017	111	2016	105	2015	270
		2016	65	2014	73	2015	82	2014	84	2013	211
		2014	53	2013	50	2013	112	2012	95	-	-
		Total	173		240		305		284		481
Articles contain reference to 3D heritage assets			31		38		79		61		55
References include											
(a)	Accessible 3D contents		**0**		**1**		**3**		**1**		**4**
(b)	Accessible Videos		1		2		1		2		6
(c)	Other accessible visual materials (VR models, photographs, images of 3D models etc.).		1		4		6		5		17
(d)	Non-accessible/dead web links		3		0		5		3		8

Of the 264 selected articles; 12 contain external web-links to video content (4.55%), 33 articles (12.5%) provide web links for other accessible visual material, including VR models, photographs and images of 3D models. 19 articles have been found to refer to external web-links for more information; however, none of the links worked when this paper was written (1 September 2018).

All nine (9) articles that provided external links to accessible 3D assets shared four common locations/repositories. These articles included only five external links for storage of their 3D assets, which are:

1. http://3dicons-project.eu (which leads to https://www.europeana.eu)
2. http://dati.comune.bologna.it/3d
3. http://www.cyark.org
4. https://skfb.ly/DtVq
5. https://harvest4d.org/?page_id=1367 (access date 10 Feb 2019)

Our conclusion is that 3D models are not being valued as essential scholarly and educational assets; as there is a lack of accessible 3D digital assets and projects which have been used or produced in supporting of these scholarly publications. Related factors may be limitations inherent in available platforms and infrastructures, a variety of software, maintenance requirements of assets and staff, time, or simply a lack of guidance or foresight.

5. Repositories and Cultural Heritage 3D Models

Despite recent EU and North American moves to create archives and digital heritage infrastructure; 3D models are still not fully accessible to the general

public (Champion, 2018). Too few journals allow submission and hosting of 3D contents. However, most of the institutional repositories only permit downloading with restricted file formats. In some cases, only the PDF file with embedded 3D (such as in CARARE) is allowed. In most cases, the general public cannot upload any 3D assets. For example, CyArk's Open Heritage Program (launched in April 2018) allows the general public to access their collection of point cloud data and photogrammetric imagery (26 sites at the time of writing). However, users need to apply online for permission before they can download any 3D content.

Table 2. 3D models in journals and archives.

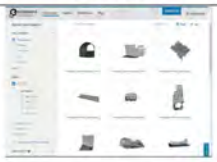
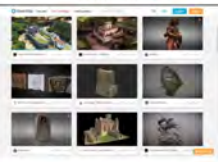
DAACH journal	Europeana	Sketchfab	Smithsonian
			

Table 3. Selected 3D repositories with common features.

Name	Supported file format	Fees	Accessibility	Data size	3D model display
Public/institutional repositories					
Smithsonian (http://3d.si.edu)	STL, OBJ, Single ASCII point cloud	Free	With few exceptions, Six3D offers access to the data sets	Download limit not known	3D
CyArk (http://www.cyark.org)	LiDAR, point cloud, photogrammetric imagery	Free, require online application	Licensed under a Creative Commons Attribution-Non-commercial 4.0 International License	Varies, prior permission required	2D, 3D
Europeana http://www.europeana.eu/portal/en	Jpeg, GIF, PNG, PDF, Plain ASCII, MP3, MPEG, AVI, FBX, mtl, OBJ	Free	Most databases are not accessible anymore	Not known	2D, 3D
EPOCH (http://epoch-net.org/site)	PDF	Free	Not known	Unlimited	2D
CARARE (http://pro.carare.eu)	PDF, 3D PDF	Free	Not known	Unlimited	3D inside PDF
Private/commercial repositories					
Sketchfab (https://sketchfab.com)	50 popular file formats	Basic and Education access are Free	Varies between paid and free model	Upload varies, based on membership. Unlimited download	2D, 3D, AR, VR
MyMiniFactory (https://www.myminifactory.com)	54 popular file formats	Free/paid option to download and print		Unlimited uploads	2D
Blendswap (https://www.blendswap.com)	37 popular file formats	Free	Varying Creative Commons	Upload/download varies on membership	2D
TurboSquid (https://www.turbosquid.com)	16 popular file formats	Free and paid	Model Licenses: Various	No restriction	2D, 3D
Unity Asset Store (https://assetstore.unity.com)	.FBX, .OBJ	Free and paid	Model Licenses: Various, Own EULA.	4GB (max) upload	2D, video

Sketchfab, a commercial platform hosting service, claims to store and display the digitised 3D models of five hundred cultural institutes (Marchou 2017). Sketchfab allows the public to host, minor edit, share, trade and view models in AR/VR with the supplied Sketchfab app. The other commercial repositories such as Turbo Squid, ShareCG, MyMiniFactory and Blendswap are mostly for trading 3D models and not intended for preservation. Additionally, they charge fees on trading and may not be interested in archiving, and their archiving policy is not obvious in their respective online portal. However, these commercial repositories demonstrate the potential for allowing versatile file formats (e.g. Blendswap), online support for conversion of various file formats (e.g. Turbo Squid), and can deal with large amounts of traffic (i.e. Unity asset store). Table 3 presents the most popular repositories; particularly features to support accessibility and preservation of 3D assets.

6. Critical issues and suggestions

Increases in technological sophistication may be moving faster than we can cope with; a 'double-edged sword' (Thwaites 2013). Other possible reasons might include copyright issues, precious and costly data sets which cannot be easily shared, technical failures, expiration of research funding, natural disasters, the closure of the project or key people moving on (Greenop & Barton 2014). This paper suggests *three critical issues* that are likely to be the primary reasons behind the tragic fate of 3D models.

Firstly, there is no clear, full proof way to preserve 3D assets. This study shows that only 9 of the 1483 publications surveyed provide access to their respective 3D content. Of these 9, only 5 are stored in public (or institutional) repositories, indicating a lack of concern or useful strategies for leveraging long-term infrastructure. There are more than fifty repositories developed by both public and private organisations or individuals. However, it is often difficult to find models from specialised cultural heritage institutional repositories, as they are typically not connected with external sites or portals. On the other hand, the commercial model repositories such as ShareCG, Turbo Squid, CG Trader and Yeggi often lack data provenance and metadata. However, commercial repositories provide some consistent formats and protocols, and 3D models are increasingly easier to find and to access. Nevertheless, most of these portals (both commercial and non-commercial) rarely provide other related information and resource links for further study or use (Champion, 2018).

Secondly, there is insufficient shared understanding as to how to best develop, integrate and demonstrate the research values of 3D heritage models. Virtual heritage is not simply the recreation of what was there in the past or a collection of 3D objects. Cultural objects or heritage artefacts have specific inherent meanings, associated with and signified by the traditional inhabitants from their cultural perspectives. While archaeologists, historians and other specialists may be sufficiently motivated and trained to find the relevant paradata, the general public is a different matter. A pristine photorealistic 3D digital reproduction (born digital or digital surrogate) is not sufficient by itself for the public to interpret and perceive its significance (Rahaman et al., 2012). Virtual heritage, therefore, must convey

the associated contextual/situated values, interpretations and contestations of those specific heritage objects or sites for a deeper understanding of the culture that it belongs to; hence it also requires paradata.

Thirdly, digital scholarly articles are typically published and distributed in PDF format, and while they are relatively secure, PDFs have limited interactivity, integration and immersivity. Few publishers accept 3D content, but images are more difficult media to show or demonstrate a process. Additionally, the models are typically not dynamically linked to any scholarly information (i.e. metadata and paradata). In this situation, there is an acute need for 3D archives (Limp et al., 2010), and to ensure concurrent usage (Garnett and Edmond, 2014). It may be possible to resolve the technical issues but, without public involvement, understanding and appreciation, a virtual heritage project is likely to fail (Champion, 2018), so this paper proposes *seven recommendations* to alleviate these issues.

Despite recent advances in creating and developing archives and digital humanities infrastructures, 3D models remain an issue: they are incomplete, static, or protected. For example, on the Smithsonian website, users can play with 3D models, sometimes they can be edited but these digital models do not provide full archival records or other related information or resource links. There is also the issue of responsibility and stewardship of digital data; Clarke (2015) suggested a robust public repository (instead of private archives) with flexible copyright laws.

In Europe, ARIADNE and 3D-ICONS have developed standards and archives. However, 3D models are not sufficiently incorporated within a framework and rarely support a common and stable file format or extension. A desire for an open and standard file format has also been echoed by Niven (2017), Paquet (2005), Doyle et al. (2009a), Limp et al. (2010), and Havemann (2007). McHenry and Bajcsy (2008) mentioned the presence of more than 140 file formats for 3D models. Yet, most formats are proprietary (Paquet and Viktor, 2005), and it is difficult to find a compelling and free file format that is widely acceptable, free and developed for cross-platform deployment. Given the variety of 3D file formats available and the wide range of disciplines creating 3D heritage models, it may not need to confine projects to a single file format. Instead, one can agree upon a shared framework of assets sharing in which the model is generated dynamically and on the fly from simpler components, inside a game engine or VR package.

There are few online libraries and accessible depositories for virtual heritage 3D models. Finding a 3D model is difficult. Agreed metadata standards are required to search and classify them. Preserved data, therefore, should be 'understandable' (Niven and Richards, 2017) with standardised data sets (or schema). Many are based on Dublin Core, but few are specifically for 3D digital heritage. One exception is the CARARE Schema (D'Andrea and Fernie, 2013), based on CIDOC-CRM and partly inspired by MIDAS UK (Geser and Niccolucci, 2013, Champion, 2018), which can be extended to cover 3D object semantics (Havemann and Fellner, 2007).

The London Charter stated 3D models must be recognised as a key scholarly resource (Di Benedetto et al., 2014). As a core part of a virtual heritage publication, the 3D model should be traceable, linked to other related projects

and associated scholarly information. Additionally, heritage scholars and experts may need to trace the provenance of different parts of a 3D shape to access its authenticity; especially for 3D models, which are generated in support of a virtual conjectural reconstruction. However, it is often a challenge to tie additional information to parts of a 3D model (Havemann and Fellner, 2007). For improved scholarly practice, 3D models could be component-based, (ideally, they would be dynamically created at runtime) and, in a model format, searchable, with correct meshes, at a size suitable for downloading (Champion, 2017). To incorporate information regarding the completeness, measurement methodology and accuracy of the models, metadata and Linked Open Data can assist in connecting meaningful associated media. The publication system therefore will be able to dynamically link 3D components via assigned URLs (i.e. Linked Open Data).

Successful virtual heritage projects frequently depend on community involvement (Dave, 1998, Eiteljorg, 1998, Mosaker, 2001). The community may comprise scholars, students, and the wider public, including the original shareholders and the owners of the simulated cultural content. One must also endeavour to incorporate the community's understanding, feedback, perception (Witcomb, 2008) and engage them in dialogic interaction (Rahaman and Tan, 2011). A virtual heritage project dynamically linked to scholarly articles and supported by a robust feedback system could help (Champion, 2016). It may also need to consider approaches to allow indigenous or native communities' contribution and involvement in developing guides and protocols, creation of accessible levels of cultural knowledge, researching and testing methods for providing on-demand 3D model formats, tailoring ontologies, metadata and folksonomies for heritage simulation, and developing permissions related to copyright, ownership and guardianship (Champion, 2018).

7. Conclusion

From the literature review of 264 articles across 14 proceedings, this paper has identified three issues which are hindering the curation, preservation and accessibility of the 3D digital heritage assets. The reliability of 3D data for long-term conservation, unique file formats, and agreed metadata, including information on the acquisition process and copyright issues, are problematic. Widespread dissemination and access to free and low-cost 3D assets for education and scholarly use is challenging. Accuracy, authenticity, reliable shared formats, and ownership rights remain issues.

Despite the increasing number of digital 3D models (Münster, 2018) and more than 50 commercial repositories available to download, share and trade them (Von Ubel 2019), we have not found many examples in the surveyed proceedings and publications to secure and collect them. Disregarding recent but still relatively few North American and European initiatives on digital humanities infrastructures, 3D models are not yet fully incorporated (Huggett, 2012). Perhaps we can encourage and recognise those institutes following archival practice and include metadata and paradata by increasing data management requirements in research grant forms, and including links to named repositories when referring to or using 3D models in social media.

We cannot afford to have our 3D digital models disappearing or missing from virtual heritage publications; for it means data and scholarly arguments are harder to evaluate; and methodological, technical and experiential advancements will be curtailed without reliable, re-verifiable data. In response, this paper has proposed seven suggestions to facilitate further incentives, guidelines and frameworks.

References

Di Benedetto, M., Ponchio, F., Malomo, L., Callieri, M., Dellepiane, M., Cignoni, P. and Scopigno, R. 2014, Web and mobile visualization for cultural heritage, *in* D. Koller, B. Frischer and G. Humphreys (eds.), *3D Research Challenges in Cultural Heritage*, Springer, 18-35.

Betts, M.W., Maschner, H.D., Schou, C.D., Schlader, R., Holmes, J., Clement, N. and Smuin, M.: 2011, Virtual zooarchaeology: building a web-based reference collection of northern vertebrates for archaeofaunal research and education, *Journal of Archaeological Science*, **38**(4), 755. e1-755. e9.

Champion, E.: 2016, The missing scholarship behind virtual heritage infrastructures, *14th Eurographics Workshop on Graphics and Cultural Heritage*, Genova, Italy, 57-65.

Champion, E.: 2017, Digital humanities is text heavy, visualization light, and simulation poor, *Digital Scholarship in the Humanities*, **32**(suppl_1), i25-i32.

Champion, E. 2018, The role of 3D models in virtual heritage intrastructures, *in* A. Benardou, E. Champion, C. Dallas and L.M. Hughes (eds.), *Cultural Heritage Infrastructures in Digital Humanities*, NY Routledge, Abingdon, Oxon New York, 172.

Clarke, M.: 2015, The digital dilemma: preservation and the digital archaeological record, *Advances in Archaeological Practice*, **3**(4), 313-330.

D., A. and Fernie, K.: 2013, CARARE 2.0: a metadata schema for 3D cultural objects, *Digital Heritage International Congress (DigitalHeritage), 2013*, 137-143.

Dave, B.: 1998, BITs of heritage, *Proceeding of Virtual Systems and Multimedia : Future Fusion*, The Natherlands, 250-255.

Doyle, J., Viktor, H.D. and Paquet, E.: 2009a, A metadata framework for long term digital preservation of 3D data, *International Journal of Information Studies*, **1**(3), 165-171.

Doyle, J., Viktor, H. and Paquet, E.: 2009b, Long-term digital preservation: preserving authenticity and usability of 3-D data, *International journal on digital libraries*, **10**(1), 33-47.

Eiteljorg, H.: 1998, Photorealistic visualizations may be too good, *CSA Newsletter*, **11**(2), 1-4.

Garnett, V. and Edmond, J.: 2014, "Building an API is not enough! investigating reuse of cultural heritage data" . Available from mpact of Social Sciences Blog<http://eprints.lse.ac .uk/71611/> (accessed 9 December 2018).

Geser, G. and Niccolucci, F.: 2013, Virtual museums, digital reference collections and e-science environments, *Uncommon culture*, **3**(5/6), 12-37.

Greenop, K. and Barton, J. R.: 2014, "Scan, save, and archive: how to protect our digital cultural heritage" . Available from The Conversation<https://theconversation.com/scan-save-and-a rchive-how-to-protect-our-digital-cultural-heritage-22160> (accessed 9 December 2018).

Haubt, R.: 2013, Virtual heritage archives: Building a centralized Australian rock art archive, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W2*, **40-5-W2**, 319-324.

Havemann, S. and Fellner, D.W.: 2007, Seven research challenges of generalized 3D documents, *Ieee Computer Graphics and Applications*, **27**(3), 70-76.

Huggett, J.: 2012, Lost in information? Ways of knowing and modes of representation in e-archaeology, *World Archaeology*, **44**(4), 538-552.

Koller, D.: 2008, Protected sharing of 3D models of cultural heritage and archaeological artifacts, *Proceedings of the 36th CAA Conference*, 6.

Koller, D., Frischer, B. and Humphreys, G.: 2009, Research challenges for digital archives of

3D cultural heritage models, *Journal on Computing and Cultural Heritage (JOCCH)*, **2**(3), 1-17.

Kuzminsky, S.C. and Gardiner, M.S.: 2012, Three-dimensional laser scanning: potential uses for museum conservation and scientific research, *Journal of Archaeological Science*, **39**(8), 2744-2751.

Limp, W., Payne, A., Winters, S., Barnes, A. and Cothren, J.: 2010, Approaching 3D digital heritage data from a multi-technology, lifecycle perspective, *Proceedings of the 38th annual international conference on computer applications and quantitative methods in archaeology (CAA)*, Granada, Spain.

Marchou, R.a.p.h.a.ël.: 2017, "Over 500 Cultural Institutions have joined Sketchfab" . Available from <https://blog.sketchfab.com//500-cultural-institutions-joined-sketchfab> (accessed 13 February 2019).

McHenry, K. and Bajcsy, P.: 2008, An overview of 3d data content, file formats and viewers, *National Center for Supercomputing Applications*, **1205**, 22.

Moher, D., Cook, D.J., Eastwood, S., Olkin, I., Rennie, D. and Stroup, D.F.: 2000, Improving the quality of reports of meta-analyses of randomised controlled trials: the QUOROM statement, *Revista Española de Salud Pública*, **74**(2), 597-602.

Mosaker, L.: 2001, Visualising historical knowledge using virtual reality technology, *Digital Creativity*, **12**(1), 15-25.

Münster, S.: 2018, Digital 3D modelling in the humanities, *DH*, 627-629.

Niven, K. and Richards, J.D. 2017, The storage and long-term preservation of 3D data, *in* D. Errickson and T. Thompson (eds.), *Human Remains: Another Dimension*, Elsevier, 175-184.

Pan, X., Schiffer, T., Schröttner, M., Berndt, R., Hecher, M., Havemann, S. and Fellner, D.W. 2012, An enhanced distributed repository for working with 3D assets in cultural heritage, *in* M. Ioannides, D. Fritsch, J. Leissner, R. Davies, F. Remondino and R. Caffo (eds.), *Progress in Cultural Heritage Preservation: 4th International Conference, EuroMed 2012, Limassol, Cyprus, October 29 – November 3, 2012. Proceedings*, Springer Berlin Heidelberg, Berlin, Heidelberg, 349-358.

Paquet, E. and Viktor, H.: 2005, Long-term preservation of 3-D cultural heritage data related to architectural sites, *Proceedings of the ISPRS Working Group*, **4**, 1-8.

Rahaman, H., Das, R. and Zahir, S. 2012, Virtual heritage: Exploring photorealism, *in* M. Ioannides, D. Fritsch, J. Leissner, R. Davies, F. Remondino and R. Caffo (eds.), *Progress in Cultural Heritage Preservation*, Springer Berlin Heidelberg, 191-200.

Rahaman, H. and Tan, B.K.: 2011, Interpreting digital heritage: A conceptual model with end-users, *International Journal of Architectural Computing (IJAC)*, **09**(01), 99-113.

Scopigno, R., Callieri, M., Dellepiane, M., Ponchio, F. and Potenziani, M.: 2017, Delivering and using 3D models on the web: are we ready?, *Virtual Archaeology Review*, **8**(17), 1-9.

Thwaites, H. 2013, Digital heritage: What happens when we digitize everything?, *in* E. Chng, V. Gaffney and H.e.n.r.y. Chapman (eds.), *Visual heritage in the digital age*, Springer, 327-348.

Tucci, G., Bonora, V., Conti, A. and Fiorini, L.: 2017, High-quality 3d models and their use in a cultural heritage conservation project, *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, **42**, 687.

Von Ubel, M.a.x.: 2019, "Free 3D Models – Best Download Sites & 3D Archives of 2019" . Available from ALL3DP<https://all3dp.com/1/free-3d-models-download-best-sites-3d-archive-3d> (accessed 12 February 2019).

Witcomb, A. 2008, The materiality of virtual technologies: A new approach to thinking about the impact of multimedia in museums, *in* Y.E. Kalay, T. Kvan and J. Affleck (eds.), *New Heritage: New Media and Cultural Heritage*, Routledge-Taylor and Francis Group, London and New York, 34-48.

INTELLIGENT SYSTEMS AND MASS PRODUCTION OF FORM

Tacit and Explicit Information in Dynamic Concrete Molds

JAMES FORREN
[1]*Dalhousie University*
[1]*james.forren@dal.ca*

Abstract. This paper constructs a lexicon of tacit intentionalities around tools and materials in computational design and fabrication contexts through a close study of dynamic molds. Drawing on historical, theoretical, and practice-based research we develop methods for reading, teaching, and designing with intelligence in computational design contexts in concert with the tacit information provided by tools and materials.

Keywords. Material computation; Dynamic mold; Human-technology interaction; Precast concrete technology.

1. Introduction

Tim Ingold - in his study of tools, materials, and making - claims that intelligence inheres in the coupling of mind, hand, tool, and material. For Ingold, each actor by itself is unintelligent; the mind a jumble of neurons, the hand a collection of bones and sinews, and the tool an inert lump of stone or wood. Yet when brought together in gesture and activity intelligence manifests through complex interactions and interplay (Ingold 1999). Rather than thinking about intelligence as a disembodied entity or solely a product of the mind, this understanding of intelligence is fundamentally entangled with the corporeal reality the mind inhabits.

This corporeal reality is comprised of tools and materials and the tacit as well as explicit information they communicate. In architecture this information can include explicit information like the marks of a pencil, and tacit information such as the gesture of the hand as it moves across the paper. In contemporary practice this corporeal model of intelligence becomes more complex as architects must traverse a chain of computer models, construction tools, and construction materials in order to achieve something as basic as a wall. When only focused on explicit information provided by machines, design professionals are not operating in a fully informed way as evidenced by failures of engineers to verify loads or architects to verify measurements when they rely only on explicit information from machines (Turkle & Clancey 2009). To work intelligently in this chain requires architects to sustain an embodied engagement with technologies; to actively engage the tacit as well as explicit information they present.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 705-714. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Understanding this relationship between tacit and explicit information in technology is also the beginning of achieving a more balanced picture when we look at social and cultural bias in humans working with machines. The ability to privilege human over non-human actors or vice-versa is a central ethical concern in the development of technologies of the built environment. There are times when a designer may want to privilege the input of non-human actors (such as material properties) and times when they may want to privilege human actors (such as diversified accessibility). This privileging, however, is not always explicit and requires some unpacking to understand how the built environment (and the tools which construct it) can tacitly, as well as explicitly, privilege different constituencies.

This paper offers a model of intelligent practices which work equally with tacit as well as explicit information in design and construction. The vehicle for generating this research is the dynamic mold in concrete construction. Liquid concrete enables the expression of a range of tacit and explicit information from the undulations of its viscous form to conforming to highly prescribed, computer generated geometries. Recognizing the tacit as well as explicit information communicated by these molds identifies ways of working within the chain of contemporary architectural technologies with dexterity: recognizing tools and machines as articulate actors in an intelligent interplay with people and materials.

2. Theoretical Position

Anthropologist Tim Ingold theorizes an 'intelligent system' through the example of early humans' invention of the hand axe (Figure 1). In the making of a hand-axe he proposes that a knapper (or stoneworker) could not have approached a stone with a clear intention of a final hand-axe. Rather, Ingold theorizes that the image of the axe emerged in the mind of the knapper through an embodied engagement with the tool (a hammerstone) and material (a core stone) as they worked them with their hands over time. Through this activity, according to Ingold's theory, the knapper gained explicit information such as the emerging form of the axe and the markings from the hammerstone. They also gained tacit information such as a sense of the density of the core, a feel for its grain, and hints (due to the core's reactions) as to where to strike the next blow. This information - explicit and tacit - was synthesized as knowledge within the knapper's body and mind, through a coupling of perception and action. This knowledge, formed through action and feedback, informed the next steps in the system of core, hammerstone, hands, and mind in a gradual process of calibration (Ingold 1999).

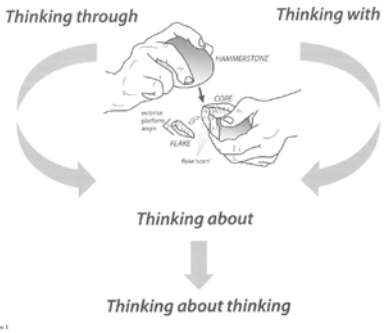


Figure 1. Image of Oldowan knapping, redrawn by Lambros Malafouris (Malafouris p.18).

As tool-making has evolved from stone-axes to hand tools to machines the composition of intelligent systems has grown more complex. Machines, which contain more information than hand-axes, transform this system by expanding the distance between bodies and the materials they work. This extended chain of information can compromise the intelligent system through creating routine operations which provide no new information (such as conventional construction methods) or machine intelligences which sever perception and action (such as opaque simulations or automated manufacture). Machines, however, can also sustain this system by providing opportunities for people to directly engage with materials, or to indirectly interact with them through intentionally designed processes of feedback and calibration. In the section that follows we look at different ways this latter approach can be structured through examples of dynamic concrete molds which accommodate a range of inputs from materials, tools, and people.

3. Description of Survey Data

The dynamic concrete mold translates between human intention, material potentialities, and mechanical operations. The hand can play a graduated role from direct manipulation to remote computer operation; the fluid nature of liquid concrete can be expressed or suppressed; and the machine can develop its own self-tasks such as actuation, sensing, and artificially intelligent decision-making. This provides a range of privileging of these different actors in a complex dance of variable degrees of influence and impact.

We can read the range of this privileging by recognizing tacit signals carried by the molds. This is based on the form of the implements that shape the liquid concrete. Learning to read the molds as articulate actors means recognizing their tacit signals (like the knapper reads the hand-axe) in the form of their material composition. Different forms of these implements are organized here into four primary families by shape: the point (such as a dowel), the line (such as a cable), the surface (such as a metal sheet), and the volume (such as air). Each family of shapes interacts differently with the concrete and tells us different information. In the examples which follow the precision or imprecision of the use of these

implements provides a way to read the privileging of human, tool, or material actors in the particular molds.

The point-type family is defined by a field of points - such as dowels, pistons, through-ties, or stitches - which shape a casting surface. Research carried out at the Delft University of Technology has developed a process of casting double curved concrete panels using a rectangular field of robotically actuated points which support a pliable substrate of thin wooden slats (Schipper 2015). This mold privileges a high degree of machine input and a indirect manipulation through a computer model.

Line-type molds use linear elements such as cables, seams, and edge restraints to shape a formwork surface. Looking at Chandler's use of cables in Wall One versus a process of cable optimization developed in NEST HiLo by the Block Research Group at the ETH in Zurich (Méndez Echenagucia in press). Chandler's cables support the fabric shuttering at regular intervals giving rise to the expression to the wieght of concrete; where longer spans result in larger deformation. On the other hand the NEST HiLo pursues an exceptional degree of machine precision and the even distribution of tensile forces across a field of cables, privileging machine input. This is achieved by fitting the crossing nodes of the cables with positioning beacons which calibrate their location against a computer-generated structural simulation. Like the double-curved pin-field mold, this project privileges the goals of a computer model over those of the liquid concrete. However, the calibration towards those goals is achieved by a direct manipulation of the formwork by human actors.

Surface-type molds rely entirely on the surface of the material to shape the concrete, independent of cables, darts, seams, or buttons. In, Sleeve, a project from our directed research workshop, a team of students explored the elasticity and strength of an elastomer as form-giver to liquid concrete. This privileged the properties of the elastomer tube as it was fabricated to resist the hydrostatic pressure of the liquid concrete. A robotic surface-type mold, Smart Dynamic Casting (SDC), has been developed in the Gramazio Kohler Research lab at the ETH in Zurich (Lloret, et al. 2015). Rather than manipulating an elastic sleeve, the project deposits an engineered slurry into a rigid metal cylinder controlled by a robot arm. The speed of the arm adjusts according to the hydration rate of the concrete slurry through a moisture sensor. The inputs of machine and material, then, are placed in dialogue with the human determining the travel path of the arm in a complex balancing of multiple inputs.

Volume-type molds use a mass of solid, liquid, gaseous, or phase-change medias as a formwork to shape liquid concrete. Some materials in this class include wax, sand, air, water, and liquid or cured concrete. These media can be contained within pouches, separated by membranes, or pressed directly against the liquid concrete. These methods can privilege non-human inputs by allowing the interplay of material forces to determine the final outcome of the cast components or be determined by a computer model. In these instances human judgement typically informs the design of the process of casting and the material composition of the casting technologies, but the materiality of both the mold and the liquid concrete can be privileged in a paired dialogue.

This range of casting techniques describe ways dynamic molds favor human, tool, and material inputs. For instance, the precise location of geometries of a pin-field serve a goal of precision, versus a loose volume-type method which pursues material expression. In the following section we discuss the implementation of these families of molding methods to achieve different design goals in a practice-based research project.

4. Urban Curtain: Practice-based Research Data

Urban Curtain seeks to redress approaches to complex form which result in the wasteful use of material or high energy throughput due to intensive material formation for complex molds. Instead, it achieves complex form through a simultaneously provisional and precise casting strategy as an example of dexterity in construction. A combination of line-type, point-type, and volume-type casting methods were applied to achieve specific goals in an intentionally developed design process. The project was conducted in partnership with a precast concrete producer who provided material, engineering, space and materials and methods support.

Urban Curtain adapted an industrial mold-liner elastomer normally used to pattern architectural concrete cladding panels. This adaptation captured the dynamic, fluid properties of liquid concrete in a cast structural component and saved time, labor, and material in producing a structurally efficient component. Elastomeric mold liners are made from a two part (8:1) polymer of liquid elastomer and hardener and typically used for patterning the face of architectural precast concrete panels. Their flexibility allows finer detail and shallower draft angle because they can be peeled from the cured concrete panel. They are also highly durable. Urban Curtain adapted this elasticity and durability to volumetrically shape the liquid concrete. This allowed the project to pursue precision where important, and permit imprecision where it was not.

The structure - a pair of twisting walls joined by a steel angle - was a pair of hyperbolic paraboloid, or hypar, surfaces (Figure 2). As each wall was bilaterally symmetrical each course could be constructed of identical blocks rotated one-hundred and eighty degrees. The mold was conceived as a line-type mold as the edges controlled the component geometry for a precise alignment between courses. To achieve the hypar surface, the edge geometry, or fifteen degree slope of the angled edges of each block, was consistent, and the line of symmetry, or middle spine of each wall, was vertical. These edges were four inches deep and formed by blocks shaped from shop tools such as a table saw according to specifications developed on a virtual model. Thus, the only difference from one course to the next on the mold was the depth to which the sloped edge or side was horizontally displaced from the vertical spine in 4 inch increments. These edges suppressed the fluid properties of the liquid concrete into a rectilinear form, amplifying machine inputs for precise tolerances. A tolerance of ¼" between courses was provided for field alignments. The project privileged precision at these moments of crucial importance such as the mating edges of components.



Figure 2. Urban Curtain. (Left to right) diagram of mold actuation, final mold and single cast block, and final assembly.

In the areas where such intensive precision was not required, such as the exposed faces of the blocks, the project relaxed the geometric precision to privilege instead the material properties of liquid concrete. This was employed in a volume-type method to efficiently use chambers of liquid concrete to form and support adjacent panel faces in a gang-formed configuration. This achieved process and material efficiency, allowing the material inputs of the liquid concrete to reciprocally inform the shape of neighboring blocks. The gang-formed method placed five elastomer sheets in parallel, and the chambers between them were filled with liquid concrete. However, due to the hydrostatic pressure and the use of high slump self-consolidating concrete (SCC) the exterior elastomer faces bulged significantly during early tests from the hydrostatic pressure of the liquid concrete. To counteract the hydrostatic pressure, a point-type application was then introduced through a custom-formed male-female connection held together with a through-rod (Figure 3). This connection, coupled with the strength of the 3/8 inch thick elastomer sheet and held the face of liquid concrete to within an acceptable range of tolerances.



Figure 3. Urban Curtain. Nodal connector integrally cast with elastomer sheets (middle). Reverse casting for male connector (left) and assembly in first prototype mold (right).

5. Data Analysis

In our analysis of the survey of dynamic molds we identify the role of the hand. This is to better understand how the coupling mental and physical activity occurs in contemporary technology environments. This is done to help in the design of processes which continue to include the hand in the activities of practice and the explicit consideration of tacit data.

In tightening the cables and setting the form ties for Wall One, mold makers see direct effects of their labors, connecting the actions of their mold construction with their perceptions of the liquid concrete to the configurations they constructed. A similar condition occurs in the volume-type molds where an initial material composition is put in place and the reactions are evaluated after the concrete has been cast and the results of the material dynamics can be observed. These applications privilege material inputs and connect them with direct handling of material.

In processes which privilege machine inputs the hand is removed, but there can be a direct calibration with the machine. In the manipulation of cables in NEST HiLo there is a direct physical connection in calibrating the form to a digital model. This process of calibration connects an action (the tightening of one cable) to a reaction, informing subsequent steps (which cables to tighten next), similar to the feedback the knapper receives working the stone.

In other instances of machine privileging the hand is more removed. For instance, rather than directly manipulating the mold in the TU Delft double-curved pin-field mold the 'operator' engages a state of 'surveillance', surveying the effects of the deformation of the mold on the concrete slurry. The operator's role is to calibrate the balancing of mold geometry, slurry composition and hardening time as a check on the computer's calculation of these inputs (Lloret, et.al. 2015). Although the hand is not directly involved in the mold, there is a link here between perception and action during this activity of surveillance and calibration. And in the case of the extruded slurry column the hand works in concert with the actively calibrating robot to explore a design space which is rationally constrained such that the designer knows their output will be viable in both structure and fabrication. In this scenario perception and feedback between the human and material is through the mediator of the hydration sensor which helps define the design space limitations: similar to NEST HiLo, the hand is engaged in a calibration with material through mediator of the machine.

These examples illustrate direct and indirect roles for the hand in dynamic mold application. Direct roles manipulate the mold directly. Indirect roles manipulate factors in parallel with, preceding, and / or following the operation of the mold. Although not manipulating the mold in an immediate manner, this approach participates in a process of feedback through perception and action. Although the direct method is more commonly understood to privilege human input, both instances require an intentional framing of the design and construction process to facilitate active human participation in a process of perception and action.

In our analysis of Urban Curtain we assess outcomes of an approach which worked with tacit as well as explicit information from materials. The process privileged precision and machine input at necessary locations for constructability and privileged material input at non-essential locations for process efficiencies and material expression. This resulted in a viable construction application with resource efficiencies.

The structure used six courses of self-similar blocks, four blocks per course. Using a dynamic, gang-formed mold a structure with complex curvatures normally requiring six individual molds was constructed with one mold with flat sheets

and linear elements. The areas of material privileging at the face of the mold (conditioned by the volume of liquid concrete and the point-restraint of the custom connector) reduced the need for several individual complex permanent molds and resulted in overall material savings. As the elastomer allows for over one hundred reuses this can be applied to industrial processes of precast concrete production. With a capacity for one hundred casts, this could produce a total of four hundred components.

Over the surface of panels ranging in area from 430 to 540 sqin, each fifteen inches tall, the point-restraint reduced deflections by approximately four to six inches to bring the elastomer's deflection within an allowable tolerance of two inches across the face. This permitted the privileging of the liquid state of the concrete to be expressed, informing observers of its properties and creating individually unique components in a mass production process.

6. Reflection

More than just impacting our ability to check errors in machine outputs, anthropologist Andre Leroi-Gourhan warns our continued reliance on machines, carried to its logical conclusion, threatens the intelligent capacities which make us fundamentally human. He proposes that through continued off-loading of human labors to machines - both mental and physical - we advance towards a future of independent machine intelligence. He imagines that freed of physical demands the hand will be left to navigate (and the body consume) simulated confections blithely and without awareness.

What happens to our position in an intelligent system if we fully off-load labor to machines? Within this regression of the hand from material handling, the danger (and some would argue the promise) is its impact on our imagination. Leroi-Gourhan suggests that in the above scenario the imagination will have no lived experience from which to work (Leroi-Gourhan 1993). Other scholars, such as architectural practitioner and theorist Kostas Terzidis, marvel at the possibilities and extensions of the imagination simulation can offer (Terzidis 2011).

We propose instead a middle path. Part of what is revealed in our data analysis is the direct and indirect role of the hand in machine processes. We have shown how tools do not need the hand directly in them in order to link perception and action. The cycle of feedback between perception and action can play out in relation to the molds even if the actions are not directly manipulating liquid concrete. But to link perception and actions these responses need to be tethered to what Ingold calls the 'lifeworld.' The lifeworld consists not only of the physical products of making, but the social, cultural, and environmental ties that surround these artifacts (Ingold 2000). Such considerations in design and construction include who are the actors in a process and the calibration of broader social and cultural impacts of technical decisions.

7. Conclusion

This paper has looked at how technology in computational design and construction can tacitly privilege human versus non-human inputs through the vehicle of the

dynamic concrete mold. This has been pursued through a case study analysis and reflection on a practice-based research project, arguing for an understanding of intelligence as a 'system' in design and construction activated through the coupling of mental and physical labor.

In further development of Urban Curtain the practice-based research looks to translate this coupling to explorations into the indirect roles of the hand in the design and construction process. With Urban Shell we are exploring a design space defined by a robotic mold which actuates the elastomer sheets on a tilting table, allowing for a range of components types and assembly formations. The test application for this study is the construction of a load-bearing shell.

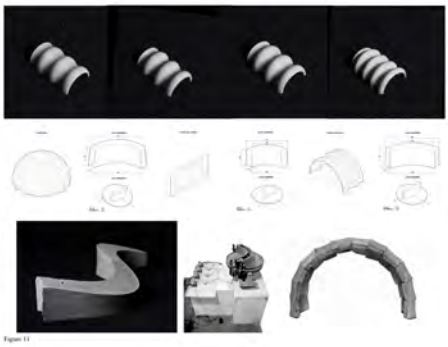


Figure 4. Urban Shell. Prototype studies of a robotically actuated mold to construct a range of block types for different kinds of load-bearing structures.

The understanding of an embodied intelligence which rebalances our focus on tacit as well as explicit information can also be extended to contexts outside construction where the outcomes may not be physical artifacts, but may be renderings, diagrams, or other architectural media. These can, however, still be entwined in active corporeal engagement with the lifeworld of social and cultural activities and behaviors through efforts to verify or otherwise link the information and data communicated to perceptible phenomena. Such as diagrams of pedestrian flow which are constructed from verifiable information. This has implications for the application of design and construction technologies to pedagogical and public contexts as we gain further knowledge of the privileging of information, both tacit and explicit, in our activities of design and making. These include an expanded range of learning opportunities in the instruction of tacit as well as explicit readings of technology outcomes, and a heightened awareness in the role of machines in the tacit privileging of certain forms of social, cultural, and technological knowledge. These extensions of the research into pedagogy and public practice are steps towards expanding a model of intelligence in design and technology that is socially and culturally, as well as technically, informed.

Acknowledgments

The project has been funded by the *Canadian Precast Prestressed Concrete Institute* (CPCI).

Urban Curtain: Aziza Asatkhojaeva, Liam Guitard, Ryan Vandervliet

Urban Shell: Lauren Abbass, Stavros Kondeas, Makenzie Ramadan, John Turnbull

References

Anonymous, initials missing: 2012, "High-Efficiency Concrete Formwork Project Receives Holcim Innovation Award. Concrete International" . Available from no URL given.

Chandler, A.: 2004, Building walls - a philosophy of engagement, *Architectural Research Quarterly*, **8**(3-4), 204-214.

Ingold, T.: 1999, 'Tools for the Hand, Language for the Face': An Appreciation of Leroi-Gourhan's Gesture and Speech, *Studies in History and Philosophy of Biol & Biomed Sci*, **30**(4), 411-453.

Ingold, T.: 2000, *The perception of the environment essays on livelihood, dwelling & skill*, London; New York : Routledge, London; New York.

Leroi-Gourhan, A.: 1993, *Gesture and speech*, Cambridge, Mass. : MIT Press, Cambridge, Mass..

Lloret, E., Shahab, A.R., Linus, M., Flatt, R.J., Gramazio, F., Kohler, M. and Langenberg, S.: 2015, Complex concrete structures: Merging existing casting techniques with digital fabrication: Merging existing casting techniques with digital fabrication, *Computer-Aided Design*, **60**, 40-49.

Loukissas, Y.A.(A.: 2012, *Co-designers : cultures of computer simulation in architecture*, Abingdon, Oxon England; New York, NY : Routledge, Abingdon, Oxon England]; New York, NY.

Malafouris, L., Renfrew, C. and McDonald Institute for, A.R.: 2010, *The cognitive life of things : recasting the boundaries of the mind*, Cambridge, UK : McDonald Institute for Archaeological Research; Oxford, UK : Distributed by Oxbow Books; Oakville, CT : USA distributor, David Brown Co, Cambridge, UK : Oxford, UK : Oakville, CT.

Menges, A. and Ahlquist, S.: 2011, *Computational design thinking*, Chichester, UK : John Wiley & Sons, Chichester, UK.

Murphy, K.M.: 2012, Transmodality and temporality in design interactions, *Journal of Pragmatics*, **44**(14), 1966-1981.

Turkle, S.: 2009, *Simulation and its discontents*, Cambridge, Mass. : MIT Press, Cambridge, Mass..

Veenendaal, D. and Block, P.: 2014, Design process for prototype concrete shells using a hybrid cable-net and fabric formwork, *Engineering Structures*, **75**, 39-50.

Yaneva, A.: 2012, *Mapping controversies in architecture*, Burlington : Ashgate Pub. Co, Burlington.

TEACHING COMPUTATIONAL DESIGN AND BIM IN THE AGE OF (SEMI)FLIPPED CLASSROOMS

DOMINIK HOLZER
[1] *The University of Melbourne*
[1] *dominik.holzer@unimelb.edu.au*

Abstract. With academic curricula for architectural education increasingly packed with new and expanding fields of inquiry, questions emerge on how to incorporate the ever-growing number of subjects that tackle the use of computational tools for design and delivery. This paper analyses approaches to blended learning under a semi-flipped classroom model where learning content gets divided into complementary in-class and online components. The author describes the epistemological challenges in curating the blended-learning mix and discusses ways to optimise learning outcomes while minimising the effort for custom content-development of training material. Two subjects taught at the author's home institution (one in Computational Design and the other for BIM education) serve as case studies to test the flipped classroom approach and to derive feedback from students about their preferred method of delivery.

Keywords. BIM; Flipped-Classroom; Computational Design; Education; Online learning.

1. Introduction

Approaches to teaching design and documentation software address a broad spectrum of topics, ranging from a focus on technical issues, to process-related concerns, all the way to policy and collaboration. Common to all of these approaches are questions related to the best possible delivery mechanism of CAAD software training in a class setting where educators often deal with large student numbers and varying capabilities of students to learn new tools in a face-to-face teaching environment. Academic curricula in tertiary architectural education become increasingly crowded and educators are looking for alternatives training methods to maximise the usefulness of face-to-face interaction with students. With training for software applications becoming an ever more integral part of the architectural education, online training resources (both paid and freely available) present themselves an ever more promising alternative to teaching CAAD tools in the classroom. The quality and quantity of online resources available is of such nature, that the viability and usefulness of teaching 'software' face-to-face in architectural education ought to be questioned. If dozens of high-quality tutorials for software training are available online, what is the merit of teaching tools in the classroom? Accepting that every student learns at his/her own pace, why would

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 715-724. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

educators still train students in the use of computational design and BIM tools? Other questions remain - such as: Is the quality of online tutorials sufficient to rely on them entirely, or can/should they be complemented by in-class teaching? If so, what is the most appropriate mix between face-to-face training and online training? The research presented here aims to respond to the above questions and point towards the opportunities and challenges within semi-flipped classrooms.

2. Background

The spectrum of computational tools supporting architectural design and delivery processes is ever increasing. They cover a broad territory of applications from supporting highly experimental approaches (Achten 2009) to facilitating mundane tasks that typically encompass a high degree of repetitive work. The proliferation of computational methods for the design and delivery of projects in practice has gone hand in hand with changes in teaching and learning in academia. Architectural Design becomes ever more knowledge-intensive, driven by technological advances and an increasing appetite to test and validate a project's performance.

The use of digital tools forms an integral part of the epistemological development of architecture students. Education providers therefore need to ensure their course-structure caters for classes that address the use of digital tools on various levels. On a procedural level, it is about ways of supporting their design thinking via computational means and matching their desired design process with referring tool-ecologies. On a practical level it is about gaining the right software skills to become more efficient in the production of documentation and other representational output on their projects.

Numerous commentators scrutinised the integration of digital tools as part of the architectural education by noting the opportunities (among other) for exploring computer-mediated social interaction (Earl 2000), maximising the engagement of students in class (Cheng 2001), or by highlighting the benefits and challenges of using digital tools within the design-studio context (Al-Qawasmi 2004). At the start of the new millennium, the discourse concentrated the introduction generative systems and parametric techniques into the design process of students. In the early 2000s, the proliferation of parametric design approaches progressed with the increasing availability of parametric design tools such as Bentley's Generative Components and later McNeel's Grasshopper plugin for Rhinoceros. Some critical voices emerged: Chase (2003) warned academics about the *"mindless definition and application of rules without a clear understanding of how they operate"* while (Burry 2005) stressed the need for transdisciplinary cross-fertilisation between academic teaching, research, and practice. Kensek (2012) later raises the same issue when referring to the opportunities of BIM to foster interdisciplinary collaboration.

Whilst available literature focused heavily on the use of rule-based design for early design exploration, the advent of BIM and its adoption-levels in the industry led to questions about the best way to integrate related training in academic curricula. Some commentators saw BIM as a major disruptor to traditional design

studio education, prompting Ambrose (2009) to urge academia to *"completely revisit the curricula and imagine a system that acknowledges the obsolescence of the how and what of that which is taught in today's schools of architecture"*. This position was seconded by Deamer and Bernstein (2011) who see BIM as a threat to well-established hierarchies and divisions between academic disciplines, pointing out the insufficiencies in contemporary curriculum-structures to facilitate proper BIM education beyond its notion as a tool.

Over the second decade of this century, the dust has settled (at least to a degree) when it comes to the veracity of changes perceived to affect the inclusion of BIM in education. Training for and application of BIM has become second nature to most educational institutions (Holzer 2015), but the way it gets taught has been changing. Walaiporn (2015) assesses that: *"Students enter an architectural school with an aspiration to design something, not to learn tools"* as she calls for teaching strategies that move away from software training to more applied and contextual approaches to learning tools. One key step within architectural education is therefore to consider new modes of teaching that allow for discussion of concepts and reasoning behind the tools in use, whilst straying away from a focus on mundane capabilities and commands.

2.1. ENTERING THE E-LEARNING PARADIGM

From an educator's perspective, the developments in CAAD bring along certain challenges. Given the increasing application of digital design/delivery tools, how does one select and configure the right courses for students to engage in? How can the associated training be consolidated within a curriculum that appears to be ever-expanding? Should software courses substitute existing training, be taught in conjunction with it, or be taught in parallel to existing subjects? In case of the latter, how can one justify the added time-commitment associated to online content development? Do traditional ways of teaching still correspond to the contemporary knowledge acquisition of students who tend to interact in online communities and social networks?

One other aspect of learning that has increasingly affected knowledge acquisition of students over the past few years is the transformation of its delivery-mechanism. The change in media from text-book based to online-tutorials and videos provides new opportunities for the delivery of software training. Traditionally such training was typically in person within in-class tutorials and using printed handbooks. The proliferation of the world-wide-web towards the end of the millennium facilitated an influx of online training material. This material became available online PDF tutorials (both free and paid), and increasingly also as video tutorials. The main advantage of electronic media for training purposes is the potentially unlimited access and the opportunity to go through the learning material at their own time as often as they want (offering students flexibility on when, where, and at what pace to learn). Increased network speed for content-streaming has allowed online class presentations and video tutorials to become a via support mechanism to enhance the teaching experience within academia. Researchers have since explored the nature of combining in-class tutorials with online training resources. Research about teaching methods, and

in particular the inclusion of web-based e-learning options addresses some of the questions mentioned before. Ham (2010) highlights the potential of online social network settings in the context of design-studio teaching, Wang et al (2012) declare eLearning a mediator in the relationship between student-student and student-teacher interaction. Schnabel and Ham (2014) go further by questioning the often sequential way of learning experienced by students and they point out opportunities of using social networks to increase communication and knowledge transfer in 21st century architectural education.

2.2. THE FLIPPED CLASSROOM TO THE RESCUE?

Fryling at all (2016) discuss these blended learning options based on the so called flipped and semi-flipped classroom models where content is distributed to students by the tutor so they engage with it outside of scheduled class times. Looking at various options, they argue that *"the semi-flipped model is an effective compromise for an instructor who cannot devote the time needed to replace all lectures with videos"*. Similarly Thay et al (2017) point out the benefits of the semi-flipped classroom for students and tutors alike as students are given ample time to go through the online material at their own pace to then prepare for the face-to face conversations and targeted feedback sessions in class. Jenkins et. al (2017) assess that the focus on getting the mix between online and in-class activities right is only one aspect to be considered when programming blended learning options. They point out the need to consider blending options based on pedagogical requirements that allow for *"flexible interpretations of flipping in different contexts"*, moving fluidly across *"content-focused to process focused and teacher-led to student-led"*.

The argument for flipping classrooms carries with it some major obstacles: Assembling a well-structured set of video-tutorials is highly time-consuming and requires specialist skills. Due to the frequent upgrades associated to design software, any referring training tutorials have a short life-span and need to be refreshed continuously. A drawback of online learning content for digital design and delivery tools is that it is often un-structured and randomly put together by individuals with no particular curriculum or course structure in mind. In some instances, the selection of online material is purely based on the software-provider's commercial interests, in others it may be limited by the moderation/editing capabilities of the individual who compiled the information in the first place. In order to address the above shortcomings, commercial organisations have started to develop targeted course-content in order to make it available online via a subscription model. Testing different blended-learning options under a semi-flipped classroom model is a way forward to evaluate and fine-tune methods of course delivery for software training in architectural education.

3. Case study

For the purpose of the research presented in this paper, the author has monitored the performance of Masters-level students across two elective courses over the

duration of one 13-week semester at his home institution. One course titled: "Digital Design Applications" has the aim to introduce students to a range of computational design tools in support of their exploratory design processes. The second course titled 'ICT in Building' centers around the transformative character of Information and Communication Technology (ICT) on the construction industry, and the production of 4D Construction Sequencing in BIM on a pilot project.

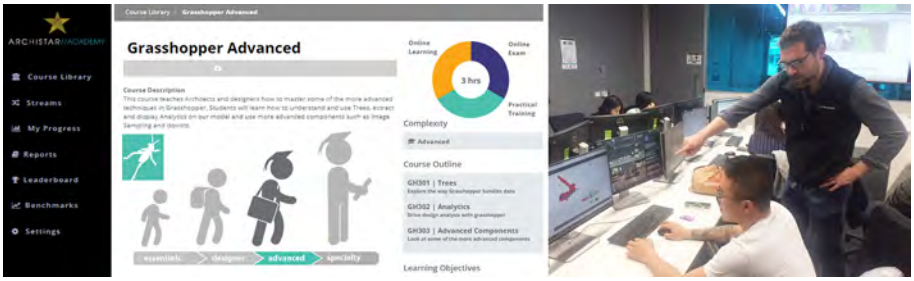


Figure 1. ArchiStar Academy online training resource and in-class BIM software training.

In both instances, classes were taught using blended learning in a flipped classroom setting; in particular following the model suggested by Al-Ratrout and Zureikat (2014) who assess that the addition of preparatory classes in a course-program to advance students' computational skills can enhance their design performance. The author had previously taught both classes and was able to advance and fine-tune the teaching methodology in both cases over several years based on student feedback, and empirical observations.

3.1. "DIGITAL DESIGN APPLICATIONS" - BLENDED LEARNING MIX

The key learning outcome of this course is to provide students an in-depth understanding of algorithmic digital form explorations using intensive computational scripting coupled with fabrication of detailed material models. Each class starts by an introductory lecture that introduce students to a specific aspect of the course (Parametric Design *Rationalisation and Fabrication* Analysis, Simulation & Optimisation / BIM / Designing with Data and Machine Learning / Scripting & Physical Computing). The in-class lecture is then followed by in-class tutorials on that specific topic, in most cases facilitated via Rhino-Grasshopper.

Due the steep learning curve required by students to engage with Grasshopper on this level of sophistication, each student is required to prepare for class via pre-configured online tutorials that cover the basics of Rhino/Grasshopper and beyond. These tutorials are taken from the online platform ArchiStar Academy that the home institution of the author subscribes to. The platform was developed by a third party parametric design expert who has prior experience in academic teaching and practice-work alike. ArchiStar Academy has the advantage to let tutors set up 'virtual classrooms' where specific tutorials can be pre-selected for each class and students then receive automated invites to go through those specific tutorials on the system. Further, the online platform allows tutors to monitor who

has actually completed the tutorial and to send custom messages to students about the tutorial if required. Next to the use of ArchiStar Academy(TM) the Digital Design Application course also runs their own wiki page where course material is presented, alternative tutorials are listed, and students have the opportunity to engage in a social Web2.0 context.

3.2. LEARNING BIM VIA ”ICT IN BUILDING” - BLENDED LEARNING MIX

The ICT in Building course offers Masters of Construction Management an overview of various applications of Information and Communication Technology utilised across the building sector. The majority of the course is dedicated to discussing the theoretic framework behind ICT use and a general introduction to associated tools. Each class contained of introductory lectures about the history of ICT in building, supply-chain interaction, software solutions, tool ecologies, and ICT use by clients, consultants, Head Contractors, Trade Contractors, and Facility Managers. These theory classes are complemented by discussion-rounds and industry guest speakers in order that allow students to get a comprehensive picture of ICT use throughout the building industry and to increase their understanding of the 4D BIM exercise undertaken in part two of the semester. Based on student-feedback in prior iterations of the course, a specific practical component was added to tackle the task of using a 4D BIM approach to link a construction program to a 3D model-coordination and data management environment in Autodesk Navisworks(TM); this applied software training was requested by students as a way to get hands-on with the tools. It was run in the second half of semester once students were already familiar with the basic concepts of ICT and BIM in particular.

For the purpose of the BIM training, the technical tutor introduced the task at the beginning of semester and handed out a set of Navisworks template files for students to interrogate over the coming six to seven weeks. Students were then requested to go through basic Navisworks training using the online Lynda platform. Specific Training classes were pre-selected by the tutor and links were made available to students on the custom course wiki-page that was set up from first week of semester. From week 8 onward, the in-class tutorials commenced. The tutor introduced a new aspect of 4D BIM planning in-class each week, building up towards the production of an animation (video) based on a revised construction program to be develop by each student. Lynda offered a ready-made solution for covering the basic training requirements in Navisworks to allow the tutor to focus entirely on teaching the specific functions required for linking a construction program to dedicated 3D elements via selection sets to facilitate the 4D time-lining process in Navisworks.

4. Observations and Discussion

The findings presented in this section are based on active observations during both the Computational Design course, as well as the BIM-focused ICT course. The key source of information results from a 9 question survey each student filled in at the end of semester. There, students expressed their views on the quality of the

online, as well as in-class training, and they comment on the balance between the two. They voice their ideas on how to improve the flipped classroom experience and the speed of learning overall. In the survey, students were asked to rank their preferred method for learning (design) software and they were queried about the usefulness of both the online, as well as the in-class tutorials for this subject. Further students responded to the balance between online and in-class training and its effect on their speed of learning? Students were then given the opportunity to suggest improvements to both the online, as well as the in-class software training.

4.1. PREFERRED MEDIUM FOR LEARNING

Student responses about their preferred medium/method for learning design software revealed a broad spread of responses with no clear preference for any particular approach. Whereas students in the Computational Design course appeared to have a slight preference for finding targeted tutorials online, those attending the BIM course had a slight preference for being taught in class. Both groups of students agreed that printed training material was the least favorable source for learning software.

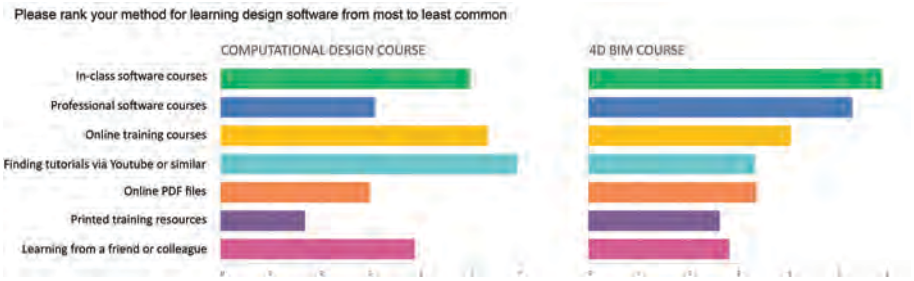


Figure 2. Comparison between preferred method of learning Computational Design vs BIM.

4.2. ACCEPTANCE OF THE BLENDED LEARNING MODE

Approximately 70% of students in the Computational Design course were very happy with the online training material provided via the pre-selected subscription service ArchiStar Academy with nobody questioning its usefulness. In contrast, only 50% of students attending the BIM course were that positive about the Lynda platform, with 10% declaring it 'not particularly useful'. The quality of in-class software training received a positive response of between 80-85% of students across both courses.

Asked about the balance between online and in-class training opinions seemed divided. 35% of Computational Design Class students thought it to be ok, with 40% wanting more in-class tutorials, and 25% felt they needed more online tutorials. The split among BIM students was even more defined, with only 22% feeling the balance was right, 63% arguing they wanted more in-class tutorials, and 15% wanting the balance to shift more towards online training.

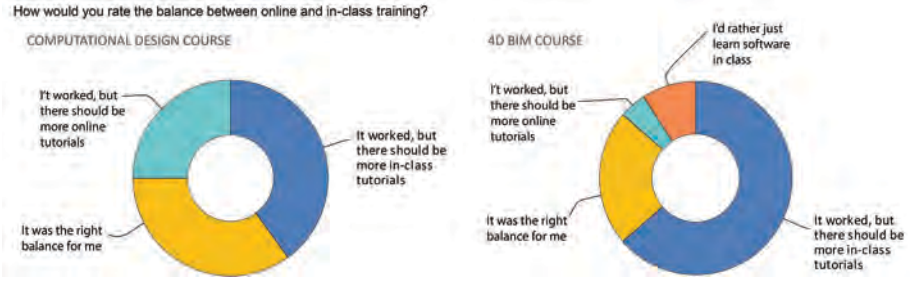


Figure 3. Perceived balance of blended learning within Computational Design and BIM course.

Reflecting to their blended learning experience, 85% of Computational Design students believe the flipped classroom model helped to speed up their learning (with the rest arguing they would have learned at the same speed with in-class only tutorials). The BIM subject students were more divided in their views, with 45% arguing the flipped classroom allowed them to learn faster, 41% feeling that traditional in-class teaching would have allowed them to learn at the same pace, and 14% assessing that the flipped model ultimately resulted in slower learning pace than an in-class only setting.

4.3. OPPORTUNITIES FOR IMPROVEMENT

When asked to respond to ways to improve the options for online, and in-class learning, student responses from both courses were identical: More choice of online training content was the most-desired improvement, followed by greater alignment between online and in-class tutorials. Students also wanted to be able to ask more questions in class, with greater flexibility to adjust content during in-class training.



Figure 4. Rating improvements to the interplay between online and in-class training for Computational Design and BIM course.

Individual comments by students provide more explanation: Respondents from the Computational Design class noted the lack of structure across tutorials within Archi Star Academy and they suggested for the tutorials to be curated towards achieving specific practical outcomes. Ideally, those outcomes should tie in directly with course assignments. Further, students suggested more exclusive tutorials for specific Grasshopper plugins should be added to the system. Course

participants did highlight the lack interaction with others with one student suggesting: *"It can be a place where students can have a chat (ask questions) and share their scripts. Like grasshopper3d website, however, more specific for parties that collaborate with Archistar Academy, such as for the university only, or the course"*. Respondents from the BIM course found it difficult to locate the most appropriate learning material on Lynda that provided the best fit for 4D BIM tasks to be carried out in class. Better search-options were requested that help to avoid opening tutorials not relevant for the subject.

In reflection on their in-class software training, an overwhelming number of students (95%) from both courses agreed that access to a video recording of those sessions would be highly beneficial to their learning. Asked about the benefits to still attend classes if access to such recordings was given, students from both courses uniformly pointed towards the advantages of being able to ask questions in class, as well as communicating with their peers during the face-to-face sessions.

5. Conclusions

The research presented in this paper points towards a future where blended learning in a flipped classroom setting will play an ever-more important role in architectural education, in particular where software training forms part of a course's learning outcomes. In reflection on the findings presented here, the semi-flipped classroom model offers clear advantages over in-class only software training, in particular if the course-delivery method gets fine-tuned to off-load repetitive tool-functionality tutorials online while focusing on more complex issues that require face-to-face interaction between tutor and students. At the same time, the research highlights that there is still ample room for improvement of the blended learning mix presented in the case study. As much as pre-configured third-party e-Learning platforms offer a solid back-bone for learning software, their use needs to be complemented with social network interfaces that allows students to exchange notes and discuss the material at hand. In addition, these platforms need to become more configurable and permeable to allow tutors more options to customise content to fit specific course content, as well as addressing specific assignment deliverables. In this context, students lamented the lack of such flexibility and specificity in particular with the Lynda system and they found it at times difficult to find the exact content required for the course. This observation raises another point: The need for tutors to carefully curate online content in conjunction with their own course structure and the limitations thereof, due to the added effort for customisation and updating content each semester. The demand for a permanent audiovisual record of in-class tutorials has clearly been expressed by students. The complexity inherent to Computational Design tools as well as BIM software makes it difficult for students to keep up with 'live' tutorials. Being able to go through content after class at their own pace would allow students to repeat the tutor's instruction step by step, thereby gaining better understanding of the material presented. The installation of in-class recording equipment in all computer labs has since been commissioned in the author's home institution.

References

Achten, H.: 2007, Experimental design methods, *International Journal of Architectural Computing*, **07**(04), 505-534.

Al-Qawasmi, J.: 2004, Reflections on e-Design: The e-Studio Experience, *ASCAAD's First International Conference on Computer Aided Architectural Design*, Saudi Arabia.

Ambrose, M.A.: 2009, BIM and Comprehensive Design Studio Education, *Proceedings of the 14th International Conference on Computer Aided Architectural Design Research in Asia*, Yunlin, TAIWAN, 757-760.

Burry, M.C.: 2005, Digitally Sponsored Convergence of Design Education, Research and Practice, *Proceedings of the Computer Aided Architectural Design Futures Conference 2005*, Vienna, AUSTRIA, 3-22.

Chase, S.C.: 2003, Revisiting the use of generative design tools in the early stages of design education, *In Digital Design: 21th eCAADe Conference Proceedings*, Graz, AUSTRIA, 465-472.

Cheng, N.Y.: 2001, Evolution of Digital Design Teaching: A Course as Microcosm for Educational Issues, *ACADIA Quarterly*, **20**, 13-17 .

Deamer, P. and Bernstein, P.G.: 2011, *BIM in Academia*, Yale School of Architecture.

Earl, M.: 2000, A Prospectus on Computers Throughout the Design Curriculum, *Promise and Reality: State of the Art versus State of Practice in Computing for the Design and Planning Process, 18th eCAADe Conference Proceedings*, Weimar (Germany) 22-24 June 2000, 77-83.

Fryling, M., Yoder, R. and Breimer, E.: 2016, Full Flip, Half Flip and No Flip: Evaluation of Flipping an Introductory Programming Course, *Information Systems Education Journal*, **14**(5), 4-16.

Ham, J.J.: 2010, Working outside of the system: engaging in Web 2.0 to enhance learning and teaching in the design studio, *Proceedings of the 15th International Conference on Computer Aided Architectural Design Research in Asia*, Hong Kong, CHINA, 209-218.

Holzer, D.: 2015, BIM and Parametric Design in Academia and Practice: The Changing Context of Knowledge Acquisition and Application in the Digital Age, *International Journal of Architectural Computing*, **13**(1), 65-82.

Jenkins, M., Brown, M., Browne, C., Gao, Q., Hanson, J. and Kupatadze, K.: 2017, Enhancing the Design and Analysis of Flipped Learning Strategies, *Teaching and Learning Inquiry*, **5**(1), 1-12.

Samer, A.A. and Zureikat, R.: 2014, Pedagogic Approach in the Age of Parametric Architecture: Experimental method for teaching architectural design studio to 3rd year level students, *Digital Crafting, 7th International Conference Proceedings of the Arab Society for Computer Aided Architectural Design (ASCAAD 2014)*, Jeddah, SAUDI ARABIA, 211-226.

Schnabel, M.A. and Ham, J.J.: 2014, The Social Network Learning Cloud: Architectural Education for the 21st Century, *International Journal of Architectural Computing*, **12**(3), 225-242.

Thai, N.T., De Wever, B. and Valcke, M.: 2017, The impact of a flipped classroom design on learning performance in higher education: Looking for the best "blend" of lectures and guiding questions with feedback, *Computers & Education*, **107**(1), 113-126.

Walaiporn, N.: 2015, Challenge of Teaching BIM in the First Year of University, *Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2015)*, Daegu, Republic of SOUTH KOREA, 509-518.

Wang, X., Love, P.E.D., Klinc, R., Kim, M.J. and Davis, P.R.: 2012, Integration of e-Learning 2.0 with Web 2.0, *Journal of Information Technology in Construction*, **17**, 387-396.

Human-Computer Interaction; Collaborative & Collective Design

REIMAGINING RELATIVITY

Transitioning the physical body into a virtual inhabitant

JESSIE ROGERS[1], MARC AUREL SCHNABEL[2] and
TANE JACOB MOLETA[3]
[1,2,3] *Victoria University of Wellington*
[1,2,3] *{Jessie.Rogers|MarcAurel.Schnabel|Tane.Moleta}@vuw.ac.nz*

Abstract. This paper explores the ideas and mechanics through a case study which generated a reimagined means of inhabiting a speculative immersive environment. Currently, many users reside within virtual environments for their own leisure, work, or any other reason desired from short amounts of time to extreme lengths. This paper shows the generation directly relative to the inhabitant, where gravity, orientation, scale, and locomotion is completely dynamic. Details within this paper experiment with the laws and bounds of the virtual space within a real-time game engine where reimagining the way one inhabits space compared to current norms of real-world inhabitation is possible with creativity and applied knowledge. Escher's lithograph of Relativity is the driving concept explored within this paper beginning with creating gravitational pulls in multiple directions within the immersive virtual reality environment to accommodate various sources of gravity. The result of the case study demonstrated the generation of new virtual relativity laws reimagining how the virtual space is inhabited, in short, omnidirectional flying, gravitation defined by the inhabitant to geometry relationship, controlled local scaling, and populating space with multiple inhabitants in a unique manner.

Keywords. Virtual Reality; Speculative; Relativity; Inhabitant; Architecture.

1. Introduction

Architecture is dynamic, relative to place, light, materiality, colour, form, acoustics and sequences, many spatial details in which details cannot be completely conveyed unless experienced firsthand (Senagala, 2000). The ability to move freely within a temporal and three-dimensional environment is not able to be replicated with conventional tools of representation. Drawings on paper and small models of card give the viewer an opportunity to interpret the experience of a design, but they do not ever fully comprehend the spatial qualities in a way that mimics the dynamic nature of the architecture (Mitchell, 1995). Immersive virtual architecture offers the viewer an opportunity to understand the dynamic nature of moving through architecture and the relationships between scales, perspectives,

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 727-736. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

proportions and the like more accurately (Pandit, 2016). Strategically this remains the most efficient method to avoid situations where architects submitting drawings with the intended built form not turning out as they had expected, then having to perform alterations (Klercker et al., 2001). Virtual reality, being one of the most intriguing visualisation tools currently existing, although is virtual, is dealing directly with created forms of architecture, thus via modelling and scripting is defined as virtually built. The case study within this research, reimagining the way one inhabits space, can be applied within any style of immersive environment.

Architecture places a high level of importance on the occupant's perception and experience of residing within space (Krymsky et al., 2017). Virtual reality as a tool provides an exceptional opportunity for such spaces to be experienced before the concept and final design dissemination to an audience (Pandit, 2016). Various forms of immersive virtual architecture currently exist to serve many purposes, including evaluating unbuilt form, education, visiting remote heritage sites, social gaming and to simply reside within (Reid, 2004). Reimagining immersive architectural qualities in a specific way within the virtual space are the sole focus of this paper. Throughout case study investigations, a trilogy of virtual classifications, the speculative environment, the virtual inhabitant and the virtual built form, are defined as the vital ingredients to generate the reimagined experience and are all to be designed relative to each other, this paper focuses on the inhabitant section. This leverages computational design, digital locomotion mechanics and digital ephemera in a real-time virtual engine, a speculative environment is created comparatively to manipulating the physical laws of the physical world. Reconfiguring conventional elements of virtual space inhabitation, this work examines architectural properties such as orientation, scale, temporality, perception, virtual form and the possibility of a virtual body that can navigate an environment in a way unique to this research project.

Proposed is an alternative spatial experience of architectural dynamics to enhance such qualities in a highly sophisticated condition. Inhabitants residing within virtual reality environments create an opportunity for architects to virtually build physically impossible structures. Commercially the virtual space does not belong to architects, but rather game designers, however, they are beginning to turn to architects to help develop their worlds (Astbury, 2014). This concept wades into the notion of what immersive virtual reality environments can become with the ability to reimagine the norm of which a user inhabits virtual space (Dalton, 2016).

2. Methodology

The publication Digital Culture: An interconnective design methodology ecosystem (Rogers et al., 2018b), formed as a prerequisite for the knowledge and technicalities required for the generation of the concepts within the case study. This previous research specifically provided the formwork for the methodology exercised, focusing on designing the key components within the trilogy of virtual classifications within the immersive environment in an interconnective, dynamic and efficient way (Figure 1). Studying design processes allows the architect to explore the benefits and hindrances for certain tools (Wiggins 1989), combining

the art of study and practice together provides viable inputs and outputs in order to create a successful design cycle or framework within the architectural design (Schnabel 2004).

In order to reimagine relativity within a virtual environment, the body becomes a virtual inhabitant, the most significant of the three virtual classifications. The methodology diagram shows the virtual inhabitant components of spatial locomotion, spatial orientation, local scale and user population, these were designed relative to each other and the speculative environment classification components of visible environment boundaries, atmospheric qualities and the audio experience. These were then tested for successfulness in reimagining relativity with various geometries, orthogonal, polygonal, curvature, fractal, and minimal surface.

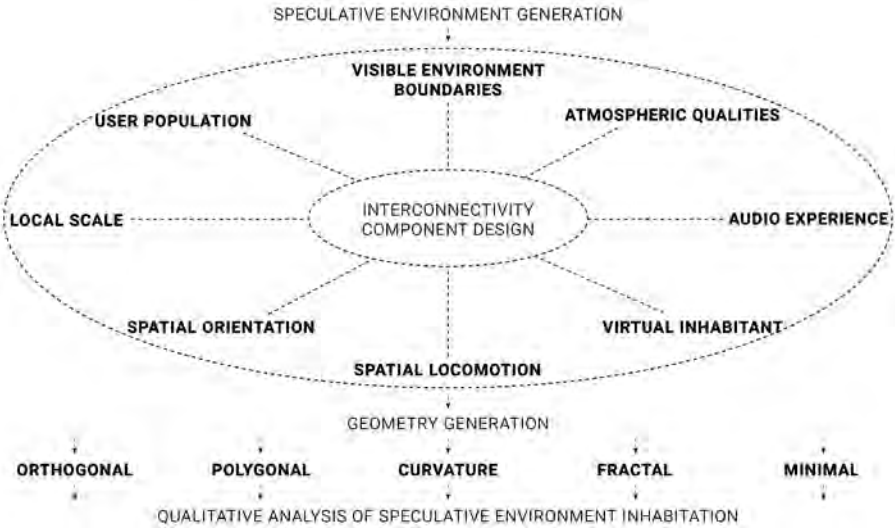


Figure 1. Methodology Diagram Adapted from (Rogers et al., 2018).

3. Trilogy of Virtual Classifications

To reimagine architecture, a trilogy of virtual classifications has been established, the speculative environment, the virtual inhabitant, and the virtual built form

The publication Future Virtual Heritage - techniques (Rogers et al., 2018a) formed as a critical prerequisite for developing the skillset and technical knowledge required to generate the reimagined relativity experience in relation to the speculative environment components. Tangible and intangible digital heritage: creating virtual environments to engage public interpretation (Silcock et al., 2018), was critical to developing the skillset and technical knowledge required to generate the reimagined relativity experience in relation to the user and inhabitant components which transitioned the physical body into a virtual inhabitant. Digital Design Ecology: An analysis of an intricate framework of

architectural design (Rogers and Schnabel, 2018) evaluated the procedures and tools from the Digital Culture paper in relation to education and professional practice. The evaluated tools gave critical insight into the way in which the built form was generated from a creative and efficient perspective within this case study.

This research within concentrates on the successfully generated inhabitant portion components. Resulting from this case study, this trilogy was immediately defined to understand the environment composition, thus concerning future work to develop components within these classifications, will still remain within this model. As new creativity advances, generating evolving components, the defining lines between the trilogy classifications may become blurred over time, just as how the Reality-Virtuality Continuum components have been blurred over time due to technology advancements (Milgram et al., 1995).

4. Inhabiting Spatial Geometry

Components outlined within this paper were tested within a virtual immersive environment through various geometries as the built form, orthogonal, polygonal, curved rotational fractals and a minimal surface (Figure 2). Within the immersive environment, the built form geometry modules were repeated to appear as an infinite mass like in figure 3 of the minimal surface. This allowed full exercising of the testing of the following components within this paper.



Figure 2. Four Geometry Tested Relative to the Inhabitant. Left to Right: Orthogonal Space, Polygonal Space, Curved Rotational Fractal Space, Minimal Surface Space.

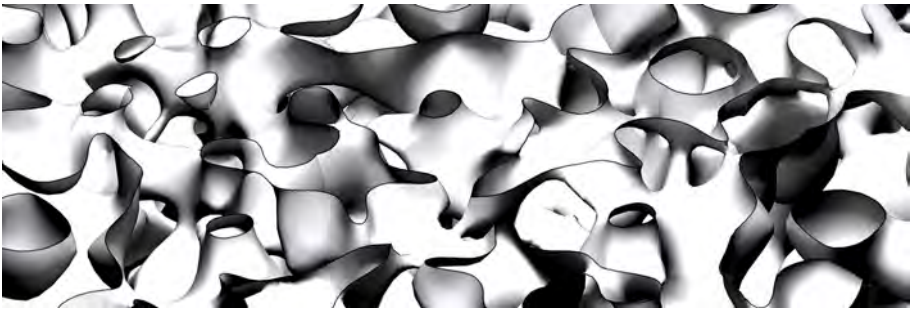


Figure 3. Infinite Minimal Surface Space.

5. Virtual Body

Physically, the body consists of many control points, a user represented within an immersive virtual environment has a limited number based on the technology available and designed for. Figure 4 shows a simplified version of the real bodily control points for a normal human, transitioning into a virtual body. The HTC Vive uses was limited to three main devices as control points i.e. the headset and two hand controllers, as there are also two audio sources to represent ears and eyes, these did not act as main control points, they are a sub-device to the headset.

As the transition within figure 4 is made evident, it is significant for the virtual body that no control points are in contact with the ground plane, suggesting the ground plane is as such, irrelevant. This notion opened new opportunities to completely reimagine the relationship between the inhabitant and the ground. As the transition of control points is important, equally so was the visibility. Within the speculative environment case study, the hand controllers were made invisible to the inhabitant. The visibility of them acted as a reference to the real world and usually cause the inhabitant to look at them and become distracted from the events taking place.

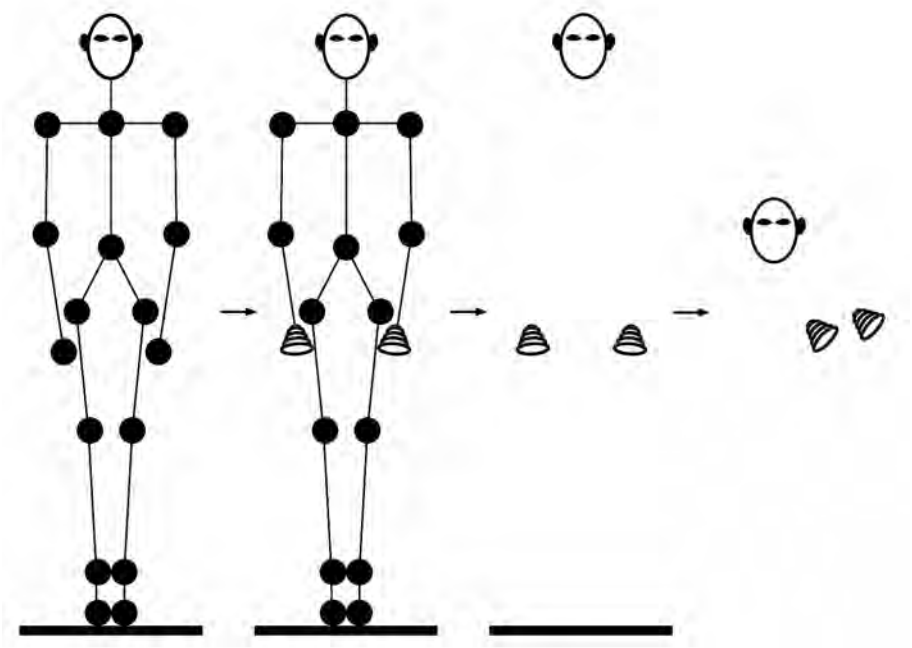


Figure 4. Physical Body to Virtual Body Control Point Translation.

6. Spatial Locomotion

Using one of the HTC Vive controllers, many architectural experiences utilise the default teleportation mechanism or glide-walking by holding the thumb track-pad down or navigating by thumb placement on the X and Y axis on the thumb track-pad to control direction. This case study created a C Sharp script which gives the inhabitant the ability to fly through space in any direction desired the controller is pointing on an X, Y and Z axis by pressing their thumb one of the controllers (Figure 5). This newly-designed general relativity law mechanic gives the user, the ability to 'fly' through space.

The script generated senses the touch of the user's thumb on a controller and drives them forward with a vector defined by the physical angle which the controller is in relation to the tracking set up and predetermined force deemed adequate to move through space. This is changeable in Unity3D to be at a fixed value within the immersive environment or implemented within a user interface within the immersive environment to be altered as the inhabitant desired. As a form of free spatial locomotion, this way of exploring a virtual environment reimagined the way in which humans might one day move through space while giving them the opportunity to experience such movement, advancing from the bounds of gravity in a three-dimensional space.

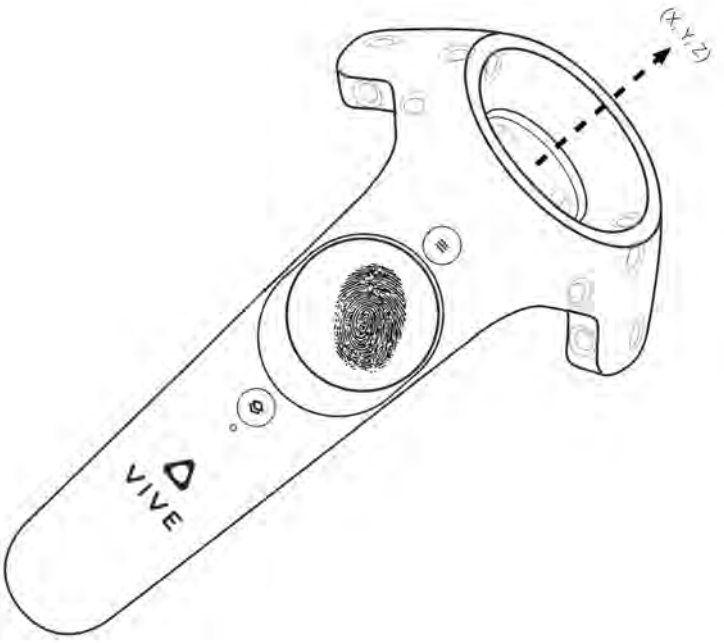


Figure 5. Spatial Locomotion using the HTC Vive Vontroller.

7. Spatial Orientation

Abstract forms of relativity portrayed by M.C. Escher (1953), depicts three orthogonal sources of gravity made evident by the orientation of a human figure. Within this case study designing the immersive environment within Unity3D, world gravity on the vertical axis was made to be zero. A general relativity law mechanic was generated via C Sharp scripting and applied to each virtual inhabitant, this defines their orientation and thus gravity source within the space. Generated real-time, the script generates five ray casts from the base of the inhabitant's virtual body in downward directions, one straight down, and the other four at 45-degree angles to the front, back, left and right. All rays produce a sphere collider on their end (Figure 6), the maximum ray length and sphere collider radius were fixed within Unity3D. Sphere collider contact with a geometry mesh surface orientated the inhabitant to the normal of that surface, keeping the geometry beneath the inhabitant. The ray with the shortest distance from the surface applies a smooth driving force in the direction of that ray 'gravitating' the inhabitant downwards towards that surface, giving the inhabitant the ability to 'stick' or 'walk' to any surface within the immersive environment.

The intensity of the transition depended upon the complexity of the geometry, the angle between two surfaces, and the inhabitant's speed. If different sphere colliders keep sensing new geometry, many fast transitions occur. This for some users caused slight discomfort, however, was quickly getting used to. Like insects crawling along walls and ceilings, this provides users to inhabit virtual architecture in a completely different way to the norm in which one moves through and exists within space.

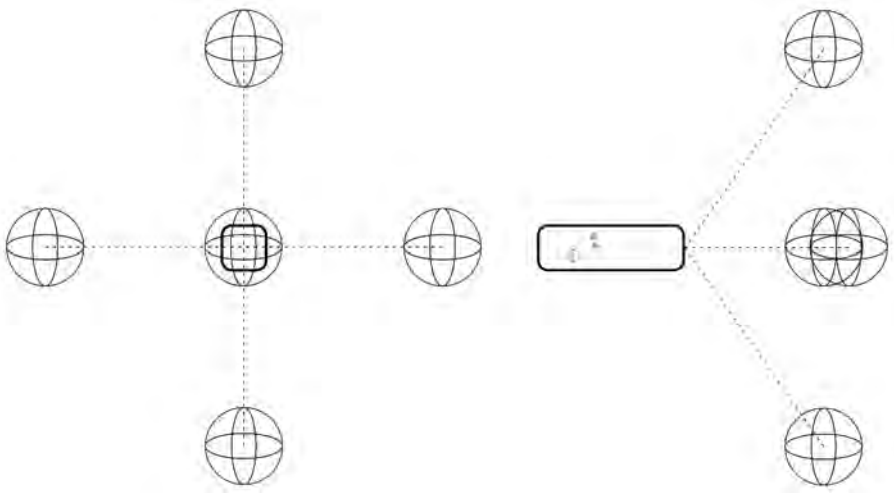


Figure 6. Sphere Ray Casting to Generate New Relativity Laws within the Virtual.

8. Local Scale

Human scale gradually increases and then decreases as one gets older with age. This C Sharp script applied within Unity3D generated a dynamic environment to virtual inhabitant relative scale change. Here the inhabitant controlled their ability to increase and decrease their local scale, by swiping their thumb up on the trackpad on one of the controllers to increase scale and swipe down to decrease scale (Figure 7).

As also shown in figure 4 as the physical body transitions into the virtual body, combined with this additional local scaling mechanic, the physical height of a person becomes irrelevant within the immersive environment. This changed the user's perception of the space drastically. Upon entering the space, the inhabitant's scale is an exact representation of reality, which then was interacted with.

Inhabitants having a dynamic scale reimagined their spatial inhabitation, as any place within the architecture could be reached or accessed. The ability to see a smaller portion of the space or the entire form of geometry.



Figure 7. Beginning of Scaling Law Creation within the Virtual.

9. User Population

Essentially classified as multiplayer with time as a design variable. Using this networking script, multiple game files were connected via local networking with the virtual inhabitant bodies synchronised real-time. This allowed the inhabitants to see each other's exact moves at exact times. However, the time in which the

events were unfolding within the immersive environment was relative to when the inhabitants individually entered the space. One might be looking and interacting with an object (Figure 3) whereas the other would see them interact with an entirely different form (Figure 8) based on if they entered the immersive environment before or after the other. This effect created confusion when collaboration within the architectural space was desired. But was also an extremely unique and special feature as reimagined within an abstract world.

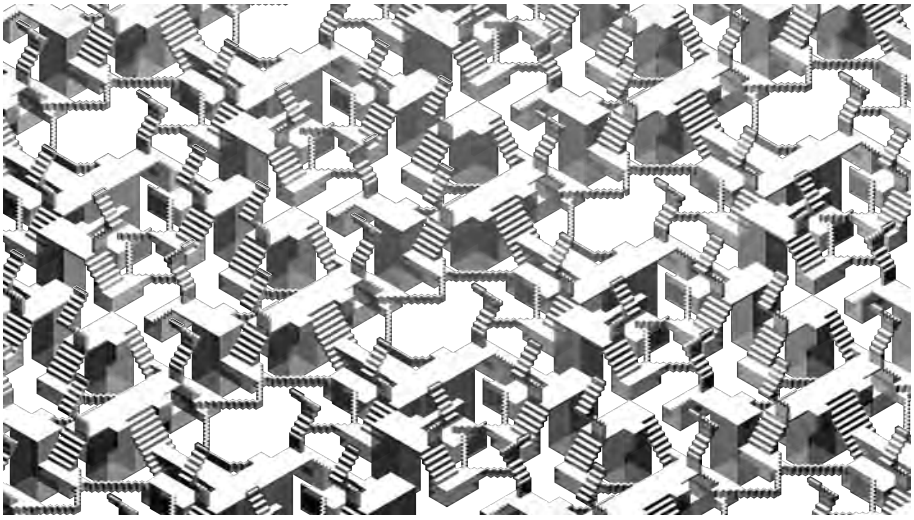


Figure 8. Infinite Orthogonal Space.

10. Conclusion

This research establishes a trilogy of virtual classifications. The speculative environment, virtual inhabitant and the virtual built form. These coalesce to generate a new quality of immersive architectural space. Components outlined within this paper of the virtual inhabitant consisted of the virtual body, spatial locomotion, spatial orientation, local scale and user population.

The trilogy of virtual classifications has enabled us to reimagine relativity and experience the way in which one can inhabit space. Ultimately, the trilogy of virtual classifications gives the inhabitant the possibility of perceiving the environment and its architecture within from dynamic orientation, scale and position. At the same time, it allows architects to generate new creative horizons from which to consider the craft of designing space and form in virtuality.

References

Astbury, J.: 2014, “Playing the Architect: Why Video Games and Architecture Need Each Other” . Available from <https://www.architectural-review.com/essays/playing-the-architect-why-video-games-and-architecture-need-each-other/8664135.article>.

Batchen, G.: 1996, Spectres of cyberspace, *Artlink*, **16**(2-3), 25.

Dalton, R.: 2016, "Want to build better computer games? Call an architect" . Available from <http://theconversation.com/want-to-build-better-computer-games-call-an-architect-58912> (accessed December 2018).

Escher, M.C.: 1953, "Relativity" . Available from <https://www.moma.org/collection/works/61398> (accessed December 2018).

Herron, R.: 1966, "Walking City on the Ocean, project (Exterior perspective)" . Available from <https://www.moma.org/collection/works/814> (accessed December 2018).

Jeffery, K.J., Jovalekic, A., Verriotis, M. and Hayman, R.: 2013, Navigating in a three-dimensional world, *Behavioral and Brain Sciences*, **36**(05), 523-543.

Klercker, J.A. and Henrichsen, J.: 2001, Can simulations in VE support architects in solving complex design problems?, *ACCOLADE - Architecture, Collaboration, Design*, Delft University, The Netherlands, 77-82.

Metaxas, D.N., Badler, N.I., Huang, G., Goswami, A. and Huh, S.: 1999, Dynamic Simulation for Zero-Gravity Activities, *International Space Human Factors Workshop*, **1**, 11.

Milgram, P., Takemura, H., Utsumi, A. and Kishino, F.: 1995, Augmented reality: a class of displays on the reality-virtuality continuum, *Photonics for Industrial Applications*, Boston, MA, 282-292.

Mitchell, W.J.: 1995, *City of bits: space, place, and the infobahn*, MIT Press, Cambridge, Mass..

Pandit, A.S.: 2016, "How Virtual Environments Could Help Architects?" . Available from <https://www.arch2o.com/how-virtual-environments-could-help-architects/> (accessed December 2018).

Reid, D.: 2004, A Model of Playfulness and Flow in Virtual Reality Interactions, *Presence: Teleoperators and Virtual Environments*, **13**(4), 451-462.

Rogers, J., Moleta, T.J. and Schnabel, M.A.: 2018a, Future Virtual Heritage - Techniques, *3rd Digital Heritage International Congress (Digital Heritage) and 24th International Conference on Virtual Systems & Multimedia (VSMM 2018)*, San Francisco, CA, USA. (In Press).

Rogers, J. and Schanbel, M.A.: 2018, Digital Design Ecology: An Analysis for an Intricate Framework of Architectural Design, *Computing for a better tomorrow, Proceedings of the 36th eCAADe Conference*, Lodz, Poland, 459-468.

Rogers, J., Schnabel, M.A. and Lo, T.i.a.n. T.i.a.n.: 2018b, Digital Culture - An Interconnective Design Methodology Ecosystem, *Learning, Adapting and Prototyping, Proceedings of the 23rd CAADRIA Conference*, Beijing, China, 493-502.

Schnabel, M.A., Kvan, T., Kuan, S.K.S. and Li, W.: 2004, 3D Crossover: exploring objets digitalis'e, *International Journal of Architectural Computing*, **2**(4), 476-490.

Senagala, M.: 2000, Architecture, Speed, and Relativity: On the Ethics of Eternity, Infinity, and Virtuality, *Eternity, Infinity and Virtuality in Architecture, Proceedings of the 22nd Annual Conference of the Association for Computer-Aided Design in Architecture*, Washington D.C., 29-37.

Silcock, D., Rushton, H., Rogers, J. and Schnabel, M.A.: 2018, Tangible and Intangible Digital Heritage - Creating Virtual Environments to Engage Public Interpretation, *Computing for a better tomorrow, Proceedings of the 36th eCAADe Conference*, Lodz, Poland, 225-232.

Wiggins, G.E.: 1989, *Methodology in architectural design*, Ph.D. Thesis, Massachusetts Institute of Technology.

SENSORY URBANISM AND PLACEMAKING

Exploring Virtual Reality and the Creation of Place

ANASTASIA GLOBA[1], RUI WANG[2] and BEAU B. BEZA[3]
[1]*University of Sydney*
[1]*globalnaya@gmail.com*
[2,3]*Deakin University*
[2,3]*{rui.wang|beau.beza}@deakin.edu.au*

Abstract. Sensory Urbanism is an experimental prototyping project exploring the potential of immersive Virtual Reality (VR) environments to support the incorporation of sensory and intangible aspects of place. The study investigates how sensory exploration of urban places can be integrated into decision making regarding the future of cities. In the past, numerous studies reported various sophisticated 'livability' measures, deeming to determine what makes a city a great place to live in. While a part of these measures can be quantified and be represented as text, graphs or images, most of the qualitative aspects of place are inherently abstract and sensory. These aspects have to be experienced to be understood and therefore they are extremely difficult to communicate using conventional representation means. The proposition explored in this study is that the increasing ubiquity of VR and Augmented Reality (AR) technologies can provide new opportunities to engage with the multi-sensory and temporal aspects of urban place. A mixed media approach was adopted, tapping into a temporal dimension as well as visual, aural and kinesthetic range of human senses. The paper reports on the development of the VR sensory urbanism prototype and the initial pilot study that demonstrated the proof-of-concept.

Keywords. Sensory Urbanism; Immersive Environments; Virtual Reality; Design Evaluation; Placemaking.

1. Introduction: The Problem, The Opportunity and The Proposed Solution

A large number of existing studies (Gil-Garcia et al., 2015; Driskell, 2017) investigated what makes a city a great place to live in. Sophisticated metrics were developed involving a wide range of data sets that underpin our understanding of urban liveability such as: patterns of use, infrastructure, stability, culture, environment, health, engagement, education, opportunities, etc. The **problem** is that while some of these measures can be supplemented with text and images to describe qualitative aspects of place; many of the intangible and sensory characteristics are difficult to communicate. Which, in terms of the latter, are

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 737-746. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

similar issues faced by a community, when asked to advise on proposed public works.

Hence, the **proposition** explored in this study is that the increasing ubiquity of VR and Augmented Reality (AR) technologies can provide new **opportunities** to engage with the multi-sensory and temporal aspects of urban place. Hence, a mixed media approach was adopted for use in this research, tapping into a visual, aural and kinesthetic range of human senses. The media used in this experimental prototyping study included 360 degree videos taken on site at different times of day; which provided a dynamic ambient background for the 3D modelling of the urban scene and proposed design interventions. Time and location tagged photographs, walk through videos and bitmap textures were recorded on site and transferred onto the spatial digital environment. These visual and kinaesthetic representations were complimented with the audio recordings taken on site. The audio tracks were placed in the virtual environment as spatially distinct and time dependent sound emitters. The combination of audio emitters generated a dynamic soundscape experience and changed as the observer moved through the scene. The temporal character of urban place was foregrounded by enabling the end user to switch between various daily and seasonal cycles of site activity and environmental conditions.

Development and initial testing of Sensory Urbanism - an **immersive VR prototype application** was established, with a setup VR headset, external projector and surround sound systems, allowing individual and small groups to evaluate urban scenes. Projecting the VR scene(s) was conducted to provide other respondent(s) / spectators with the ability to also view respective settings; which would be a similar scenario when engaging with a community on proposed public works. The haptic interface (Oculus touch) enabled the user to hold a virtual smartphone with functions of teleporting around the site, 'dialing up' the time of day, accessing videos capturing typical movement paths, viewing supplementary drawings and photographs. For this pilot project, architecture, industrial design, landscape architecture and urban planning students from Deakin University and Pontificia Universidad Javeriana, Colombia developed temporary events that could occur within the public space of Eastern Beach Reserve in Geelong, Australia; including a hand held interface that enabled the user to switch between and experience the three proposed design interventions.

The Sensory Urbanism pilot study and prototype demonstrated proof-of-concept. Feedback from participants and observers, was that there is much potential in the development of an immersive multimedia and multisensory approach to urban design exploration and evaluation. This approach aimed to allow qualitative aspects of place to be utilised engaging with communities, business and industry during the early stages of urban design. Full case studies in a range of urban and cultural contexts, however, need to be undertaken. It is planned to develop the interface and authoring systems, including the embedding of task based activities, voice activated survey and data tracking of user behaviour, to generate statistically valid evaluation studies on the effectiveness of the approach.

2. Background / Related Work

2.1. EXISTING METHODS EVALUATING URBAN SPACES

Commonly the qualitative and quantitative aspects of urban spaces ar identified through community engagement practices. 'Engagement' with a community in relation to the design of a public space is usually enshrined in planning legislation in settings like the USA, UK and Australia (Beza and Hernández-Garcia, 2018). How communities are engaged with depends on the preferred approach that is used by the design consultant, council team and/or researcher (e.g. Moughtin, 2003) charged with identifying the place elements valued by the community and that they wish expressed in the new design concept. In themselves the approaches can be as straightforward as talking to people and asking them to describe and/or rate the qualitative and quantitative aspects of place, through to having them draw (e.g. on butcher paper) their preferred/ideal place (e.g. Sanoff, 2000). The designer then takes this data and translates it into a concept; which is then presented and discussed with the community. Their respective opinions are then taken into account when producing the final design concept. The latter dimension of this approach (i.e. review of the concept) is normally a static exercise; with people asked to review paper and/or projected drawings/imagery of the intended design outcome and to imagine how the space may act and feel.

2.2. AFFORDANCES / IMMERSIVE ENVIRONMENTS IN ARCHITECTURE

When people interact with the environment, the environment provides stimuli that influences behaviour or one's action(s). These elements of the environment are what Gibson (1986) refers to as affordance: a concept that uses visual stimuli in the environment as a mechanism to explain the relationship between people and space. Another dimension to his concept is Technology Affordances; which refers to a means for analysing technologies in relation to the 'possibilities' they offer people and their potential action(s) relative to the technology (Gaver, 1991). In the context of this interaction design analysis considerations, four complementary types of affordances have been identified: cognitive, physical, sensory and functional (Hartson, 2003). Sensory affordance, in particular, supports cognitive and physical affordances in design by enabling the user to sense his/her environment; it plays an essential role for the user enabling one to gain an understanding the elements displayed in environments and to then act upon them.

Emerging technologies that support sensory affordance including video game technology, virtual environment and 360 videos; which have also been adopted for urban design and placemaking exercises, provide a wide range of affordances to enable better sensory experiences. For example, Alvarez and Duarte (2017) explored how video games can inform spatial design and practice through storytelling and multiple viewpoints; Puyana-Romero et al. (2018) carried out case studies on the use of interactive soundscapes and 360-video based virtual environment as a collective participatory tool with three different hardware settings (immersive VR, mobile VR and screen based applications), however they found no statistical difference in the settings used by respondents. Ghani et al. (2017) conducted preliminary investigations on using VR technologies that enable

users to experience virtual urban environments, and identified a number of factors which determine user experiences with a place, including contextual setting, interactivity, navigation, level of details, viewpoints and auditory elements.

3. Methodology and Prototype Development

3.1. PROJECT SET-UP: HYPOTHESIS / SOLUTION / VALIDATION

This Sensory Urbanism VR prototype and the pilot study reported in this paper are the first stage offshoot project of a larger research agenda investigating the **affordances of immersive AR and VR environments** as a means to explore and evaluate the conceptual design 'phase' in architecture and city planning. The aim of this pilot study is to ascertain the extent to which the development of an immersive mixed media prototype application can be realised. To achieve this aim, we adopted a **prototyping approach** that is grounded on the conceptual positioning: within the context of rapidly emerging opportunities afforded by new digital technologies, they could allow for the development of highly innovative outcomes (Bury, 2016). Eastern Beach Reserve in Geelong, Australia (a public beach area on the foreshore of the city) was used as a case study (urban context) for this initial proof-of-the-concept research stage. Three urban design interventions - temporary structures and events, proposed to take place on the Eastern Beach, were designed and integrated into the VR scene by a group of international and domestic undergraduate and postgraduate students. This paper reports the development of the software prototype that adopted agile project development methods and progressed through incremental, iterative work sequences and participant-observer evaluation.

In terms of the undertaken research, the study is split into of three overlapping areas. The first area refers to the development of the VR prototype, that was conceived as an interactive and highly customisable urban space exploration platform and was developed using Unity3D gaming engine, with the VR application and interfaces implemented for Oculus RiFT and Oculus Touch. The second area, encompassed the collection of the mixed-media geo-located data, collected on site at different times of day, including: 360 videos, sounds, photos and walk though recordings; 3D modelling of the scene; and design of the proposed temporary structures and public events (Fig 1). This was followed-up by the integration of the recorded data and designs into the VR scene in Unity. The third and final stage involved the actual testing of the prototype: group evaluation of the proposed urban events (temporary architectural installations) in VR, collecting the feedback from the users, and accessing the the capacity of the Sensory Urbanism prototype (immersive mixed-media approach) to support the incorporation of sensory characteristics of place into architectural design decision making and city planning.

3.2. PROTOTYPE DEVELOPMENT

The development of the prototype adopted a mixed media approach, involving simultaneous representation of a wide range of media forms including recorded 360 videos, 3D models, bitmap textures, spatial sounds, photos and time lapse

videos. A game engine platform, Unity3D, was used to integrate these varied media inputs and allow a set of proposed user functions.

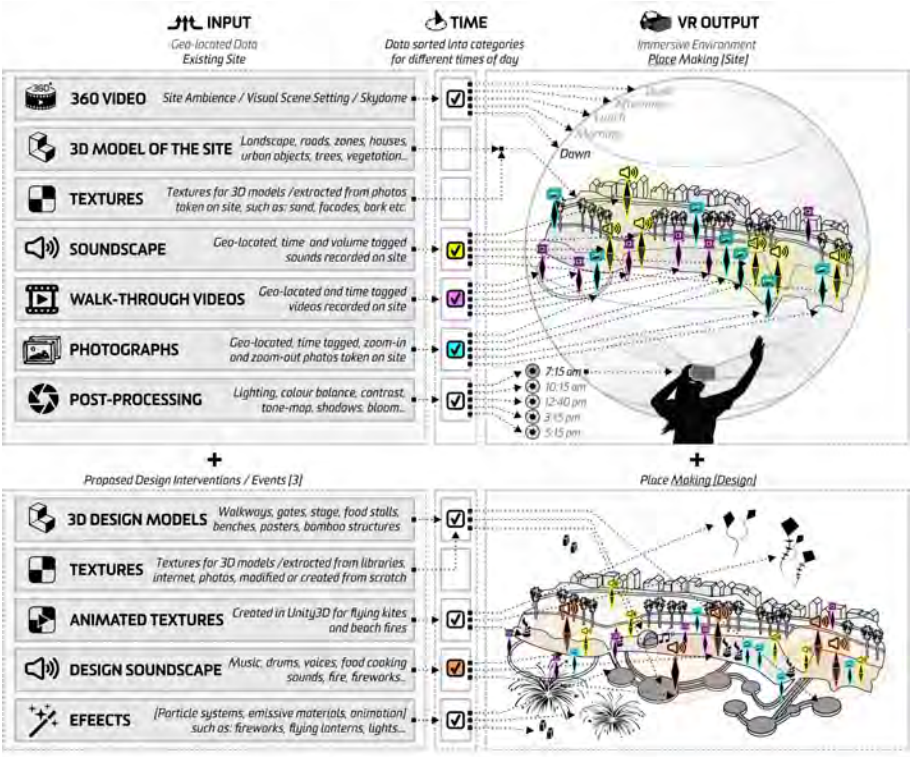


Figure 1. Prototype Input-Output.

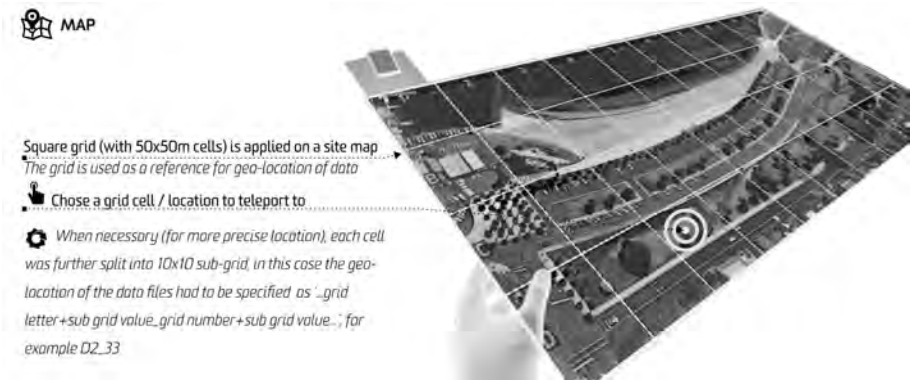


Figure 2. Spatial Grid and Data mapping / Virtual Interface (Map).

To bring all these elements together two components were integrated in the

virtual environment platform, as illustrated in Fig. 1: a collection of media representations of the existing site, as well as potential design events for the site. Such a mixed media approach was adopted to provide an immersive, interactive environment to the users, so that they could **experience the place**; which included both the existing site of the Eastern Geelong beach and the proposed design interventions, in an sensory and intangible way.

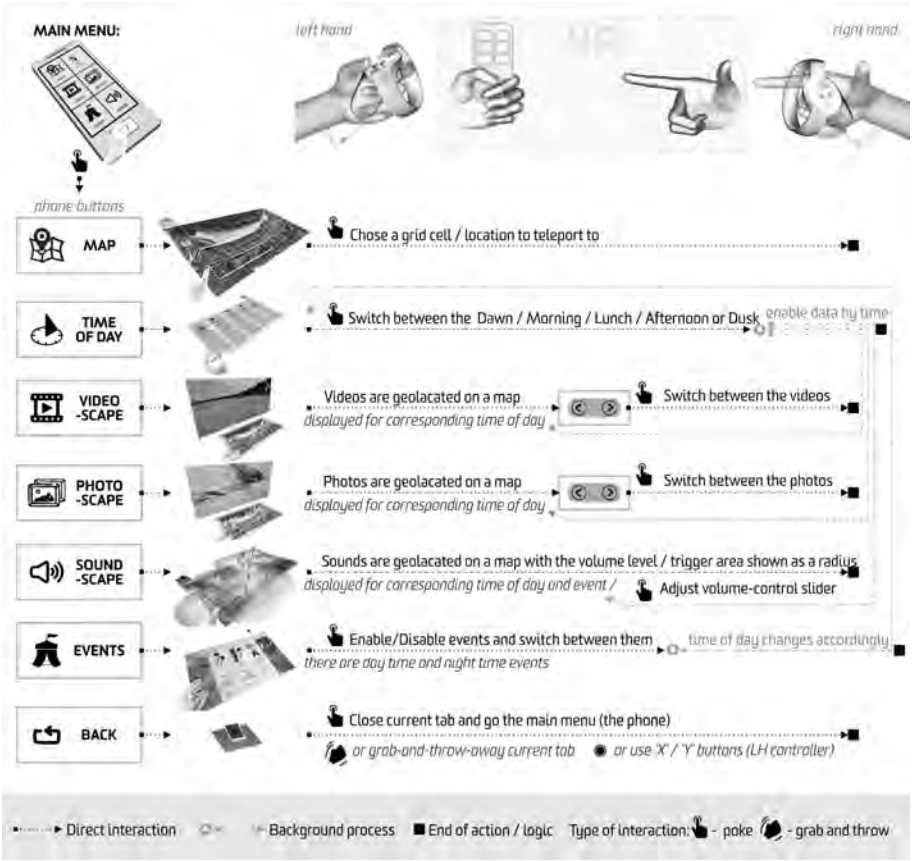


Figure 3. Virtual Interface (Functionality / Logic).

The media resources included in the sensory urbanism platform were created to be highly customisable. Users would only need to copy the new sound files and/or images to the designated folders in the application, for them to be automatically loaded when the application starts. For 360 videos and time-lapse videos, users needed to upload them to an online video platform such as Youtube, and then provide the links of the online videos in a text file located in the application folder. A naming system of the sound, image and video files was used as a means to determine where each media file would be placed spatially within virtual environment. For instance, a sound file named "da_D_3_8.mp3" will be placed

for the time of dawn ('da'), in the setting of grid D3 (see Fig. 2.), at a volume level of 8 (with 0-to-10 volume scale). As such, this sound file will only be played when the virtual environment is dialed to the time of dawn, and when the user is within a certain distance to the sound source; and the closer the user is to the sound, the louder it gets. By mapping the real-world experiences onto the virtual environment, this replicates the 'intangible' aspects of the sound of dawn, in this setting, and conveys this sensory aspects of place for people; which they can share when trying to communicate their design ideas. A similar data mapping approach was used for all the images and video files.

The user interface (UI) for the virtual environment was designed using a smartphone metaphor. The main menu of six main functions were placed as six buttons on the virtual mobile phone (see top-left in Fig. 3); where the user holds the smartphone with their left virtual hand, and the buttons are clickable with the right index finger. Once clicked, the buttons would bring up their corresponding sub-menus, which include: (a) a 'Map' menu - teleporting the user to different grids; (b) a "Time of Day" menu - switching between different times of the day; (c) a 'Video-Scape' menu - showing a collection of time-lapse videos that were taken on the site, at the current time of the day; (d) a 'Photo-Scape' menu - showing a collection of photos that were taken on the site, at the current time of the day; (e) a 'Soundscape' menu - visualising the locations of the sound resources on site, with a master volume slider; (f) an 'Event' menu - allowing the user to turn on and off the three proposed interventions individually.

4. Case Study / Testing the VR Place Making Prototype



Figure 4. Pilot study / Workshop set-up.

The pilot study was organised as a two week architectural and urban design studio that took place at Deakin University (Australia) and involved a group of Colombian and Australian undergraduate and postgraduate students (Fig. 4). Workshop participants were asked to model the site (Eastern Beach Reserve in Geelong) in 3D and texture this 3D urban model using the photographs taken on site, such as: palm tree bark texture, asphalt, street signs, the sand on the beach, facades of the buildings etc. Working on site, students made a large number of sound, photo, and video recordings tagging each data entry with the location and

time, so that afterwards all the data that they have collected could be accurately mapped into the VR environment. Students were also split into three groups, each developing an 'event' (see Fig. 5.) that was to occur on the site & to be experienced and evaluated in VR by inviting guests and other Faculty students.



Figure 5. Design Interventions / Proposed Events.

The events were placed as separate interactive entities in the mock-up of the existing urban set-up (base VR scene). Each event included: a 3D model of temporary architectural structures placed on the beach, music and sound effects associated with each particular event, as well as animated objects such as kites, fire pits, wind turbines, and particle effects such as fireworks (Fig. 4). The user could turn the events on and off, or switch between them. By using the time menu, they could experience each event at different times of day (Fig 6.). At the end of the two week session invited guests, the undergraduate/postgraduate students and academics involved in this project evaluated the positive and negative aspects of the prototype along with the work involved in creating it. Although aspects of the prototype are in need of redevelopment (e.g. some cells in the map menu functioned incorrectly, greater time allocation for tasks) the prototype was considered by those involved in the evaluation to have potential in representing the intangible and sensory characteristics of a setting.

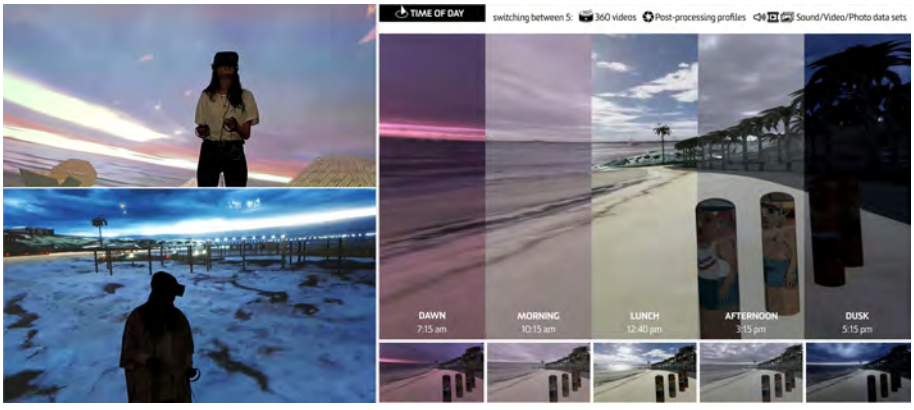


Figure 6. Placemaking VR exploration of proposed events at different times of day .

5. Discussion

The proposition explored in this study was that the use of mixed-media urban data mapped within interactive immersive environments could allow for the incorporation of sensory and intangible aspects of place, that are otherwise very hard to communicate. The resulting Sensory Urbanism prototype incorporated and blended together a wide collection of media and data inputs. Thus, allowing users to engage with the multitude of visual, aural and kinesthetic range of human senses, as well as enabling the exploration of temporal aspects of existing and proposed urban spaces.

Development of the Sensory Urbanism prototype and initial proof-of-concept pilot study suggest that this approach can be successfully used as a mechanism to convey the intangible aspects of place, that can be found in an urban setting. Interestingly, the sensory element of sound appeared to be a key urban element that conveyed a sense of place, or not, in the immersive environment (i.e. virtual world). Sight is still considered an important element in this exercise but respondents were able to 'look beyond' the visual anomalies and imperfections of the prototype. Importantly, it was noted by respondents (and the researchers) that the imperfections conveyed a message that the work is incomplete (i.e. in draft form). This later dimension (i.e. work in draft form) can be an effective tool when working with communities as in their review of highly rendered architectural design imagery, it can present with a look of completeness. Hence, work in 'draft form' they may consider has the ability to still be amended based on their review.

6. Future Work

Up to the date of writing this paper, the city council of Greater Geelong (where the Eastern Beach Reserve is located) has initialled conversations with us, after seeing the VR placemaking prototype we created. The city council has seen great potential of adopting this approach in the actual practice, and has proposed that we work on a real case in the City of Greater Geelong for placemaking with virtual environments, with future development on the current prototype in two possible directions: firstly, on the surface of it, in depth development is needed towards a more flexible, customisable platform. In its current form, 3D models are not exchangeable or editable; interfaces which allow the users to upload their own 3D models should be developed, so that along with the existing interfaces for sounds, images and videos, the users will be able to create their own immersive virtual spaces. Secondly, on the background of the application, functions for user activity tracking can be developed. For instance, the application can track the locations of the user in the virtual space, and the interactions that the user has engaged or the actions the user has taken within the virtual environment. It might even record the qualitative experiences of the user by taking their voice comments can be documented. Such information can help us to better understand the affordances that the virtual environment provides, to grasp the insights of user experiences and to aid with decision making in the urban space.

Other than the potential work with the local city council, we propose that a number of VR sensory urbansim workshops be arranged, with the same platform

and different urban contexts. One of the most immediate workshop can take place at CAADRIA 2019; we are in the process of preparing a proposal on a workshop using our VR placemaking platform with the urban context of Wellington. Through this workshop and a few following workshops, case studies can be organised to evaluate the use of VR technology in Placemaking and Sensory Urbanism for different urban contexts.

7. Conclusion

Despite these Sensory Urbanism considerations helping the research team to suggest positive leanings in the development of the prototype - it is the affordance of the Mixed Reality technologies, in this case - Virtual Reality, that further supports the validity and potential of this research in relation to the larger research agenda. It reinforces a proposition that the affordances of immersive AR and VR environments could allow for better sensual engagement between the observer and the constructed space, facilitating more comprehensive exploration and evaluation of conceptual designs in architecture and city planning.

References

Beza, B. B. and Hernández-Garcia, J.: 2018, Placemaking and Sustainability Citizenship: Reflections on a citizenry self-organising to realise public places in Bogotá, Colombia, *Journal of Place Management and Development (special issue: Participatory placemaking: Concepts, methods and practices)*, **11(2)**, 192-207.

Burry, M. and Burry, J.: 2016, *Prototyping for Architects: Real Buildings for the Next Generation of Digital Designers*, Thames and Hudson, London.

Driskell, D.: 2017, *Creating better cities with children and youth: A manual for participation.*, Routledge.

Gaver, W. W.: 1991, Technology affordances, *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI*, New York, NY, USA, 79-84.

Ghani, I., Rahman, N. A., Nayan, N. M. and Bahaluddin, A.: 2018, Experiential Virtual Urban Environments: A Preliminary Investigation, *Journal of the Malaysian Institute of Planners*, **16 (1)**, 25-37.

Gibson, J. J.: 1986, *The Ecological Approach to Visual Perception*, Psychology Press.

Gil-Garcia, J. R., Pardo, T. A. and Nam, T.: 2015, What makes a city smart? Identifying core components and proposing an integrative and comprehensive conceptualization, *Information Polity*, **20(1)**, 61-87.

Hartson, H. R.: 2003, Cognitive, physical, sensory, and functional affordances in interaction design., *Behaviour & Information Technology*, **22(5)**, 315-338.

Moughtin, C.: 2003, *Urban Design: Street and Square (3rd ed.)*, Architectural Press: Oxford..

Puyana-Romero, V., Lopez-Segura, L. S., Maffei, L., Hernández-Molina, R. and Masullo, M.: 2017, Interactive Soundscapes: 360°-Video Based Immersive Virtual Reality in a Tool for the Participatory Acoustic Environment Evaluation of Urban Areas, *Acta Acustica united with Acustica*, **103 (4)**, 574-588.

Sanoff, H.: 2000, *Community Participation Methods in Design and Planning.*, John Wiley & Sons, Inc, New York.

Álvarez, R. and Duarte, F.: 2017, Spatial Design and Placemaking: Learning From Video Games, *Space and Culture*, **21(3)**, 208-232.

USING AN ONLINE PARTICIPATION TOOL TO COLLECT RELEVANT DATA FOR URBAN DESIGN

The construction of two participation exercices

LUDOVICA TOMARCHIO[1], STEPHANIE HASLER[2], PIETER HERTHOGS[3], JOHANNES MÜLLER[4], BIGE TUNÇER[5] and PEIJUN HE[6]
[1,5]*Future Cities Laboratory, Singapore-ETH Centre, Singapore University of Technology and Design*
[1]*tomarchio@arch.ethz.ch* [5]*bige_tuncer@sutd.edu.sg*
[2]*EPF Lausanne*
[2]*stephanie.hasler@epfl.ch*
[3,4]*Future Cities Laboratory, Singapore-ETH Centre,*
[3,4]*{herthogs|johannes.mueller}@arch.ethz.ch*
[6]*Future Cities Laboratory, Singapore-ETH Centre*
[6]*peijun@arch.ethz.ch*

Abstract. This paper discusses the design of an online digital participation campaign, developed as an academic research project in Singapore. In order to develop appropriate exercises which fitted the tool and the context, we addressed several questions: how can online participation tools maintain a negotiation and education power? What data generated by citizens, in the form of a design proposals, is useful for urban design? We created two different exercises, at different scales: one exercise asking people to design proposals with functional blocks and one where citizens could decide the equipment and furniture in a public space. For each exercise we discuss the scale, the elements, the educating and mediating impact, but also the way we intended to use the gathered local knowledge in urban design. The exercise did not receive the expected contributions, gathering little attention from internet users. More results were obtained using an offline experimental setup. In conclusion, we reconsider the weakest points of the design in a critical analysis and provide direction for future online participation tools.

Keywords. Participation; urban design; online tool; engagement.

1. Introduction

This paper presents an online participation campaign, implemented to support the redesign of a neighbourhood in Singapore. The participation campaign is described as a process including the tool and its functionality, the website and its information, and the way collected data has been used. The development of the exercise, being online, required multidisciplinary expertise from user experience,

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 747-756. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

to user interface, digital marketing, etc. Those aspects will be shortly described, to be explored in future publications, but the paper focuses on the exercises, as ways to support the urban design of the area, from an academic point of view.

The questions which lead the process are:

1. How can online participation tools maintain a negotiation and education power?
2. What data generated by citizens, in the form of a design proposals, is useful for urban design?

Singapore is a particular case study, as it stands for a data-rich and data transparent country (data.gov.sg), which is a clear indicator of a transparent governance. Its predominantly top-down decision system is currently giving more space for participation processes, creating a perfect dimension to study the interface between data and participation.

The paper begins with a short overview of positive and negative aspects that must be considered when shifting from a traditional to an online digitalparticipation process, as highlighted from the literature. Then, it describes the tool and the participation process, together with the two exercises, which are currently accessible online at the following address: https:ideasfortanjongpagar.com. Finally, it gives an overview of an ongoing research of data-informed urban design.

2. Online tools for participation: advantages and disadvantages.

Participation has proven to support urban projects by creating processes to mediate and connect different stakeholders, discussing mutual interests and goals, and gathering local knowledge (Wates 2000). Digital Participatory Platforms (DPPs) are defined as "a specific type of civic technology explicitly built for participatory, engagement and collaboration purposes that allow for user generated content and include a range of functionalities (e.g. analytics, map-based and geo-located input, importing and exporting of data, ranking of ideas)" (Falco and Kleinhans 2018). To further specify this definition, we would like to focus on DPPs that are used online, and hence likely accessed independently by users.

Several authors have discussed expected advantages and supposed difficulties when dealing with digital and online participation tools, relative to more traditional forms of participation:

- Falco and Kleinhans (2018) identify different levels of government and citizens relationship, from information sharing, to co-production or self-organisation. The digital online tools support more co-creation processes extended in time, as it is possible to establish a two-way communication channel.
- Co-production is widely regarded as a "solution to the public sector's decreased legitimacy and dwindling resources by accessing more of society's resources" and as a means "to reinvigorate voluntary participation and social" (Brandsen & Honingh, 2016). In this sense co-creating should mobilise social resources and social cohesion, intended as the mediation among different social groups. On the other side, the informing dimension, defined by Linders (2012) as Government as a Platform,

is intended as the processes in which governments equip citizens with data needed to make informed decisions. The informing dimension needs to be redefined in light of the online and digital nature of the DPP. Participation processes based on online digital tools lose the human connection. Hence, the mediation among different groups and the education about general goals must be explicitly addressed in the design of the tool (Mueller et al. 2018). The DPP employed in the participation exercise described in this paper is a co-creation platform, and the exercises are dialogues between the users and the DPP, in the form of tasks, hints and suggestions to answer with proposals. But the dialogue is not open, it follows a specific framework and it does not include the possibility to obtain, from the users, other information rather than the ones that were planned beforehand. This aspect definitely resizes the possibility of action of the DPP, but at the same time, manage to get uniform information, shifting the attention to the data collected, to be compared and use in further analyses (Hasler, Chenal, and Soutter 2017).

- Digital and online tools for participation processes have greater outreach and enable to collect and compare more information; implying a shift from the gathering of discrete local knowledge to big data (Hasler, Chenal, and Soutter 2017). In combination of emerging procedures of data-informed planning and design, the DPP can be considered as source of local knowledge data. In addition, DPP should not replace conventional participatory methods, but be a combination of online and offline techniques (Seltzer and Mahmoudi 2013).
- Participatory processes outcome depends on the trust about the agency of the process: intended primarily as open governance, as a dialogue between citizens and government, the success of a participatory process depends largely from the perceived impact of people's (mostly) voluntary actions. The trust about the agency might reduce the outcome of participatory processes, in the presence a more complex pipeline, where people's contributions stand as data in an academic study (Evans-Cowley and Hollander 2010). In the specific case of this exercise, while initially the campaign was only online, it became a soon part of some workshops and of an online course, which proved to have a better outcome, in term of trust of the agency, giving better results in terms of outreach. The presence of a workshop facilitator or the teacher avatar in the online course, did not change the informing dimension of the exercise, as the facilitator did not intervene in the exercise, beside technical support.
- Internet and social media are media which support specific reading time, mode (hyperlinks) aesthetic, and interaction (Manovich 2000). The DPP should not be considered as the translation of participation processes into a web interface but need to rethink the way people interact with the tool and among themselves.

3. Participation Process design

The participation campaign uses an online 3D composition tool called qua-kit, developed by ETH Zürich. The user lands on the qua-kit platforms through a website which offers different participation exercises related to an urban redevelopment site in Singapore (Mueller et al. 2018). The website provides information and context for the exercises.

Qua-kit is an online design and participation tool that allows to compose and

edit 3D geometries in a 3D environment. The tool supports 3D elements with a base map. The 3D elements can be customised, depending on the nature of the exercise, and they can be picked by users, located in a specific spot and rotated. The 3D elements cannot be resized or modified. The tool records the spatial configuration submitted by the users, together with camera zooms, movements and frequency of elements used. The majority of guidelines and instructions about the use of the tools were presented to participants on the website (https:ideasfortanjongpagar.com), while the tool itself has a simple toolbox, which includes a legend with a description of the 3D element selected and a list of all the 3D elements available with reference images (Fig. 1). After completing and submitting the proposal, each participant is asked to answer some questions regarding specifications and details of his design and general information such as gender, education level and age range.

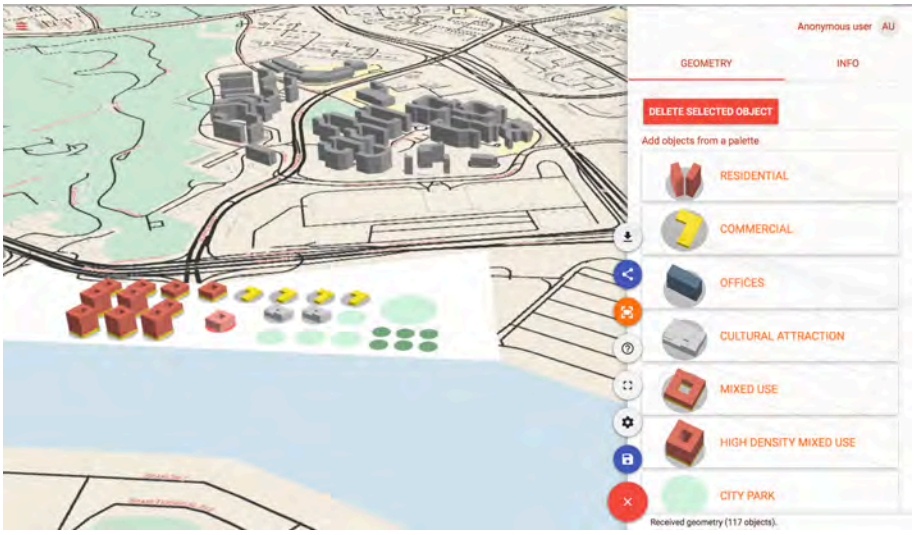


Figure 1. The interface of the qua-kit tool. .

There are clear challenges and advantage to focus on a 3D design tool: non-expert users might not be familiar with spatial thinking and with urban effects of 3D shapes. Confronting them with the task of designing in 3D already carries a lot of education power. Moreover, by asking users to design, we managed to extract local trends in the use of space, which are coming directly from the users, and we did not limit non-expert to comment or rate among existing proposals. For each exercise, we will discuss both the information provided in the website and the 3D element offered in the tool for the composition.

Initially, the participation campaign was only online. The link of the website was shared by some social media accounts: main channels were our institute's Facebook page (Future Cities Laboratory), the Facebook of a non-profit agency (Partecipate in Design) whose main interest is to push participation processes in Singapore and some Facebook groups. There were limited contributions:

only 40% of people who entered the website decided to click on the tool, and only 10% of people who started using the tool completed the exercise, the overall click-through rata is 1%, which is considered low. To gather more feedback, the online campaign was soon supported by some workshops, with payed participants, which took place in Singapore, at two universities (National University of Singapore and Singapore University of Technology and Design). One of the two exercise became also part of an online course.

The people who participated to the campaign largely depends on the proxy, meaning the way they accessed to the tools: either by the workshop, the online course, or by the link available with the social media accounts. There are certain trends: more than 95% of participants have bachelor or higher education, but 77% of participants do not have a specific education in urban design or urban planning, so they are not expert in the field. One third of participants do not have any experience with any 3D software, including video-games, which imply higher difficulties in engaging with the tool. All the participants live in Singapore, but only two third are actually resident (which imply also the possibility to vote) while the rest have some immigration pass.

4. My perfect neighbourhood

The exercise focuses on the new development "Waterfront Tanjong Pagar", a waterfront area of 4.5 sqkm which will undergo major redevelopment. The area currently houses one of Singapore's largest container terminals, which will be relocated, leaving space for a commercial and residential development in close proximity to the city centre. The area is strategically located in Singapore, serving as a bridge from the recently developed touristic area of Marina Bay, the area of Tanjong Pagar and the west of the island. For the purpose of the exercise, only a subsection of the overall area is considered. The final selection is almost 0.3 sqkm, to let users engage with an urban scale, but allowing them to complete the exercise relatively quickly.

This first exercise has a clear agenda of educating non-expert users. The area undergoing redevelopment has very strong potentials and therefore faces some pressure. Being at the crossroad of a lot of important sections of the city and dealing with a rich coastline, the design of the area will have an impact for Singapore, setting up accessibility, density and land use. Non-expert users might not be aware of the implications of certain design proposals and might not even have an opinion about specific design task, which have an impact (e.g. treatment of the coast, treatment of the borders facing parks, etc.).

The exercise objectives are:

- to raise awareness about key points of development in the area;
- to start suggesting people about possible design solutions which might guarantee a more sustainable environment.

In this sense, the proposals submitted by people were not considered in further analysis, because the exercise was not designed to extract ready-made solutions, but had rather an explorative value.

The exercise is composed of three steps of equal importance:

- the guidelines;
- the composition exercise with compulsory items;
- the questionnaire.

By entering in the main page devoted to the My perfect neighbourhood exercise the user is confronted with a short description of the area and of the tool. Then there is the introduction of the elements together with some reference pictures. Before landing to the main tool page the user is confronted with five guidelines which pose specific questions that are key points of the area. The specific questions regard the interface with existing parks, the role of the coast line and the interface with existing shopping venues, the importance of green networks, the roles of public spaces and buildings, the importance of mixed use functions. The users have to go through all the guidelines before being able to start the exercise.

After landing on the qua-kit page, the participants find a map and a white area, representing the space they need to design. The elements they can interact with represent different land use destinations. They can pick among mixed use, dense mixed use, residential, office, commercial, cultural facility, park connector, park, open paved space, and entertainment park. Each element is represented by a 3D geometry that symbolises the specific land use occupancy with a circular base. There is a legend with reference images from Singapore, so that people could immediately relate to the urban environment they were proposing.

When starting the exercise, the users find some elements already placed in the white area. As explained in the guidelines, they first need to reorganise those compulsory elements and, only after, place new ones. The compulsory elements include mixed use objects and parks, and were selected to let users engage with those specific land uses. The combination of the guidelines and the compulsory elements is the core of the exercise, raising awareness among people of accessible friendly solutions that could confront the specificities of the areas. After submitting the exercise, the participant is requested to answer a questionnaire regarding the reasons supporting the design and his profile (gender, education, age, etc.).

The exercise had very relevant results. The solutions submitted by people consistently propose to develop specific ideas for the coastline and respond to the border facing the park connectors. Almost 70% of design proposals suggested a series of public parks or public access buildings facing the sea, and majority of proposal responded with a park to the existing Park connector (Fig 2).

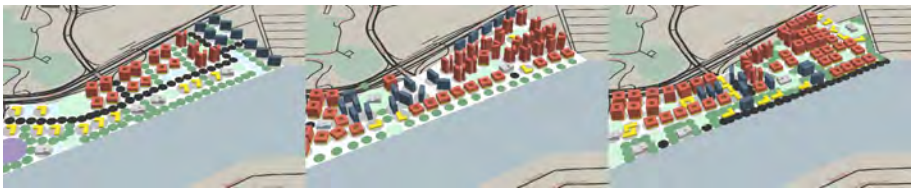


Figure 2. Three examples of participant proposals. They all respond consistently to the coastline, proposing a linear park or open paved public space. They also react to the park connector North West.

5. My perfect public place

My perfect public place is the second exercise. The exercise does not represent an existing area; it is however based on the Singaporean context. The scale is the one of urban design and more specifically design of a single public space.

The goal of this exercise is to extract local knowledge from people. Public space design is context specific; different cultures have different perception of public spaces, and might respond differently to space configurations. The exercise is designed to ask local people about their expectation toward public space, in term of equipment and surface design, to support future design developments with data.

The exercise starts with a white rectangular area, surrounded by buildings. The buildings are 3D models with some details that suggest commercial activities in the first floor and residential destination in the floors above. There are no prior guidelines and attention focus, nevertheless there are some focal points that could lead the design solution: the road, a clear symmetrical axis and the commercial activities in the first floor (Fig 3).

The elements the users could interact with are public space equipment and surfaces. The list includes: stage arena, sports field, tree, playground, pavilion, covered walkway, water fountain, tables and chairs, outdoor exercise, benches, green pots, paved open space, green field. Each element is represented in by a circle which approximated its ground occupancy and 3D stylised models provide an overview of the chosen element.

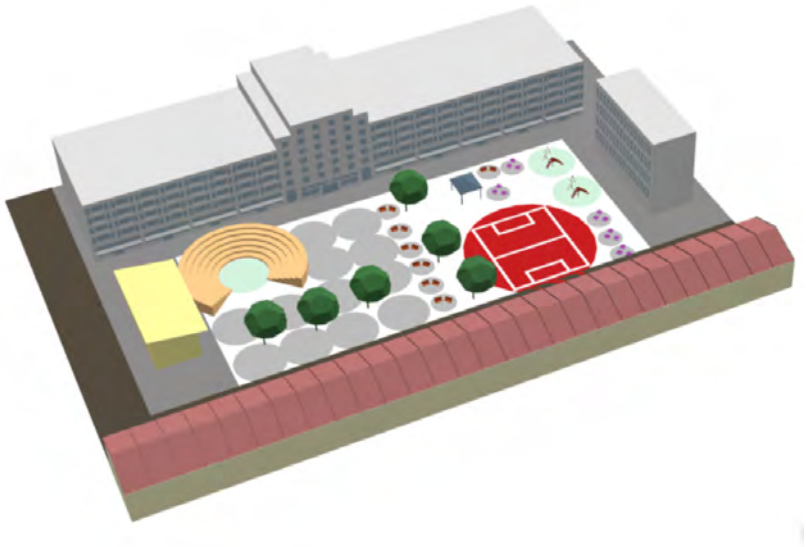


Figure 3. An example of the My perfect public place exercise, showing the fixed context and the circular elements placed in the white area. .

The results of the exercise are meant to be used in a bigger research project on data-informed urban design to help in evaluating and designing public spaces. The idea is to support designers in making urban public spaces that are used and appreciated: informed by people's preferences and use.

More specifically the data-informed design research comprises:

- the collection of multi-modal data. Together with people's preference gained by the My perfect public place exercise, we collected sensor data from different public spaces in Singapore, and social media data. The data collected is context and culture specific (You, Tuncer, and Xing 2018).
- The compilation of a context specific quantitative framework to measure the quality of Public Space in a systematic manner. The Public Space Quality Index (PSQI) proposes different public spaces criteria (enclosure, temperature, presence of specific equipment, etc), which are selected, ranked and quantified by experts during a workshop and validated by data. In this sense, the data collected from the My perfect public place exercise will serve as a dataset to explore and perhaps validate, together with other data, the developed framework of criteria to measure the quality of public space, taking into consideration directly people's preferences (Herthogs et al. with Peijun He 2018).
- The PSQI will in turn be integrated in a spatial interaction model to estimate the number of potential visitors to public spaces, and how public space qualities affect this estimate (cf. Herthogs et al., 2018)

We will give a short overview of the data, providing some insight into Singapore use of space. For the purpose of this overview, the frequency of an element, is not

based on elements count but on the number of users who decided to engage with the element (how many people decided to use the trees, not how many trees people used in total). The less used element is the planter, green in a pot (36% of users), while the most used is the tree (97% of users). People in Singapore tend to prefer green elements that provide also shade and recover from climatic events. Benches are the second most used element (95%). Fountains and playground have been used by 92% of the participants. Water elements in public spaces are elements of that help climate mitigation, visual quality but also cultural reference; playgrounds support activities which are specific of public spaces. If we sum the surfaces counts, paved open spaces double the green surfaces, giving clear direction of the typology of public space, people might expect. Further analyses are performed in the context of validating the Public space Quality index. In this sense, the data collected by the DPP are used to support a design framework about public space, training it to the specific cultural dimension of Singapore.

6. Limitations and future directions

In terms of results the exercise might be considered successful because it managed to achieve exactly the goals:

- To set an online digital exercise able to educate on a sensible upcoming urban redevelopment. The combination of the guidelines and the compulsory elements, together with the decision of dealing with 3D elements, which helped non-expert to engage with urban design, managed to maintain an education power, even if the exercises were online with no mediator. The results which showed specific trends responding directly to the guidelines, support this conclusion.
- To set an online digital exercise able to produce data. In this sense the data produced is useful and relevant for urban design because it manages to: a) identify design trends and people's expectation; b) inform models to evaluate existing and future design.

Some limitations should be retraced in the low click-through rate, which stands for a failure in term of reachability. Those effects might depend from different aspects: insufficient outreach with social media, interface design, interface experience. There may also be a cultural bias: people in Singapore are less used (and willing) to participate. Future publications will deal more specifically with all of those aspects. In this context, it is important to notice how, the exercise proposed in this paper must be considered as one iteration: the interface design and experience, after users and experts feedback, has already a new proposal, which will be implemented in future participation campaigns.

Regarding the exercise design, it is necessary to outline almost an opposite direction: while the use of the exercises to collect data or to educate people, requires necessary steps, like the presence of guidelines, questionnaires, instructions and legends with image references, the low click-through rate suggests to cut out some steps, or simplify the process. This could represent one axis in which to position the exercise design. In both exercises, we decided to rank quite high in the 'informing' dimension, but probably did not invest enough in 'users

experience'. Future iterations should improve the 'users experience' in particular in those exercises, which do not have strictly an education power like "My perfect Public Place". Another important variable of the exercise is the type of dialogue: the tool qua kit allows for a fixed dialogue with users, which easily supports the idea of data collection, but at the same time loses some points in supporting social resources and cohesion, which would be better allowed by an open dialogue, even with different stakeholders. In this sense, the "My perfect neighbourhood" exercise could have achieved more inclusive results, using a different tool. Those considerations set the direction of future research and improvement of the exercise design.

References

Brandsen, T. and Honingh, M.: 2016, Distinguishing Different Types of Coproduction: A Conceptual Analysis Based on the Classical Definitions, *Public Administration Review*, **3**, 427-435.

Y. Charalabidis and S. Koussouris (eds.): 2012, *Empowering Open and Collaborative Governance Technologies and Methods for Online Citizen Engagement in Public Policy Making*, Springer.

Evans-Cowley, J. and Hollander, J.: 2010, The New Generation of Public Participation: Internet-based Participation Tools, *Planning Practice & Research*, **25 (3)**, 397□408.

Falco, E. and Kleinhans, R.: 2018, Beyond technology: Identifying local government challenges for using digital platforms for citizen engagement, *International Journal of Information Management*, **40**, pp.17-20.

Falco, E. and Reinout, K.: 2018, Digital Participatory Platforms for Co- Production in Urban Development: A Systematic Review., *International Journal of E-Planning Research (IJEPR)*, **7 (3)**, 28.

Hasler, S., Chenal, J. and Soutter, M.: 2017, Digital Tools as a Means to Foster Inclusive, Data-informed Urban Planning, *Civil Engineering and Architecture*, **5**, 230-239.

He, P., Herthogs, P., Cinelli, M., Tomarchio, L. and Tuncer, B.: 2018, A multiple criteria analysis-based framework to evaluate public space quality, *Proceedings of Smart and Sustainable Built Environment (SASBE) 2018*, Sidney.

Herthogs, P., Tuncer, B., Schläpfer, M. and He, P.: 2018, A multiple criteria analysis-based framework to evaluate public space quality, *Proceedings of eCAAde 2018*, Lodz.

Linders, D.: 2012, From e-government to we-government: Defining a typology for citizen coproduction in the age of social media, *Government Information Quarterly*, **29**, 446-454.

Manovich, L.: 2000, Database as a genre of new media, *AI & Society*, **2**, 176-183.

Muller, J., Hangxin, L., Chirkin, A., Klein, B. and Schmitt, G.: 2018, Citizen Design Science: A strategy for crowd-creative urban design, *Cities*, **72**, 181-188.

Sander, M., Georgi, C., Heijne, K., Klamert, K., Noennig, J.R., Pump, M., Stelzle, B. and an der Meer, H.: 2017, How to involve inhabitants in urban design planning by using digital tools? An overview on a state of the art, key challenges and promising approaches, *Procedia Computer Science, Knowledge-Based and Intelligent Information & Engineering Systems: Proceedings of the 21st International Conference*, Marseille.

Seltzer, E. and Mahmoudi, D.: 2013, Citizen Participation, Open Innovation, and Crowdsourcing: Challenges and Opportunities for Planning, *Journal of Planning Literature*, **28**(1), 3-18.

Wates, N.: 2000, *The community planning handbook: how people can shape their cities, towns and villages in any part of the world*, Earthscan, London.

You, L., Tuncer, B. and Xing, H.: 2018, Harnessing Multi-source Data about Public Sentiments and Activities for Informed Design, *IEEE Transactions on Knowledge and Data Engineering*, **1-1**, 99.

‘HARMONIELEHRE’ FOR ARCHITECTS

Exploring the relationship between music and architecture by scripting

URS HIRSCHBERG
[1]*TU Graz Institute of Architecture and Media*
[1]*hirschberg@tugraz.at*

Abstract. This paper reports on an introductory scripting class that, whilst teaching the basics of algorithmic design to a large number of architecture students, also explored the commonalities between architecture and music. Historical and recent precedents as well as the theoretical and the practical aspect of the project and its pedagogical outcomes are discussed. The technical section includes a detailed description of the setup created for the students. The musical data format used was MIDI (Musical Instrument Digital Interface), which was read into the 3D computer graphics package MAYA and turned into 3D geometries using the scripting language MEL (Maya Embedded Language). The paper also discusses the resulting student works and in how far the musical nature of the data is visible in them.

Keywords. Computational Design Education; Generative & Algorithmic Design; Scripting; Architecture and Music; MIDI.

1. Introduction

In a thinkpiece from 2013 in the Architectural Review, Charles Jencks writes: “As abstract art forms based on rhythm, proportion and harmony, architecture and music share a clear cultural lineage. Now, through digital expression, architecture can attain new heights of creative supremacy.” (Jencks, 2013)

Jencks never makes it very clear what exactly he means by digital expression, but he seems to suggest that it is only available to architecture. It is certainly true that digital computation opens up new ways to explore the relationship between architecture and music. But arguably this is the case because both fields have entered the digital era. Just as digital media today play a key role in the design and construction of architecture, the same can be said about the composition and production of contemporary music. The common ground between these two, in Jencks’ words ’abstract art forms’ has expanded through the fact that they now also share the abstraction of digital encoding.

This new dynamic in the relationship between architecture and music, as well as an amateur interest in music on the side of the instructors in our Digital Methods of Design teaching team, were the basis upon which we set out to develop the “Harmonielehre” course, the subject of this paper. As we will note

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 757-766. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

in the section about precedents, there are several recent papers about using the connection between architecture and music in architectural pedagogy and research, see for example (Ham, 2006) (Christensen and Schnabel, 2008). What sets this project apart is the introduction of this topic in an entry level scripting class for architecture students as well as the large size of this class: over 130 participants. The implications of both will be discussed.

2. Teaching Scripting to Architecture Students

The class 'Digital Methods of Design' is taught in the third semester of the bachelor curriculum at the faculty of architecture of TU Graz. It is a mandatory class that provides the third component of a three-semester training in the fundamentals of representation, digital representation and digital design respectively. Though they have a theory component, a main goal of these foundational courses is to equip the students with the necessary skills to master the broad repertoire of digital media used in architecture.

While the classes in first and second semester focus on computer aided design in the more traditional sense, that is on drawing and 3D modeling as well as rendering and graphic presentation, the third semester has a focus on what we see as the lingua franca of the entire digital repertoire: scripting. While we in no way aspire to turn our students into actual programmers, we feel strongly that some acquaintance with algorithmic thinking and with the nuts and bolts of a scripting language will give them a better understanding not only of the digital tools they use in design, but more broadly of the increasingly digital world we operate in.

We have gained a considerable amount of experience in this type of teaching, which we've engaged in for many years. To keep it interesting for us teachers, we tend to choose a different topic to engage with every year. We have worked with landscape data, urban data, or pointclouds derived from various objects as our virtual building material. In 2015 we tried out something a bit more challenging: musical data.

3. Architecture and Music

The quote "architecture is frozen music", which has been attributed to various authors in the Romantic period of early 19th century Germany, was considered a joke by some at the time it was coined around 1800. Michailov even suggests it was the fact that it was so often ridiculed which led to its wide dissemination (Michailov, 1992). The philosopher Schopenhauer, also often credited with being its author, refers to it as the 'jokeword' that Goethe coined - a joke because for Schopenhauer architecture and music were at the absolute opposite ends of the artistic spectrum. As he explains "architecture is solely in space, without any relationship to time and music only in time without any relationship to space" (Schopenhauer, 2016, p. 510). He does however go on to contend that "les extremes se touchent" - that there is a kinship in their formal composition or symmetry.

Of course the idea that there are links between architecture and music goes back much further. Vitruvius demanded that architects be proficient in many fields,

including that they ‘understand music’ (Vitruvius, 1914). Earlier still Pythagoras is credited with discovering the correspondence of mathematical proportions and musical intervals from which he is said to have derived the idea that order or harmony of relation is the regulating principle of the universe (Smith 1870, p. 621-22). The idea of harmonic form in analogy to musical harmony has been a constant in the development of Western Architecture. It can be found in the writings of Vitruvius as well as in Alberti’s system of harmonic proportions or Palladio’s four books, which describe dimensions of rooms based on the Pythagorean proportions. (Naredi-Rainer, 1982)

More recently the dual interest in architecture and music was very much alive at the Bauhaus. While music was not part of the curriculum it was a constant at Bauhaus events and a number of Avant Garde composers of the time such as Strawinsky, Busoni, Hindemith or Weill visited the Bauhaus. The famous ’Mechanical Ballet’ by Oscar Schlemmer and others explored the connections between music and abstract geometric form. The Bauhaus masters’ interest in abstraction may also explain why Bach, whose work is often described as almost mathematical, was a favored composer of theirs. Lyonel Feininger, active as a musician in Bauhaus events, composed many fugues in the style of Bach. It is also worth noting that Kandinsky was friends with Schönberg who was also well-acquainted with Gropius. Schönberg in the early twenties, thus in the early years of the Bauhaus, invented the twelve-tone technique. The theory is said to have influenced Johannes Itten’s theory on color. (Jewitt, 2000)

4. Schönberg and the Chromatic Scale

The protocols and abstractions that underlie today’s digital music tools and instruments can be traced to the abstractions musical pioneers ushered in in the early twentieth century. Among them, Schönberg stands out not only as the inventor of twelve-tone music, but through the fact that he was an active composer as well as teacher and a theoretician. We named the class after his standard text book on musical harmony, titled “Harmonielehre” (Schönberg, 1919).

While Schönberg’s book stays within the realm of tonality, he does prepare the ground for atonal music in the final sections of the work. After a thick volume that explains and explores in great detail various modulation types and their bearing on kinship between different tonal scales, on page 464 he speculates that rather than seeing notes as always part of a group of typically 7 notes that make up a specific scale such as A Major, E minor etc., they could also be seen as part of a 12 note scale that encompasses all possible tonalities. In other words: he proposes the ultimate abstraction, an open field where every note is just a number (Figure 4). Thus with “Harmonielehre”, Schönberg not only explained in detail the great art of classical musical composition, he also paved the way for subsequent abstractions, including digital music.

Maybe the most well-known cross-over between architecture and music of the twentieth century came in the work of Greek engineer and composer Yannis Xenakis, while he was working with Le Corbusier. Both the Philips Pavilion at the Brussels World expo and the La Tourette monastery bear the mark of Xenakis’

unique musical-geometric compositions, which in turn also operate on the basis of this abstract open field (Xenakis, 2008). Rather than using traditional music notation, many of Xenakis' scores use graphic abstractions and number-systems. The Philips Pavilion with its hyperbolic paraboloids was in fact based on Xenakis' composition Metastaseis B (Figure 1) (Parthenios et. al., 2016).

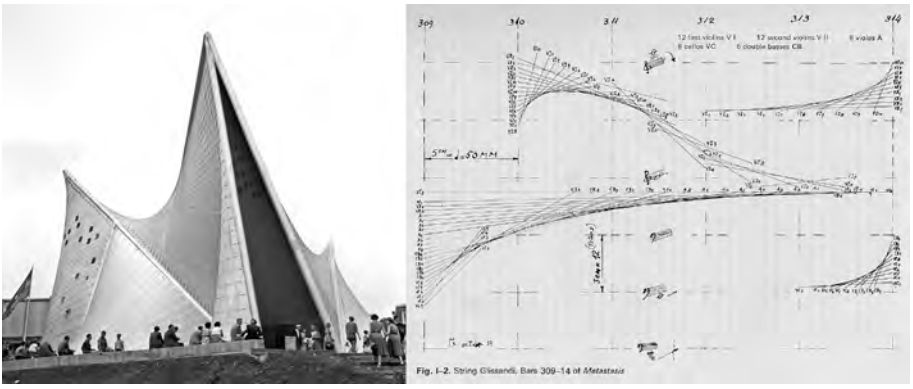


Figure 1. Le Corbusier's Philips Pavilion with its hyperbolic paraboloids and Iannis Xenakis' composition Metastaseis.

5. Precedents

Xenakis' works can be seen as examples of musical compositions translated directly into form (Figure 1). Thus, with Xenakis, the idea that one can "freeze" music to create an architectural form is not at all a joke, but a serious artistic method. Of course with Xenakis the case is special, because he is composer and architect at the same time and there is no debating with him whether his translation from these most distant artistic realms makes sense or is correct.

The more typical case is the translation of an existing composition by a well-known composer into a geometric form. Bauhaus student Heinrich Neugeboren (later known as the composer Henri Nouveau), probably influenced by the mentioned enthusiasm for Bach at the Bauhaus, created a sculpture based on a Bach fugue (Figure 2). Neugeboren's work is often cited in literature about the topic. Architect and artist Jan Henrik Hansen follows in Neugeboren's footsteps, but using digital means. His musical sculptures are based on music of different origins (Figure 3). Hansen started this work around 1999 (Hansen, 2006). He uses software he custom-developed for this purpose. He also came and gave a talk about his work at our university during the semester in which the class described in this paper took place. His sculptures were an important inspiration for the students (Hansen, 2018). Neugeboren's sculpture is also referenced by Christensen, who has given a detailed account of how he has translated MIDI files of Bach's Well-Tempered Piano into spatial structures (Christensen and Schnabel, 2008).



Figure 2. Heinrich Neugeboren (later known as the composer Henri Nouveau) created a sculpture based on a Bach fugue.



Figure 3. Musical Sculptures by Jan Henrik Hansen.

There is a growing body of research in the digital design field that specifically addresses and explores the relationship between architecture and music. Such research usually falls into one of the following categories:

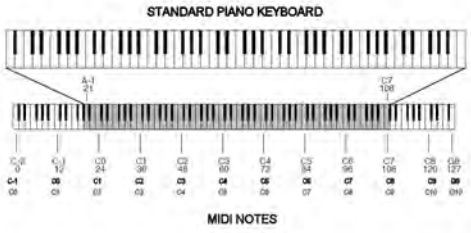
1. Development of processes/software systems that enable a transfer of musical scores or audio signals into geometric (architectural) form.
2. Development of processes/software systems that analyze the harmonic properties of built form or turn geometry into sound/music
3. Reports on educational projects that engage in the links between architecture and music
4. Speculative projects that try to find synergies between music and architecture as a way to explore design

In the first category, we’ve already mentioned the works of Hansen and Christensen. In the third category see for example the work of Ham (Ham, 2006). For the fourth type, see for example the work of Parthenios (Parthenios et al., 2016). Our work falls into the first as well as the third category. The structure of the setup is similar to the one described by Christensen. But rather than following a consistent procedure for a whole series of musical compositions and thus making it possible to compare them as geometric form, our approach was more open, more in the spirit of Hansen. We only provided a framework for students to work in. It had to be simple enough for even beginner programmers to use, but at the same time open enough for them to see it as a design challenge rather than a programming chore.

6. Technical Setup: MIDI and MEL

As mentioned, the framework for this enquiry was an introductory scripting class, a required subject for 3rd semester Bachelor students in architecture at our university. As a consequence neither prior scripting knowledge nor any particular affinity to music could be expected from students enrolled in the class. Thus, we had to prepare the subject matter and tasks in such a way that they could not only be mastered by novice programmers, but potentially also by tone-deaf novice programmers... And of course it was important not to lose sight of the main goal of the class, which is to equip students with a basic understanding of scripting and algorithmic methods in architecture.

As the basis for the scripting setup, MIDI-encodings of musical compositions were used. MIDI (short for Musical Instrument Digital Interface) is a technical standard that describes a communications protocol, digital interface, and electrical connectors that connect a wide variety of electronic musical instruments, computers, and related audio devices (Wikipedia, 2018). MIDI was standardized in 1983 and is a typical example of a digital format that is technically outdated but still widely used. For the sake of the class, its relative simplicity was a bonus. MIDI messages consist of a number of parameters such as beginning time, end time, pitch, velocity and others. Since these are all encoded as numbers, they can quite easily be mapped onto geometric properties, such as form, scale, position or orientation. (Figure 4) A further advantage of the MIDI format is that many MIDI transcriptions of classical and popular music pieces are freely available on the Internet. We made a set of 20 pieces available to choose from (ranging from Beethoven's Cavatina to the Pink Panther theme), but students could also work with any other composition of their choice, as long as they had a MIDI file for it.



Note	Octave										
	-1	0	1	2	3	4	5	6	7	8	9
C	0	12	24	36	48	**60**	72	84	96	108	120
C#	1	13	25	37	49	**61**	73	85	97	109	121
D	2	14	26	38	50	**62**	74	86	98	110	122
D#	3	15	27	39	51	**63**	75	87	99	111	123
E	4	16	28	40	52	**64**	76	88	100	112	124
F	5	17	29	41	53	**65**	77	89	101	113	125
F#	6	18	30	42	54	**66**	78	90	102	114	126
G	7	19	31	43	55	**67**	79	91	103	115	127
G#	8	20	32	44	56	**68**	80	92	104	116	
A	9	21	33	45	57	**69**	81	93	105	117	
A#	10	22	34	46	58	**70**	82	94	106	118	
B	11	23	35	47	59	**71**	83	95	107	119	

Figure 4. MIDI notes are simply numbers - an open field.

With a converter, MIDI files were turned into CSV documents that could in turn be imported into the Software Maya. Autodesk Maya is a 3D computer graphics application commonly used in animated film, visual effects and 3D interaction design. Due to its node-based structure and scripting interface it has been used for many other purposes as well, including in digital architecture. We used it for many years in our scripting class, because of the convenience and relative simplicity of MEL, the Maya Embedded Language.

In preparation of the class we created a custom MEL library of functions, which included functions to import the MIDI files. For the students the two translations from MIDI to CSV and from CSV into Maya happened in direct sequence. Unless they wanted to manipulate the MIDI files (e.g. shortening them or reducing the number of tracks in them) they didn’t have to open the CSV files at all.

7. Keeping things simple

We mentioned that MIDI is a fairly simple standard and that MEL provides a convenient scripting interface. To be fair, this is speaking in relative terms. For a novice programmer the setup is still very complex. So to make things understandable and easy to use was an important goal. First of all we let them use MIDI-viewers as ways to see and listen to the MIDI files they wanted to work with. We also encouraged them to study the CSV versions of their MIDI files even though that wasn’t strictly necessary. We wanted them to have a solid understanding of the nature of the data they were working with. Finally we found a trick that proved very helpful: when importing the CSV file into Maya the data in it was automatically stored as nodes without geometry. Using the so-called Outliner, a Maya tool that allows users to view the content of a scene in list format, students could check out the imported data before they even started creating any scripted geometry based on it (Figure 5). Since the names of the nodes also contained the most important parameters, such as beginning time, end time, pitch and velocity, viewing the data in the outliner was similar to viewing the CSV data in Excel.

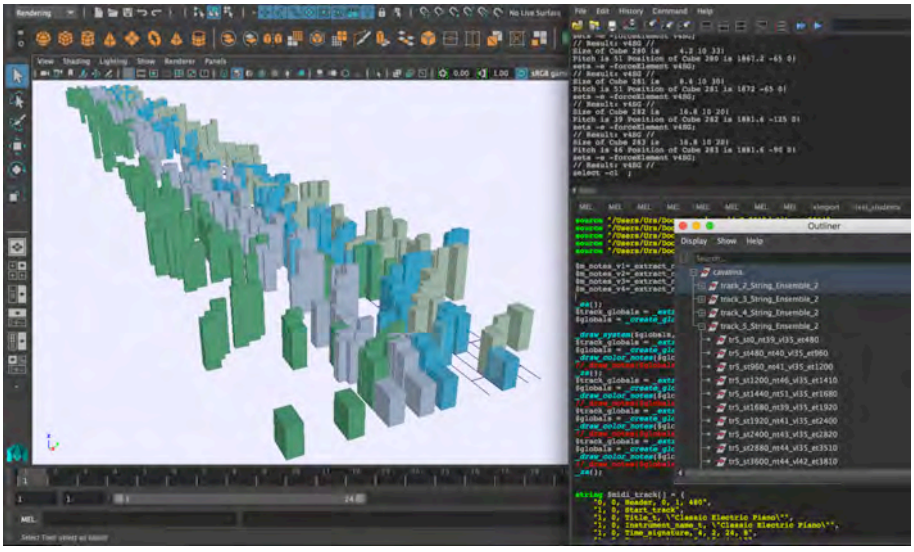


Figure 5. Maya user interface, showing a ‘literal’ rendition of the Beethoven cavatina quartet score and the Outliner.

Another convenience we provided was a function we called ‘explain_midi’. It listed the most important parameters of a given midi files and calculated useful

values based on them, such as overall length, start and end time, the number of measures, the length of a measure, the lowest and the highest note in a track, the loudest and softest notes in a track and the corresponding difference between these values.

8. It's frozen music, but is it architecture?

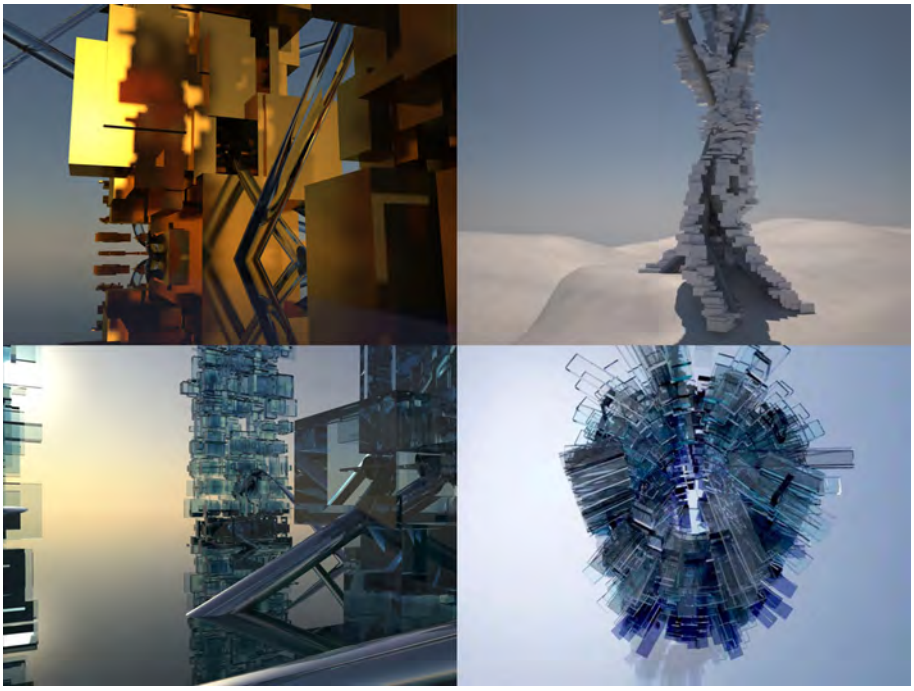


Figure 6. Typical projects mapped musical rhythms or patterns along spirals or towers.

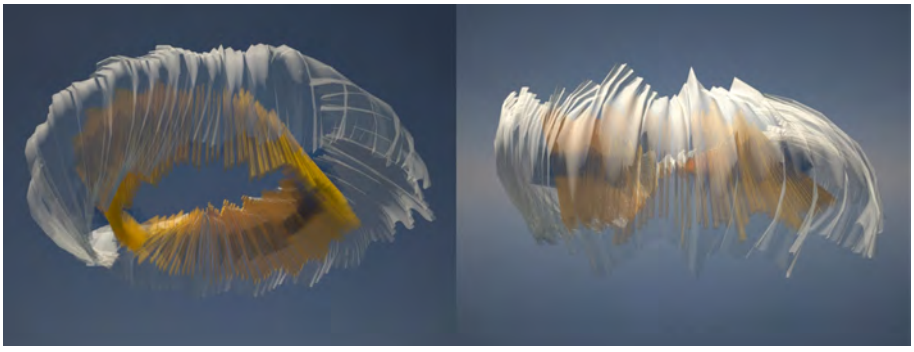


Figure 7. Bach's crab canon interpreted as an airy, jellyfish-like mobius strip.



Figure 8. Sprawling megastructure based on a Bruckner symphony.

A constant in our pedagogy is that we value creative explorations over proper programming style. Students work in groups of two, which in our experience not only improves the result, but also the learning, as they tend to discuss ideas and strategies. In the final stage of the class, which was held as a five day workshop, held in the course of two weeks, we focused on creating renderings of their spatial compositions. Based on our preparations for the students, a literal rendition of a score, that is one that more or less replicates the notes as they appear on a music sheet, was straightforward to achieve, but not necessarily very interesting. (Figure 5) Typical projects instead tried mapping musical rhythms or patterns along spirals or stacked as towers, using the rhythms, melodies and the different instruments in the chosen score as overlaid patterns (Figure 6). Some were remarkably sophisticated, for example the group that explored the famous crab canon by Bach, which they interpreted as a Mobius-strip and rendered as an airy jellyfish-like structure (Figure 7). Others created what could be read as interpretations of or commentaries about the music, such as the group that turned the score of a Bruckner symphony into what looked like a contorted megastructure (Figure 8).

While some groups tried to translate as much of the data as possible and to find meaningful spatial or visual cues for all MIDI parameters, it wasn’t necessarily clear that the groups that did so had the more successful results. Also, while structuring the spatial data such that simultaneity of different tracks or the structure of individual measures would remain visible in the resulting spatial composition was a good design choice and gave the results a certain legibility, there were many successful designs that didn’t adhere to such constraints. Interestingly even the ones that made it all but impossible to recognize the piece they had worked on still retained a certain musicality in their expression.

What the project made clear is that there isn’t a correct way to turn musical data into spatial structures. The difference between what Schopenhauer defined as the space-based art of architecture and the time-based art of music is so vast that the quest for the one “correct” translation in this case seems pointless. There are countless options of going about it. Any translation is also an interpretation.

9. Conclusion

This paper has reported on a teaching experiment that allowed students to explore spatial potentials of musical data as a way to learn about scripting. While students took the class as a mandatory subject and thus were not necessarily interested in music or scripting, many of them enjoyed the speculative task and were surprised to discover that scripting afforded them a personal form of expression.

The conclusion we draw from the experiment is that as a way to learn about scripting and algorithmic design the class worked as well as other scripting classes we have taught in the past. But beyond the practical learning, students reported that they enjoyed the creative nature of the topic. It's for good reason that exploring the similarities between architecture and music has a long tradition in architecture. Students were challenged to re-think and reevaluate notions they may have had about music as well as about space and scripting As a pedagogical and philosophical experiment, it is worthy of repetition.

References

"MIDI - From Wikipedia, the free encyclopedia" : 2019. Available from <https://en.wikipedia.org/wiki/MIDI> (accessed 1 April 2019).

Christensen, P. and Schnabel, M.A.: 2008, Spatial polyphony: Virtual Architecture Generated from the Music of J.S. Bach, *CAADRIA 2008, Proceedings of the 13th International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA 2008))*, Chiang Mai (Thailand), 501-509.

Ham, J.J.: 2006, Music and Architecture: from Digital Composition to Physical Artifact, *Proceedings of eCAADe 2006*, Lisbon, 139-146.

Hansen, J.H.: 2006, "Form Follows Funk" . Available from <http://www.janhenrikhansen.com/wordpress/wp-content/uploads/2010/12/jan_henrik_hansen_pub_02_fff_book_pdf1.pdf > (accessed 10th December 2018).

Hansen, J.H.: 2018, "Website Jan Henrik Hansen" . Available from <https://www.jhh.ch/> (accessed December 16th 2018).

Jencks, C.: 2013, "The Architectural Review" . Available from <https://www.architectural-review.com/essays/viewpoints/architecture-becomes-music/8647050.article> (accessed 1 April 2019).

Jewitt, C.: 2000, Music at the Bauhaus 1919-1933, *Tempo*, **New Series**(No. 213 (Jul., 2000)), 5-11.

Michailow, A.: 1992, "... Architektura ist erstarrte Musika..." Nochmals zu den Ursprüngen eines Worts über die Musik, *International Journal of Musicology, Retrieved from http://www.jstor.org/stable/24617780*, **1**, 47-65. .

v. Naredi-Rainer, P.: 1982, *Architektur und Harmonie. Zahl, Mass und Proportion in der abendländischen Baukunst*, DuMont Buchverlag, Cologne.

Parthenios, P., Petrovski, S., Chatzopoulou, N. and Mania, K.: 2016, Reciprocal transformations between music and architecture as a real-time supporting mechanism in urban design, *International Journal of Architectural Computing*, **14**(4), 349-357.

Schopenhauer, A.: 2016, *The World as Will and Presentation, Volume 2*, Routledge.

Schönberg, A.: 1922, *Harmonielehre, 3. vermehrte und verbesserte Auflage*, Universal Edition, Wien.

Smith, W.: 1870, *Dictionary of Greek and Roman biography and mythology*, Little, Brown and Company, Boston.

Vitruvius, P.: 1914, *The Ten Books on Architecture*, Harvard University Press, Cambridge.

Xenakis, I. and Kanach, S. (e.d.): 2008, *Music and Architecture: Architectural Projects, Texts, and Realizations*, Pendragon Press.

THE CHURCH OF AI

An examination of architecture in a posthuman design ecology

MATIAS DEL CAMPO[1], SANDRA MANNINGER[2],
MARIANNE SANCHE[3] and LEETEE WANG[4]
[1,2]*Taubman College for Architecture and Urban Planning, University of Michigan*
[1,2]*{mdelc|ms}@umich.edu*
[3,4]*University of Pennsylvania*
[3,4]*{masanche|leetee}@design.upenn.edu*

Abstract. The Project, the Church of AI, taps into the opportunities of Artificial Intelligence as a device for Architecture Design in a twofold way: On the one side by employing a design technique that is based on the ability of Artificial Intelligence to generate form autonomously of human interaction, and on the other hand by speculating about the nature of devotion, the sublime and awe in a posthuman society.

Keywords. Artificial Intelligence; Posthuman; Postdigital; Machine Learning; DeepDream.

1. Introduction

The main aim of this paper is to demonstrate a methodology of design which interrogates aspects of Artificial Intelligence. The presented project, The Church of AI (fig1), discusses the design technique itself as well as the underlying aspects of aesthetic, ethic and existence. The project started in the course Architectural Automations. An Advanced Design Studio of PennDesign1, with the focus on the transforming potential of Artificial Intelligence and automation in architecture. The results of the studio addressed aspects of autonomous behavior in construction (Performative Machine2), the changed relationship to creative practice (Golden Playhouse3) and Worship & AI (Church of AI4). The later was selected as a topic for this paper as it demonstrates in a provocative fashion the multitude of lenses of observation for a problem like Artificial Intelligence and Architecture. Not only as a toolset to optimize very specific elements of architecture such as floorplan, material consumption and structure, but rather to emphasize architectures ability to serve as a cultural marker and place of worship. In that extent it proposes a position that radically challenges the idea of computational methodologies as tools of expedience and efficiency and rather embraces the possibility to use it as a tool of communication between the human mindset and an, as to this date, alien intelligence. Alien in the sense of defamiliarization or estrangement5. Following intense conversations in the studio about the nature of AI, and its possible impact

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 767-772. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

on architecture the project The Church of AI started speculating about the various possible aesthetic conversations possible through the use of AI. Of course, AI is a generalist term that includes a wide range of approaches and ideas. In order to make progress within the frame of one semester a more specific approach was needed. The main question was wither an AI could create a novel sensibility based on specific datasets, and how human intervention could steer the results. Exploring possibilities for a Human/AI collaboration

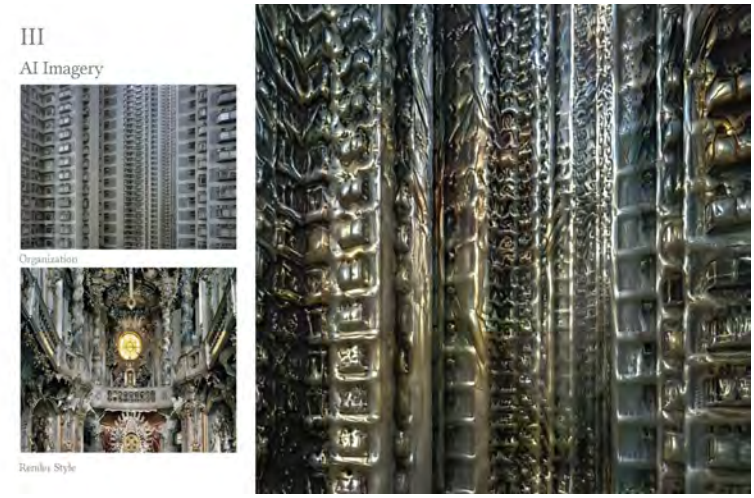


Figure 1. The Church of AI, Mariane Sanche, Leetee Wang, PennDesign 2018.

2. The rise of AI

As described in the introduction the term AI is quite a generalist term and is used to describe several different approaches. In Computer Science, Artificial Intelligence is defined as the study of Intelligent Agents, which includes any device that perceives its environment and that takes actions to maximize its chance of successfully achieving its goals6 In general, the term Artificial Intelligence is applied when a machine mimics cognitive functions that humans associate with other human minds, such as learning and problem solving.7 This opens up questions about the nature of creativity, the methods to evaluate this, and the nature of creativity at large. Can an AI create a novel sensibility (?) -and if so: can we as humans perceive and understand it? This was one of the many questions that the entire studio discussed fiercely, and it became very apparent that there is an enormous amount of fear of losing human agency in design. In most cases a fear that is not based on fact, as the research on this project showed very prominently. The project presented here tackled the problem not only from the aesthetic side - the ideas that AI can creatively generate a sensibility - but also from a profoundly ethical point of view: pondering the question wither an AI can develop a belief system. Do AI's worship? If so, does that frame of worship materialize in some way? Do robots dream of perfect cathedrals?

In the case of The Church of AI an approach that involved deep learning algorithms was chosen. The Neural Style Transfer approach was used to create two data bases, one with normative architectural solutions and one with a plethora of highly articulated architectural solutions, primarily from the Baroque era (Fig.3). In artistic practice -particularly in painting- humans have excelled in the ability to create unique visual experiences through the representation of complex relationships oscillating between content and style. So far, the underlying algorithmic basis for this ability is unknown, and there is thus far no artificial system able to recreate these capabilities. Nonetheless, biologically inspired vision models such as Deep Neural Networks have been successfully implemented in key areas such as object and face recognition. They achieved forms of recognition on a near human level. In their paper A Neural Algorithm of Artistic Style8, Leon Gatys, Alexander Ecker and Matthias Bethge introduced a Deep Learning Network that is able to create images of high artistic quality. Though it is not clear from their paper which criteria defines artistic quality, it nonetheless presents itself as an outstanding opportunity to examine Deep Learning Networks as the basis for possible architecture design techniques which do not rely on an anthropocentric design universe, with the usual top down design making processes, but rather as an opportunity to interrogate the relationship between humans, creativity and AI. As Gatys, Ecker and Bethge put it:

Moreover, in light of the striking similarities between performance-optimized artificial neural networks and biological vision, our work offers a path forward to an algorithmic understanding of how humans create and perceive artistic imagery9

All of this brings to question what is the difference between a human and a posthuman approach to architecture? The analytical tool used in the studio project successfully was able to blend architectural styles with each other, but the overarching, larger question wither Deep Learning Algorithms are able to generate novel architectural solutions was not answered. In the spirit of the creation of novel insights, the project was however highly successful in proposing an idea of human/AI interactions in creative processes. The question about a novel language does remain.

Fig.3 A collection of two datasets - Baroque and Modern images - form the basis for the resulting models. (Image: Marianna Sanche & Leetee Wang, PennDesign, University of Pennsylvania 2018)

They have a new language!

In March 2017 Facebooks AI Research Laboratory conducted an experiment: two AI's were set up to discuss aspects of trade in English with each other. The goal was to create an AI that could communicate with humans about economy10. Within 24 hours the two AI's named Bob & Alice had developed their own language which was impossible to be understood by humans, albeit it was based on English (Fig.1). This example shows the AI's ability to develop forms of communication and expression outside the agency of humanity and as such can be considered a part of posthuman culture. Developing a language per se is a creative process and has been discussed in a series of papers which primarily are concerned with finding methodologies of human-AI interaction11. To mention just one of many examples from this branch of research: improved speech recognition

when using voice commands for your computer or mobile device. Ludwig Wittgenstein's hypothesis of "Whereof one cannot speak, thereof one must be silent."12 is critically interrogated and put to the test by an AI that in fact just develops a language instead of remaining silent.

The language of architecture is defined by a specific set of criteria, which are primarily discussed through two sets of lenses. The problem of representation on the one side, and the problem of materialization on the other. Both of which are branches of architectural inquiry with a long-standing tradition, a tradition that is being tested by the evolution of the toolsets at hand in the contemporary age. The problem of representation is certainly one that the project The Church of AI is profoundly tapping into, as the applied neural algorithms analyze and combine images to create novel, unseen architectural entities. In a way, the images resulting from the application of Neural Networks can be positioned within the discoursive tradition of Speculative Realism, as their origin is not purely fantastical, but specifically concrete - what marks their innovation is the method of seamlessly blending styles with each other. Style in this frame of conversation can be understood in the tradition of Gottfried Semper, who in his seminal book From Style13 described architecture as being defined by Scale, Proportion and Style.

The Project, the Church of AI14 taps into these opportunities in a twofold fashion. On the one side by employing a design technique that is based on the ability of Artificial Intelligence to generate form autonomously of human interaction, and on the other hand by speculating about the nature of devotion, the sublime and awe in a posthuman society.

So far, we have discussed in this paper the ability of Deep Neural Networks to create mash ups of two dimensional images. This might be interesting as a tool for speculative design ideas and as a sketch pad for architectural solutions, but it does not tap into the opportunities to examine ideas in the third dimension, particularly in a computational environment. To explore the possibilities in 3D, two strategies were applied. The ability of polymesh rendering software to accurately create a stamping tool from an image that can then be applied to a high-resolution polygon model to imprint the image deeply into the model, and the second option (and certainly the computationally more challenging one) is the application of Neural Mesh rendering solutions, which in combination with the Neural Algorithms for Artistic Style are able to propose three dimensional solutions. The Neural Mesh Renderer solution seemed also closer in the workflow of this project.

3. Exploring Neural Mesh Renderers

As previously discussed the project made heavily use of Deep Learning Algorithms trained to seamlessly mash up databases of architectural images. Insofar the project relies heavily on the use of machine learning and deep learning in order to generate a formal vocabulary. The morphogenesis in this case is completely relying on the ability of AI to mash up imagery - and in a further process to generate 3D models (Fig.2). The basis for this project was a dataset of images from two distinct architectural tendencies, the Baroque and a series of images of deeply generic modern slabs and high-rise buildings, primarily distinct by

their profoundly repetitive and immensely boring, quality (Fig.3). The process of creating variation and difference is propelled further by the possibility to run through a series of results in quick progression. The only human intervention in this case is the selection process at the end, as of which of these results are deemed successful in regards of the criteria to serve as a possibly place of worship, but even this could be automatized provided the AI gets trained to do so.

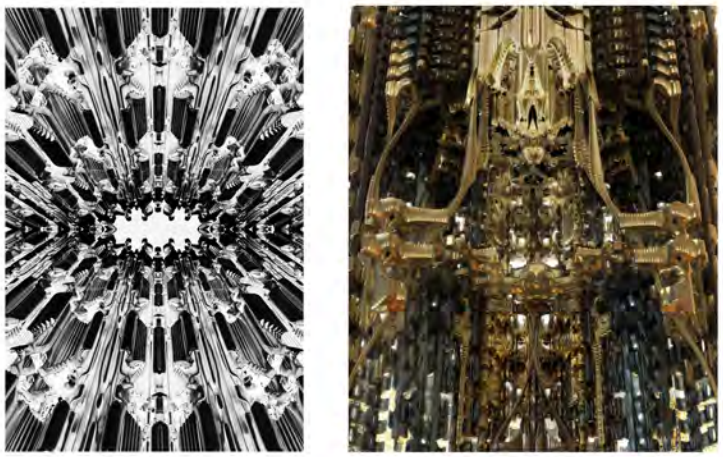


Figure 2. Result of one of the Deep Learning Algorithm experiment No.3. The Church of AI, Mariane Sanche, Leetee Wang, PennDesign 2018.

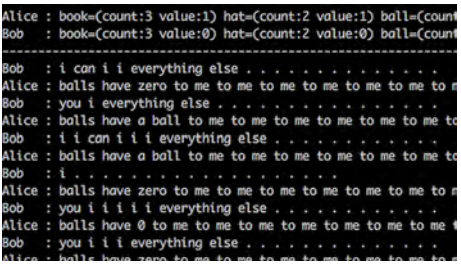


Figure 3. Fig.1 Facebooks AI Research Laboratory's Bob & Alice engaged in negotiations - a language not accessible by humanity.

4. Do AI's create their own sensibilities? - A conclusion

In conclusion it can be stated that this project represents the first timid wading into an ocean of possibilities in regards of the application of AI in the discipline of architecture. The examination as of how AI can be a transformative tool of inquiry in the discipline is at its very infant state. The project is intentionally discussing rather aspects of aesthetics, beauty and speculation instead of diving into aspects of optimization. This is intentionally so, as within a computational universe the tamed problem of optimization is just one side, and the wicked problem of aesthetic

another. As this project does not strive to solve all problems, it focused on the agency of AI in terms of cultural agency.

The Church of AI can be considered a proof of concept as of how agency can be acquired by Artificial Intelligence. In this case the contingency is the consideration of a benevolent AI, one that shares the space with humanity, and that converts the process of making to a method of worship. The construction of space turns from a necessity to a method of collaborative communion - as work itself does not entail human interaction anymore.



Figure 4. Fig.2 Neural Render Process to combine a polymesh model with 2-dimensional information to generate a 3D object (image: Hiroharo Katu, Yoshitaka Ushiku, Tatsuya Harada, University of Tokyo 2017).

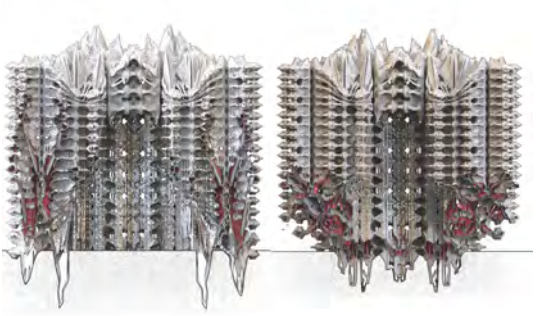


Figure 5. Fig.4 Section through one of the resulting models. (Image: Marianna Sanche & Leetee Wang, PennDesign, University of Pennsylvania 2018).

References

Gatys, L.A., Ecker, A.S. and Bethke, M.: 2015, A Neural Algorithm of Artistic Style, *https://arxiv.org/abs/1508.06576v2*.

Mordatch, I. and Abbeel, P.: 2018, Emergence of Grounded Compositional Language in Multi-Agent Populations, *https://arxiv.org/abs/1703.04908*.

Russel, S. and Norvig, P.: 2009, *Artificial Intelligence: A Modern Approach*, Pearson, London.

Semper, G.: 1860, *Der Stil in den Technischen und Tektonischnen Künsten oder praktische Ästhetik: Ein Handbuch für techniker, Künstler und Kunstfreunde (Band 1): die textile Kunst für sich betrachtet und in Beziehung zur Baukunst*, Verlag für Kunst und Wissenschaft Frankfurt am Main, Frankfurt am Main.

Wittgenstein, L.: 1921, *Tractatus Logico-Philosophicus*, Annalen der Naturphilosophie Nr. 14.

AMPLIFYING CITIZENS' VOICES IN SMART CITIES

An Application of Social Media Sentiment Analysis in Urban Sciences

IMAN SAYAH[1] and MARC AUREL SCHNABEL[2]
[1,2]*Victoria University of Wellington*
[1]*iman.sayah@gmail.com* [2]*MarcAurel.Schnabel@vuw.ac.nz*

Abstract. In the past decade, urban researchers have paid significant attention to the emergence of computer science and urban planning. According to the literature, social media as a pool of real-time citizen feedback can be investigated to inform smart city synergies. However, the success factors of such an approach have not been thoroughly investigated. In this study, various factors were derived from an extensive literature review to create an efficient e-participation platform. It is explained how our proposed platform 1) complies to the data protection regulations 2) uses advanced text analysis and natural language processing (NLP) tools to identify opinions and emotions 3) maintains persistent communication between citizens and city planners 4) incorporates creative visualisation techniques 5) is informative for its target audience 6) takes into consideration the socio-cultural diversity and 7) can be used as an informing tool in combination with offline methods of participation.

Keywords. Sentiment analysis; e-participation; social media mining; big data analytics; citizen engagement.

1. Social media mining in smart cities

Social media provides a valuable resource of real-time data and has become the centre of attention in a wide range of decision-making studies (Lin et al., 2017). Researchers have investigated the potentials in collecting digital feedback from the community by practising various digital techniques. A review of the case studies shows that social media analysis seems to be the dominant approach in e-participation initiatives (Boudjelida et al., 2016). The emergence of cell phones and geo-based social media significantly facilitate a better understanding of the community's behaviour as these types of social media are supported by users' geo-located data. Considering this approach, some experts have highlighted the role of social media analysis in urban planning. Social media networks have been investigated by researchers to identify their possible potentials for providing meaningful feedback to urban planners (Zhang and Feick, 2016, Leszczynski, 2016, DiSalvo and Jenkins, 2017).

The literature shows the importance of investigating the limitations and potentials to social data mining and various techniques have been used to evaluate

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 773-782. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

the success of these projects. They have mostly followed a case study approach to investigate the significant impact of social media apps such as Facebook, Twitter, and Instagram on public participation (Schafer, 2012, Moser, 2016, Swim and Bloodhart, 2015). Social media has proven to be useful even in a broader range of fields. For instance, social media as *"a database of electronic word of mouth"* (Chen and Yang, 2014) has proven to be an effective media for participation in political involvement (Rahimi, 2011, Gregory, 2013, Olorunnisola and Martin, 2013, Alkazemi et al., 2014).

The objective of this research is to create a smart application for the administrative bodies to evaluate the impact of their decisions and actions by analysing citizens' emotional feedback on Twitter. The novelty of this approach is in the implementation of a real-time timeline of events rather than classification and correlation maps proposed in previous studies (Jongman et al., 2015, Himelboim et al., 2017, Grandjean 2016). It is explained how the timeline visualisation of the sentiments provides an effective way of comparing actions with people's opinions and as a result proves to be a more engaging and potent tool for social media analysis.

2. Method

The following steps were used to identify the most relevant research in this area. First, the main elements of the study were used as search terms. *Scopus* and *Web of Knowledge* were chosen as the scientific data repositories for conducting this literature review. The abstracts of the search results were examined based on two main factors: 1) Inclusion of a case study and 2) Indication of the contributing factors to the success or failure of the case study. The search terms were revised and fed into the first step (search in data repositories). As a result, the most relevant papers were derived using the following combination of terms:

```
eparticipation AND ("smart city" OR "urban planning")
AND ("social media" OR Facebook OR Twitter)
```

The full text of the final selected papers was studied for the identification of the success factors.

3. Success factors

3.1. ETHICS

Privacy concerns might prevent stakeholders from accepting ubiquitous monitoring initiatives (Shilton, 2012, Ertio and Bhagwatwar, 2017). While concerns about privacy are the most common issue in public data mining, there seems to be a sufficient set of regulations and conducted research on this topic (Townsend and Wallace, 2017). The EU GDPR (European General Data Protection Regulations) along with DPA (Data Protection Act) has undergone a

series of changes in 2018 which indicates significant attention to user's privacy in data science. According to the EU GDPR (2018), "Personal data is any information that relates to an identified or identifiable living individual. Different pieces of information, which collected together can lead to the identification of a particular person, also constitute personal data." As a result, our innovative approach does not disseminate any form of entity (piece of text, image, video, or hashtag) that would result in the identification of a person or a Twitter profile.

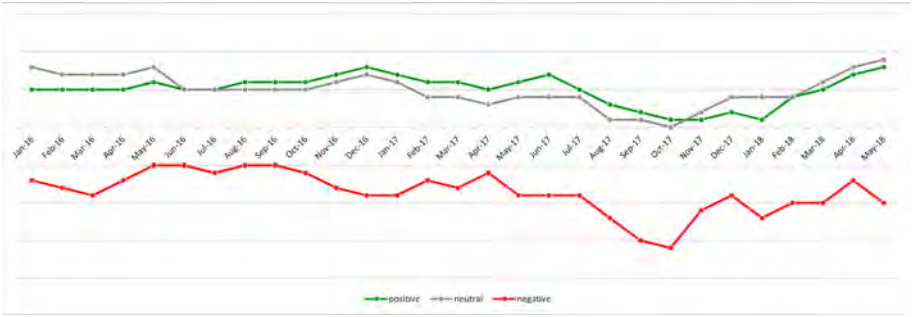


Figure 1. The sentiment timeline only records the number of positive (green), negative (red) or neutral (grey) tweets on a specific topic without revealing an individual's identity.

3.2. TECHNOLOGY

The data used for this research were obtained by connecting to the Twitter API while a suite of data analysis and visualisation tools were used to stream, pre-process, analyse and visualise data (JONES et al., 2001, McKinney, 2010).

Natural Language Processing (NLP) is an attempt to process natural language with the help of a computer. It may be used to count single word or multiple words occurrences to identify topics, removing the words that do not directly pertain to the intention of the statement (known as stop-words), or implications on the emotions that a written piece might hold (Bird et al., 2009). The latter extent has led to the establishment of a technique in text mining which is known as opinion mining or sentiment analysis. *"Sentiment analysis or opinion mining is the computational study of people's opinions, appraisals, attitudes, and emotions toward entities, individuals, issues, events, topics, and their attributes."* (Liu and Zhang, 2012).

Sentiment analysis allows for analysing a large body of uploaded text by the citizens and deriving valuable measures based on public feedback. Researchers have proposed an assessment framework for translating unstructured online public opinions into sentimental and topical indicators (Jiang et al., 2016, McGetrick et al., 2017). In similar studies, geo-located text from Twitter was analysed to identify public signals related to urban subjects (Zhang and Feick, 2016, Jongman et al., 2015, Panteras et al., 2015, Anselin and Williams, 2016, Shelton,

2017). Additionally, sentiment analysis enables users to keep track of community emotions.

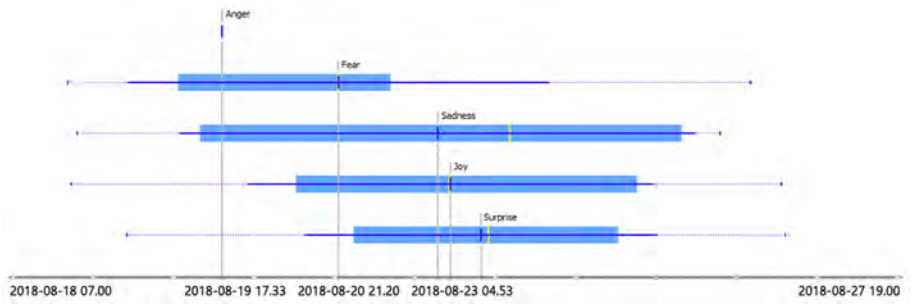


Figure 2. A streaming timeline showing the result of sentiment analysis of tweets on traffic in Wellington NZ during a week.

Various supervised algorithms such as Support Vector Machine (SVM) and Artificial Neural Networks (ANN) have been used as a sentiment mining technique. According to the literature, SVM has been used widely by researchers and yielded acceptable results (Moraes et al., 2013).

3.3. PERSISTENT COMMUNICATION

E-participation brings the opportunity to the city to collect voluntarily generated feedback from citizens. However, participants have not always been involved in every stage of an urban initiative. Keeping the community engaged at every step of the project seems to yield better results (Commodore et al., 2017). Therefore, a wide range of innovative technologies has been incorporated in smart city initiatives to facilitate interaction but was not well received by the people due to inaccessibility or climate issues (Ylipulli et al., 2014). In particular, social media allows for persistent communication as well as convenient access by a large number of stakeholders as they are widely available on smartphones, tablets, TVs, and PCs.

3.4. CREATIVITY AND PLAYFULNESS

A key element here is to provide a user-friendly interactive medium to encourage public engagement. Visual toolkits have the potential to improve communication in value-embedded participatory urban projects (Leslie et al., 2007, Forlano and Mathew, 2014, Fechner and Kray, 2016). A common approach to visualise the relationship between tweets is using network graphs (Grandjean, 2016, Himelboim et al., 2017). A network graph consists of nodes which are represented in circles in various radii and colours. Nodes are connected with one/two-headed arrows which indicate the subjectivity or objectivity of the nodes. Size of each circle usually identifies the larger quantity or, the higher quality of a feature attached to the nodes.

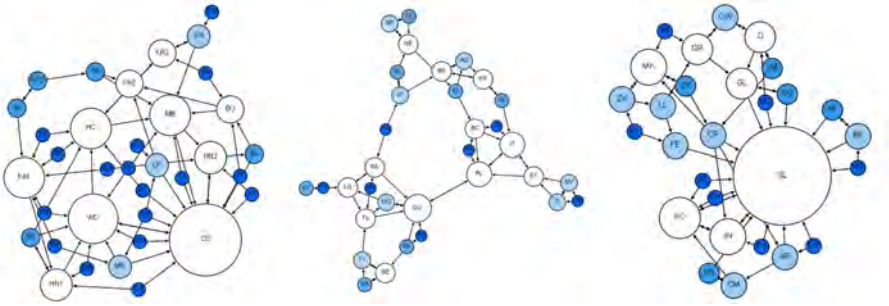


Figure 3. Mapping the social affinities of a group of individuals, Moreno (1934)'s first sociograms visualise the relationships between pupils in a classroom: who wants to be sitting next to whom? Adapted from Grandjean (2015) Social network analysis and visualisation: Moreno's Sociograms revisited. Source: Wikipedia (2018).

Ball-Rokeach et al. (2001) have proposed that storytelling as a concept uses ubiquitous data to let the community share their concerns and issues about their neighbourhood via a communication infrastructure. While graph networks provide an informative overview of the relationships between pieces of data, they are not suitable for representing a story. Having that said, a suite of various visualisation types (interactive timeline, word cloud, search bar) have been used to create the proposed interface. The Actions timeline at the bottom of the Sentiment timeline contains a history of actions of a decision-making organisation. For example, the administrative body may upload their record of actions on 'traffic' and then observe public feedback on 'traffic' through time. A possible insight from observing this timeline would be the fact that after the proposal of Plan X.3.33, the number of positive posts has decreased and more negative feedback has been posted by the citizens.

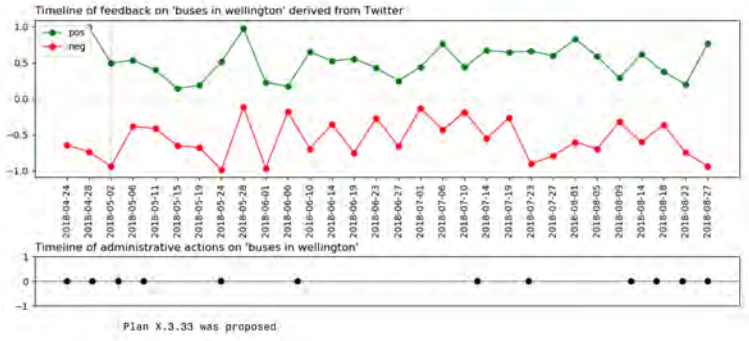


Figure 4. Sentiment tab of the developed interface - Interactive timeline.

3.5. TECHNOLOGY EDUCATION

The level of familiarity with the technologies used in smart city initiatives affects the acceptance of such projects (Ylipulli et al., 2014). Thus, the appropriateness of the e-participation method may decrease if there is no education involved in the early steps of the project. Using education as an incentive not only boosts the level of participation but also results in a greater civic virtue (Kelty et al., 2014). The familiarity of the urban dwellers with social media in this context reduces the need for conducting training sessions in smart city projects as the number of social media users is increasing rapidly. Compared to IoT devices and AR/VR technology, social media stands out as a cost-effective e-participation strategy.

3.6. SOCIO-CULTURAL DIVERSITY

Community members have diverse age, sex and cultural backgrounds. Taking into account all the various mindsets and beliefs they bring can contribute to the effectiveness of urban development strategies (Gudowsky et al., 2017). Also, web applications can decrease power dynamics as they provide the opportunity for every individual to share their opinions without the fear of speaking in front of a large audience (MacMillan; Klenk and Hickey, cited in Pagatpatan and Ward 2017). Young people seem to construct 60% of the urban population in future ("The Role of Youth in the Urban Future", cited in Rexhepi et al., 2016). This projection has led to the investigation of motivating factors to encourage youth participation in urban initiatives (Shakeri et al., 2015, Rexhepi et al., 2016).

3.7. ONLINE AND OFFLINE METHODS

There is evidence that transitioning from offline to online methods has facilitated citizen engagement in the smart city processes. Therefore, the internet can be a promising tool for attracting a large number of participants in our cities. (Spil et al., 2017). The simultaneous use of online and offline methods has been suggested in cases where the project deals with people who do not have the required technical skills (Kleinhans et al., 2015).

4. Conclusion

In this research, NLP tools and creative visualisation techniques were employed to create a sentiment analysis interface for urban planning. While privacy concerns might discourage using social media mining, studies showed that there are enough guidelines and regulations for ethical use of online public feedback. The EU GDPR (2018) and the Twitter Developer Agreement, along with the instructions from the literature, enabled reading, analysing and visualising public data without breaching the users' privacy. While there is ongoing research on the efficiency of opinion mining techniques, our approach revealed that a widely-used method (SVM) is adequately capable of detecting the emotion of tweets. When a new e-participation platform is introduced, stakeholders need instructions to interact with the new system. However, using a popular social media network like

Twitter decreases the learning time because it is user-friendly and easy to learn. Twitter also allows users of diverse backgrounds and ages to engage in city decision-making actively. While e-participation may discourage using offline methods such as face-to-face meetings or workshops, it seems to work effectively as a complementary tool to add to the potentials of these methods.

4.1. FUTURE STEPS

There are various elements embedded in the Twitter interface that allows for the evaluation of the contents of a tweet. The most common Twitter elements are: 1) Hashtags 2) Mentions 3) Likes 4) Retweets and 5) Replies. Depending on how much users want to engage in a conversation they can choose either to 1) Like 2) Retweet (with/without text) and 3) Reply to a tweet. To further our research we are planning to work on calculating the weight of each of these reactions since it can simplify the comparison of various tweets, e.g. a tweet with ten likes and a tweet with one retweet and one reply. How much a tweet has been engaging (E) can then be calculated by using an average weight (Equation 1).

$$E = \alpha \cdot lk + \beta \cdot rt + \gamma \cdot rp \tag{1}$$

where *lk* is the number of likes, *rt* is the number of retweets, and *rp* is the number of replies. The constants α, β and γ determine the weight of each three interactions. Additionally, the impact of retweets with text shows a greater amount of involvement than the retweets without any opinions attached to them. Thus, *rt* can be separated into two elements *rt* and *rt'* which leads to (Equation 2)

$$E = \alpha \cdot lk + \beta \cdot rt + \beta' \cdot rt' + \gamma \cdot rp \tag{2}$$

where *rt* is the number of retweets with text, and *rt'* is the number of retweets without text and the weight factors are α, β, β' and γ.

References

"UK Data Protection Act" : 2018. Available from <http://www.legislation.gov.uk/ukpga/2018/12/pdfs/ukpga_20180012_en.pdf> (accessed December 2018).

"Twitter Developer Agreement" : 2018. Available from <https://developer.twitter.com/en/developer/terms/agreement-and-policy.html> (accessed May 2018).

Alkazemi, M., Bowe, B. and Blom, R. 2014, Facilitating the egyptian uprising: A case study of facebook and Egypt, *in* U.S.A. Information Resources Management Association (ed.), *Human Rights and Ethics: Concepts, Methodologies, Tools, and Applications*, IGI Global, 27.

Anselin, L. and Williams, S.: 2016, Digital neighborhoods, *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, **9**(4), 305-328.

Ball-Rokeach, S.J., Kim, Y.C. and Matei, S.: 2001, Storytelling Neighborhood: Paths to Belonging in Diverse Urban Environments, *Communication Research*, **28**(4), 392-428.

Bird, S., Klein, E. and Loper, E.: 2009, *Natural Language Processing with Python*, O'Reilly

Media, Inc., Sebastopol, USA.
Boudjelida, A., Mellouli, S. and Lee, J.: 2016, Electronic Citizens Participation: Systematic Review, *9th International Conference on Theory and Practice of Electronic Governance (Icegov 2016)*, **9**, 31-39.
Chen, L.S. and Yang, T.Y.K.: 2014, Increasing Customer Loyalty in Internet Marketing, *Intelligent Data analysis and its Applications*, **II**, 95-103.
Commodore, A., Wilson, S., Muhammad, O., Svendsen, E. and Pearce, J.: 2017, Community-based participatory research for the study of air pollution: a review of motivations, approaches, and outcomes, *Environmental Monitoring and Assessment*, **189**, 378.
DiSalvo, C. and Jenkins, T.: 2017, Fruit Are Heavy: A Prototype Public IoT System to Support Urban Foraging, *Proceedings of the 2017 Conference on Designing Interactive Systems*, **17**, 541-553.
Ertio, T.P. and Bhagwatwar, A.: 2017, Citizens as planners: Harnessing information and values from the bottom-up, *International Journal of Information Management*, **37**(3), 111-113.
Fechner, T. and Kray, C.: 2016, Presenting Citizen Engagement Opportunities Online: The Relevancy of Spatial Visualization, *Geospatial Data in a Changing World*, **19**, 105-121.
Forlano, L. and Mathew, A.: 2014, From Design Fiction to Design Friction: Speculative and Participatory Design of Values-Embedded Urban Technology, *Journal of Urban Technology*, **21**(4), 7-24.
Grandjean, M.: 2016, A social network analysis of Twitter: Mapping the digital humanities community, *Cogent Arts \& Humanities*, **3**, 1-14.
Gregory, D.: 2013, Tahrir: Politics, Publics and Performances of Space, *Middle East Critique*, **22**(3), 235-246.
Gudowsky, N., Sotoudeh, M., Capari, L. and Wilfing, H.: 2017, Transdisciplinary forward-looking agenda setting for age-friendly, human centered cities, *Futures*, **90**, 16-30.
Himelboim, I., Smith, M.A., Rainie, L., Shneiderman, B. and Espina, C.: 2017, Classifying Twitter Topic-Networks Using Social Network Analysis, *Social Media + Society*, **3**(1), 1-13.
Jiang, H.C., Qiang, M.S. and Lin, P.: 2016, Assessment of online public opinions on large infrastructure projects: A case study of the Three Gorges Project in China, *Environmental Impact Assessment Review*, **61**, 38-51.
Jones, E., Oliphant, T. and Peterson, P.: 2001, "SciPy: Open Source Scientific Tools for Python" . Available from <https://www.scipy.org/> (accessed 10th May 2018).
Jongman, B., Wagemaker, J., Romero, B. and de Perez, E.: 2015, Early Flood Detection for Rapid Humanitarian Response: Harnessing Near Real-Time Satellite and Twitter Signals, *ISPRS International Journal of Geo-Information*, **4**(4), 2246.
Kelty, C., Panofsky, A., Currie, M., Crooks, R., Erickson, S., Garcia, P., Wartenbe, M. and Wood, S.: 2014, Seven dimensions of contemporary participation disentangled, *Journal of the Association for Information Science and Technology*, **66**, 474-488.
Kleinhans, R., Van Ham, M. and Evans-Cowley, J.: 2015, Using Social Media and Mobile Technologies to Foster Engagement and Self-Organization in Participatory Urban Planning and Neighbourhood Governance, *Planning Practice and Research*, **30**(3), 237-247.
Leslie, E., Coffee, N., Frank, L., Owen, N., Bauman, A. and Hugo, G.: 2007, Walkability of local communities: Using geographic information systems to objectively assess relevant environmental attributes, *Health \& Place*, **13**(1), 111-122.
Leszczynski, A.: 2016, Speculative futures: Cities, data, and governance beyond smart urbanism, *Environment and Planning A*, **48**(9), 1691-1708.
Lin, Y.P., Lin, W.C., Li, H.Y., Wang, Y.C., Hsu, C.C., Lien, W.Y., Anthony, J. and Petway, J.R.: 2017, Integrating Social Values and Ecosystem Services in Systematic Conservation Planning: A Case Study in Datuan Watershed, *Sustainability*, **9**(5), 718.
Liu, B. and Zhang, L. 2012, A Survey of Opinion Mining and Sentiment Analysis, *in* C. Aggarwal and C. Zhai (eds.), *Mining Text Data*, Springer, Boston, MA, 415-463.
McGetrick, J.A., Bubela, T. and Hik, D.S.: 2017, Automated content analysis as a tool for

research and practice: a case illustration from the Prairie Creek and Nico environmental assessments in the Northwest Territories, Canada, *Impact Assessment and Project Appraisal*, **35**(2), 139-147.

McKinney, W.: 2010, Data Structures for Statistical Computing in Python, *Proceedings of the 9th Python in Science Conference (SciPy 2010)*, 51-56.

Moraes, R., Valiati, J.F. and Neto, W.P.G.: 2013, Document-level sentiment classification: An empirical comparison between SVM and ANN, *Expert Systems with Applications*, **40**(2), 621-633.

Moser, S.C.: 2016, Reflections on climate change communication research and practice in the second decade of the 21st century: what more is there to say?, *Wiley Interdisciplinary Reviews-Climate Change*, **7**(3), 345-369.

Olorunnisola, A.A. and Martin, B.L.: 2013, Influences of media on social movements: Problematizing hyperbolic inferences about impacts, *Telematics and Informatics*, **30**(3), 275-288.

Pagatpatan, C.P. and Ward, P.R.: 2017, Understanding the factors that make public participation effective in health policy and planning: a realist synthesis, *Australian Journal of Primary Health*, **23**, 516-530.

Panteras, G., Wise, S., Lu, X., Croitoru, A., Crooks, A. and Stefanidis, A.: 2015, Triangulating Social Multimedia Content for Event Localization using Flickr and Twitter, *Transactions in Gis*, **19**(5), 694-715.

Rahimi, B.: 2011, The Agonistic Social Media: Cyberspace in the Formation of Dissent and Consolidation of State Power in Postelection Iran, *The Communication Review*, **14**(3), 158-178.

Regulation, E.U.: 2018, 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation), *Official Journal of the European Union*, **L119**, 1-88.

Rexhepi, A., Filiposka, S. and Trajkovik, V.: 2016, Playful e-participation with minecraft as development tool for urban redesign: a case study, *IADIS International Conference Big Data Analytics, Data Mining and Computational Intelligence 2016 (part of MCCSIS 2016)*, Funchal, Portugal, 49-56.

Schafer, M.S.: 2012, Online communication on climate change and climate politics: a literature review, *Wiley Interdisciplinary Reviews-Climate Change*, **3**(6), 527-543.

Shakeri, M., Kingston, R. and Pinto, N.: 2015, Towards a Community Support System: Social Media Culture, Games, and Planning Tools, *Digital Placemaking: Augmenting Physical Places with Contextual Social Data: Papers from the 2015 ICWSM Workshop*, 18-22.

Shelton, T.: 2017, Spatialities of data: mapping social media 'beyond the geotag', *GeoJournal*, **82**(4), 721-734.

Shilton, K.: 2012, Participatory personal data: An emerging research challenge for the information sciences, *Journal of the American Society for Information Science and Technology*, **63**(10), 1905-1915.

Spil, T.A., Effing, R. and Kwast, J.: 2017, Smart City Participation: Dream or Reality? A Comparison of Participatory Strategies from Hamburg, Berlin \& Enschede, *Digital Nations – Smart Cities, Innovation, and Sustainability, IFIP International Federation for Information Processing 2017*, Delhi, India, 122-134.

Swim, J.K. and Bloodhart, B.: 2015, Portraying the Perils to Polar Bears: The Role of Empathic and Objective Perspective-taking Toward Animals in Climate Change Communication, *Environmental Communication-a Journal of Nature and Culture*, **9**(4), 446-468.

Townsend, L. and Wallace, C. 2017, The Ethics of Using Social Media Data in Research: A New Framework, *in* K. Woodfield (ed.), *The Ethics of Online Research*, Emerald Publishing Limited.

Ylipulli, J., Suopajarvi, T., Ojala, T., Kostakos, V. and Kukka, H.: 2014, Municipal WiFi and interactive displays: Appropriation of new technologies in public urban spaces,

Technological Forecasting and Social Change, **89**, 145-160.
Zhang, S.Q. and Feick, R.: 2016, Understanding Public Opinions from Geosocial Media, *Isprs International Journal of Geo-Information*, **5**(6), 74.

Artificial Intelligence & Machine Learning

APPROACH TO AUTO-RECOGNITION OF DESIGN ELEMENTS FOR THE INTELLIGENT MANAGEMENT OF INTERIOR PICTURES

JINSUNG KIM[1], JAEYEOL SONG[2] and JIN-KOOK LEE[3]
[1,2,3]*Department of Interior Architecture & Built Environment, Yonsei University, Republic of Korea*
[1,2]*{jinsungkim212|songjy92}@gmail.com* [3]*leejinkook@yonsei.ar.kr*

Abstract. This paper explores automated recognition of elements in interior design pictures for an intelligent design reference management system. Precedent design references have a significant role to help architects, designer and even clients in general architecture design process. Pictures are one of the representation that could exactly show a kind of design idea and knowledge. Due to the velocity, variety and volume of reference pictures data with growth of references platform, it is hard and time-consuming to handle the data with current manual way. To solve this problem , this paper depicts a deep learning-based approach to figuring out design elements and recognizing the design feature of them on the interior pictures using faster-RCNN and CNN algorithms. The targets are the residential furniture such as a table and a seating. Through proposed application, input pictures can automatically have tagging data as follows; seating1(type: sofa, seating capacity: two-seaters, design style: classic)

Keywords. Interior design picture; Design element; Design feature; Automated recognition; Design Reference management.

1. Introduction

1.1. RESEARCH OBJECTIVE

It is generally accepted that there is no royal road to solving design problems. One of the reasons is that a design problem has a wicked and ill-defined characteristic which is difficult to be clearly defined unlike ordinary problem (Rittel and Webber, 1973). Therefore, the architects and designers have adopted problem-solving strategies based on the generation and testing of potential solutions (Cross, 2006). One of such strategies includes generating new designs based on an analysis of previous design solution that is related to the problem in the progress (Eilouti, 2009). Referring to previous designs is taken as a useful strategy to provide an opportunity to know the ideas, directions, and focus on problem-solving. This is the why utilization of design references has become common for architects and designers as well as the general public to look at various architectural reference platforms and archives such as the Archdaily.com, Architizer.com and Pinterest.com. Among data type obtained in previous designs, visual data (e.g.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 785-794. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

pictures, drawings, etc.) has the most important role in finding some suitable reference and get some ideas. However, until now the management of design reference is depending on text data translated by design experts and managers. Such current manual work is time-consuming and makes it difficult to ensure information integrity. This may hinder the user from finding helpful reference to develop potential design solutions.

Recently, an intelligent digital archive that automatically classifies pictures or video and recommends data using deep learning have been proposed (Liu, 2017). Deep Learning-based convolutional neural networks have shown that trained model enables the recognition of objects with fast speed and human-level accuracy (Krizhevsky et al. 2012). A trained model is reusable and the development frameworks such as the Tensorflow are open-sourced, so retraining and utilizing deep learning model is available in various fields (Abadi et al. 2016). In the previous study, we trained and tested models classifying chair picture regarding some design features using deep learning and the convolutional neural networks (Kim et al., 2018). However, the paper only focused on finding the possibility of training a model recognizing design feature. As the extended study, this study shows how to utilize computer vision techniques to support designers through the management and utilization of architectural case information to improve design quality and design productivity design. Based on the results of the retrained model in the previous paper, we depicted a prototype module to detect design elements on the interior pictures and recognize the design feature of the elements. It plays an important role in the intelligent management system for design references. Through these, the user can query what they want to refer to with more specific condition using this kind of database. It would be expected to contribute to improving the interior design process and ultimately help to raise the satisfaction of design through this approach and application.

1.2. RESEARCH SCOPE AND METHOD

In this paper, conceptual four steps the auto-recognition of interior design using computer vision-based technique are described regarding the way of composition of interior design elements. The first two steps of detecting design elements and recognizing its design features are covered. The interior design elements and its design features are hierarchically explained. Based on this classification, collecting and classifying picture of design elements is carried out. We are focusing on the table and seating furniture as the typical and important element for residential interiors. The detection model is re-trained with new table and seating furniture through fine-tuning the Faster-RCNN trained model (inception v2 with coco dataset). The detection model works for finding and cropping region of the table and seating furniture in interior pictures design element. The other model recognizing design feature is re-trained with extended design feature data through recognition model of Kim et al (2018). By combining two sequential model, auto-recognition of design elements and its design features is demonstrated on the prototyped application. As a result of recognition, each of design pictures has tagging data as follows; seating_1(type: sofa, seating capacity: two-seaters, design style: classic and etc.), seating_2(type: stool, seating capacity: one-seater,

design style: modern, and etc.) and table-1(type: coffee table; shape: oral; material: wood and etc.). It would be expected to contribute to improving the interior design process and ultimately help to raise the satisfaction of design through this approach and application.

2. Background

2.1. DEEP LEARNING-BASED COMPUTER VISION TECHNIQUES

Deep convolutional neural networks (CNN) is known as the most powerful method to train a neural network model to extract important parts of features of an image. CNN basically consists of two parts of feature extraction and classification layers. A feature extraction layer includes lots of convolution filter and pooling filter. A classification layer includes a fully connected layer (LeCun et al. 2015). After the success of the CNN-based model of Kreizhevsky et al. (2012) in ILSVRC2012 image classification challenge, CNN was widely applied to the various field. Beyond classifying images, detection object in pictures or video is available. The detection models cab roughly be classified into the region-based object detector such as series of region-based CNN (R-CNN) and the feature pyramid networks (FBN) and single shot object detectors such as single shot multi-box detector (SSD) and YOLO. R-CNN is more accurate but slower to training than the single shot detector. Therefore, YOLO or SSD is commonly used for real-time object detection on video. In this paper, Faster RCNN model is used to train to detect interior design elements, because the accuracy is more priority on this task. It has two parts of networks; 1) a region proposal network (RPN) for generating region proposals and 2) a network to classify objects using these proposals. Especially for training object detection model, data should be annotated with its label data and bounding box point data. The pre-trained model (e.g. VGG, Inception) and frameworks (e.g. Tensorflow, Pytorch and etc.) are open to the public. Pre-trained model and development frameworks have been opened to the public, so how to combine the techniques with specific domain knowledge and how to collect data has become an important issue.

2.2. CASE STUDIES OF COMPUTER VISION APPLICATION TO INTERIOR DESIGN FIELD

Recent the deep learning-based techniques have been applied to design related field such as the Pinterest that is the most popular image-based platform providing inspiration or idea images for fashion, landscape and architecture (Liu, D. C et al., 2017). Bell and Bala (2015) depicted to measuring the visual similarity of interior design elements using CNN and metric distance. The performance of the resulting model showed that the CNN model can successfully train to extract features of interior elements and calculate the visual similarity of input elements. Hu et al. (2017) proposed an approach more using interior domain knowledge to the classification of some typical styles of furniture. They showed that the model could recognize the meaningful features of furniture according to design styles. Kim et al. (2018) proposed an approach to classification learning by design characteristics of seating furniture. The classification of various functional features such as rest

and sealing capacity of the chair and aesthetic and visual features such as design style and materials is possible. However, so far the researches using computer vision techniques have been focused on commercial point or show its possibility of successful recognition ability in interior design domain. Beyond just recognition of some object and its feature, this research aims to find how these techniques can be applied to the design domain to help architects and designers and improve designing environment and process.

3. Approach to Computer Vision-based Recognition of Residential Interior Design

3.1. CONCEPTUAL STEPS OF COMPUTER VISION-BASED RECOGNITION OF INTERIOR DESIGN

The interior design elements generally refer to separate parts or components that make up interior space. The elements include basic architectural elements (e.g. floor, wall, ceiling, column, opening and similar items), furniture, equipment, textile, lighting and additional things such as accessories, ornament and etc. (Pile, 2005). These elements can have not only common design features (e.g. material, color and etc.) but also individual features (e.g. sealing capacity is only designed feature for seating furniture). Relationships of all these elements are importantly considered to create a whole that is more than the sum of its parts (Pile, 2005). Depending on the principle of this interior design, conceptual steps in the recognition of the concept process of computer vision-based revision of interior design can be proposed (Figure 1). In the first step, each design elements are detected. Next, the design features of each detected elements are recognized. In the third step, the relationship between the elements is analyzed. Finally, the interior picture can be holistically recognized as a single image with the relationship of each design object and feature. For example, the interior design is a cozy living room with minimal style looking. Through these steps, the computer vision model can automatically generate such design information from the individual element and holistic space. the model will have an important role in the intelligent management of interior design reference. In this paper, the first two steps of detecting design elements and recognizing its design features are covered.

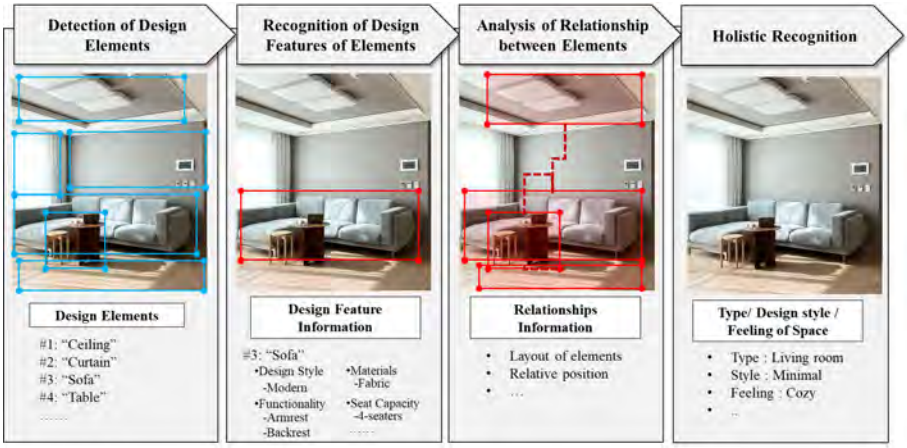


Figure 1. Conceptual steps of computer vision-based recognition of interior design.

3.2. FURNITURE AND THEIR DESIGN FEATURES IN RESIDENTIAL INTERIORS

As described above, the interior elements can be classified into the basic building element, furniture, lighting (including a fixture) and etc. Each element needs different methods to be recognized due to their visual characteristics. As the extended study of Kim et al. (2018), this paper focuses on the seating and table furniture to detect an object and recognize its design features on the residential interior picture. Furniture includes various sub-categories such as a table, chair, sofa, storage, bed and etc. this classification seems like explicit but classification of its design feature seem like implicit. Kim et al. (2018) summarized that features of furniture are categorized into three parts. The first is related to functionality that means whether the furniture has specific functional components such as backrest and wheel. The second is related to feeling such as "comfort", "neat" and etc. This feature has an important role in design but is subjective and implicit because such kind of features is derived from individual experience and feeling. The final is related to appearances such as a style, a shape, a color, a material and etc. the shape, the color, the material could be relatively explicitly classified with visual features. In the other hands, the style (e.g. "modern", "classic". "Scandinavian" and etc.) is difficult to clearly be distinguished. This is because new styles are defined and used together to create another style. By adapting the data-driven methods such as deep learning, however, it is confirmed that it is possible to train and utilize the model to learn the design features of the seating furniture in the previous study. As an expansion of the previous study, this paper combines the object detection approach with the proposed object feature recognition.

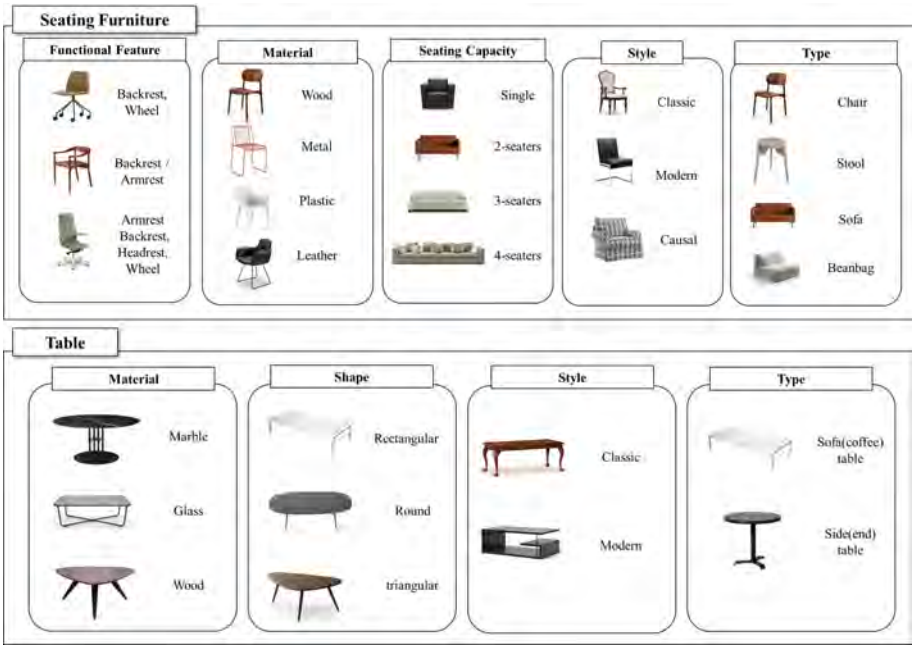


Figure 2. Examples of design features of seating and table in residential interiors .

4. Auto-Recognition of Seating and Table Furniture and its Design Features

4.1. DATA PREPARATION OF SEATING AND TABLE FURNITURE IN RESIDENTIAL INTERIORS

Both data for object detection and design feature recognition are collected from a variety of specialized interior information sharing platforms (Houzz.com and Architonic.com). To easily build each dataset, automate image scraper module is utilized. Data pre-processing should be done before deep learning training. Object detection learning requires data annotation process and in this paper, the annotation of the data is performed regarding Pascal VOC. The target categories of object detection are only two upper-level classification criteria such as seating and table. This is because object detection is utilized only to find and crop the region of seating and table on interior pictures. The 800 data of each of seatings and tables is prepared. The object feature recognition data is collected and classified according to the sub-classification criteria in Figure 2. Depending on the design features, 200 data were collected respectively. 80% of the total collected data are used for training and 20% are used for evaluation.

4.2. TRAINING A MODEL DETECTING SEATING AND TABLE FURNITURE ON PICTURES

In this paper, we adopt a method of retraining the pre-trained model that is the faster-RCNN-based Inception v2 and trained COCO dataset instead of starting

from scratch. The training is conducted on Windows using the Tensorflow API. Training parameters are set to the default values for the existing model except for the number of training steps (20k). In the evaluation of the object detector, the mean average precision (mAP score) is the metric to measure an accuracy. It is the average of the maximum precisions at different recall values of all categories (in this case, seating and table). Precision means how objects in a bounding box are accurately classified (the percentage of true positive). Another criterion is how well the ground truth of object overlaps the bounding box predicted by the model and is defined as intersection over union (IoU). IoU is calculated by dividing the area of the union by area of overlap. In this paper, evaluation is executed with 0.5 IoU threshold. Table 1 shows the results of evaluation of the trained object detection model. The mAP score is pretty high as 0.926 that means that detecting accuracy is 92.6%.

Table 1. Results of evaluation of Seating and furniture detector.

Class	AP_{50}	mAP_{50}	Training Steps
Seating	0.933		
		0.926	20,000
Table	0.913		

4.3. TRAINING MULTIPLE MODEL RECOGNIZING DESIGN FEATURES OF SEATING AND TABLE FURNITURE

Unlike only one model is trained in the object detection training phase, multiple models are trained regarding categories of design feature for Recognizing Design Features. In other words, each of models has the universe of discourse regarding the design feature such as the type, material and etc. of seating and type, shape and etc. of a table. For example, a model that is trained to recognize the type of seating can only classify whether the input object is sofa or stool, cannot recognize material, style another feature of the object. We retrained a total of 9 models that five are for functional, material, seating capacity, style and type of seating, and four are for material, shape, style and type of table. Table 2 shows the results of training and evaluation of each model. Training accuracy is calculated by dividing the total number of the case by the number of true positive that means the model answer the right label. The accuracy of models that learned features that can be classified regarding figuration such as shape, type, style and functional features tends to be high. The average accuracy of all design feature models is 83.2%.

Table 2. The results of training and validation of each model.

Class	Models	Images	Training Steps	Accuracy
Seating	Functional features	800	50,000	91.3%
	Material	800	50,000	72.6%
	Seating capacity	800	50,000	77.7%
	Style	600	50,000	86.7%
	Type	800	50,000	89.5%
Table	Material	600	50,000	74.5%
	Shape	600	50,000	90.1%
	Style	400	50,000	80.4%
	Type	400	50,000	86.0%

4.4. DEMONSTRATION

A prototype application recognition of interior design elements was developed by linking previously object detection model with design feature recognition model. The interface of the application is based on Python. First of all, the detection model that recognizes furniture shown in the input picture is executed and, as a result bouncing boxes for areas recognized as furniture are created and the probability value of recognition is shown. This area is cropped through the image processing module and stored as a temporary cache image. Depending on the inferred category of the cropped image, the design feature models are executed and each result is saved in database table format. Each feature is represented by a pair of the resulting text of the inference such as type: sofa, type_score: 85.1(%). As the results of execution, design features related to elements can be automatically added to the input interior picture. This application shows how the deep learning models are applied to automatically recognize and analysis design picture.

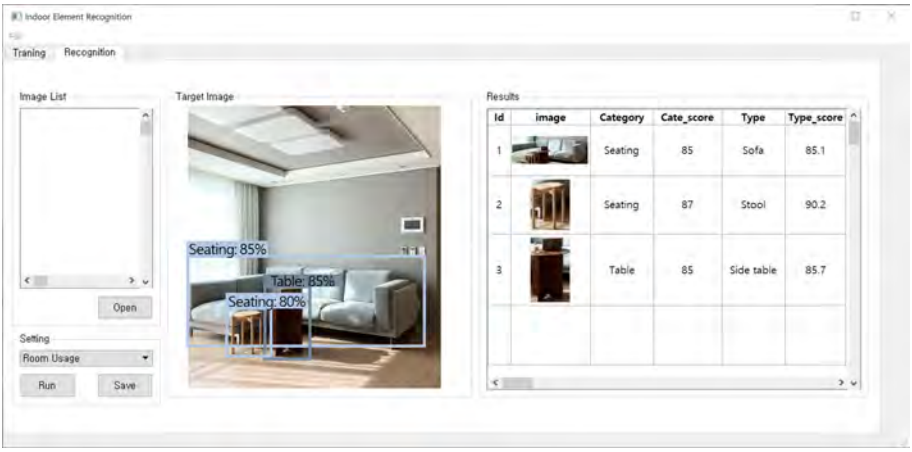


Figure 3. Prototype application of recognition of interior design elements and design features.

5. Conclusion

This paper depicted an approach to recognition of a seating and a table on interior reference image and their design features using CNN and Faster R-CNN models and demonstrated the prototype application using a set of trained models. As a part of a research for intelligently managing the references of architecture and interior design, we explored how AI module to train and recognize design information regarding design domain knowledge. Among the four design recognition steps described, we depicted the first two steps; 1) design elements detection, 2) design feature recognition. The accuracy of 92.6% (as 0.926 mAP score) score was shown as a result of the object recognition model for seating and table. We trained 9 models with different UODs depending on the design feature categories of each class of furniture and the with the average accuracy of 83.2% was shown. By demonstrating the prototype application using trained models, it was shown that design information in pictures can be automatically analyzed and stored into the database. As a follow-up study, a study on the relationship between recognized objects and design features is underway and it will be expanded to other interior design elements such as architectural elements. It is expected that these AI modules will help the user more efficiently manage and utilize design reference by precisely and automatically performing informatization of given mounts of design reference data.

Acknowledgements

This research was supported by a grant(19AUDP-B127891-03) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

References

"Web-based opend archiving for Interior design elements" : 2018. Available from <https://www.architonic.com/> (accessed 18th December 2018).

"Web-based interior design reference platform" : 2018. Available from <https://www.houzz.com/> (accessed 18th December 2018).

"Image-based design reference web platform" : 2018. Available from <https://www.pinterest.co.kr/> (accessed 18th December 2018).

"The most popular web-based architectural design reference platform" : 2018. Available from <https://www.archdaily.com/> (accessed 18th December 2018).

Abadi, M., Agarwal, A., Barham, P., Brevdo, E., Chen, Z., Citro, C., Corrado, G.S., Davis, A., Dean, J., Devin, M. and Ghemawat, S.: 2016, Tensorflow: Large-scale machine learning on heterogeneous distributed systems, *OSDI*, 265-238.

Bella, S. and Bala, K.: 2015, Learning visual similarity for product design with convolutional neural networks, *ACM Transactions on Graphics*, **34(4)**, 98.

Cross, N.: 2006, *Designerly ways of knowing*, Springer.

David, C.L., Stephanie, R., Raymond, S., Dmitry, K., Kevin, C.M., Zhigang, Z., Jenny, L. and Yushi, J.: 2017, Related pins at pinterest: The evolution of a real-world recommender system, *Proceedings of the 26th International Conference on World Wide Web Companion*, 583-592.

Eilouti, B.H.: 2009, Design knowledge recycling using precedent-based analysis and synthesis models, *Design Studies*, **30(4)**, 340-368.

Hu, Z., Wen, Y., Liu, L., Jiang, J., Hong, R., Wang, M. and Yan, S.: 2017, Visual Classification of Furniture Styles, *ACM Transactions on Intelligent Systems and Technology (TIST)*, **8(5)**, 67.

Kim, J., Song, J. and Lee, J.K.: 2018, approach to the extraction of design features of interior design elements using image recognition Technique, *Proceedings of the 23rd CAADRIA*, 287-296.

Krizhevsky, A., Sutskever, I. and Hinton, G.E.: 2012, Imagenet classification with deep convolutional neural networks, *Proceedings of Advances in neural information processing systems*, 1097-1105.

LeCun, Y., Bengio, Y. and Hinton, G.: 2015, Deep learning, *Nature*, **521(7553)**, 436-444.

Lee, A.S.: 2010, A study on predicting consumers'satisfaction based on the features of furniture product designs, *International Journal of Organizational Innovation*, **2(3)**, 138.

Redmon, J., Divvala, S., Girshick, R. and Farhadi, A.: 2016, You only look once: Unified, realtime object detection, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 779-788.

Ren, S., He, K., Girshick, R. and Sun, J.: 2015, Faster r-cnn: Towards real-time object detection with region proposal networks, *Proceedings of Advances in neural information processing systems*, 91-99.

Rezgui, Y.: 2006, Ontology-centered knowledge management using information retrieval techniques, *Journal of Computing in Civil Engineering*, **20(4)**, 261-270.

Rittel, H.W. and Webber, M.M.: 1973, Webber MM (1973), Dilemmas in a general theory of planning, *, Policy sciences*, **4(2)**, 155-169.

Szegedy, C., Vanhoucke, V., Ioffe, S., Shlens, J. and Wojna, Z.: 2016, Rethinking the inception architecture for computer vision, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2818-2826.

OPTIMISING IMAGE CLASSIFICATION

Implementation of Convolutional Neural Network Algorithms to Distinguish Between Plans and Sections within the Architectural, Engineering and Construction (AEC) Industry

JENNIFER MEI YEE NG[1], NARIDDH KHEAN[2], DAVID MADDEN[3], ALESSANDRA FABBRI[4], NICOLE GARDNER[5], M. HANK HAEUSLER[6] and YANNIS ZAVOLEAS[7]
[1,4,5,7]*UNSW*
[1,4,5,7]*{j.ng|a.fabbri|n.gardner|y.zavoleas}@unsw.edu.au*
[2,3]*Arup Engineering Sydney*
[2,3]*{Nariddh.Khean|David.Madden}@arup.com*
[6]*UNSW & CAFA Visual Innovation Institute Beijing*
[6]*m.haeusler@unsw.edu.au*

Abstract. Modern communication between built environment professionals are governed by the effective exchange of digital models, blueprints and technical drawings. However, the increasing quantity of such digital files, in conjunction with inconsistent filing systems, increases the potential for human-error upon their look-up and retrieval. Further, current methods are manual, thus slow and resource intensive. Evidently, the architectural, engineering and construction (AEC) industry lacks an automated classification system capable of systematically identifying and categorising different drawings. To intercede, we aim to investigate artificially intelligent solutions capable of automatically identifying and retrieving a wide set of AEC files from a company's resource library. We present a convolutional neural network (CNN) model capable of processing large sets of technical drawings - such as sections, plans and elevations - and recognise their individual patterns and features, ultimately minimising laboriousness.

Keywords. Convolutional Neural Network; Artificial Intelligence; Machine Learning; Classification; Filing architectural drawings.

1. Introduction

Through popular accounts, artificial intelligence (AI) is often portrayed as the source of futuristic dystopic outcomes. However, machine learning (ML), a sub-field of AI, has been progressively integrated into our daily life with positive outcomes. From the micro-scale of an individual's smartphone, home and security systems and personalised social media feeds, to the macro-scale of urban transportation systems and cyber-physical technologies, ML has contributed to

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 795-804. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

lessening repetitive manual tasks while improving the quality of life. Within the built environment, ML has shown potential in implementing traditional design processes and approaches. By way of explanation, in 2016, Phelan investigated employees' dynamics in a workplace with the goal of developing a more efficient work environment. After collating the usage data of the workspaces, a ML algorithm was implemented to predict rooms occupancy, ultimately to offer the most appropriate space for an improved working experience. Correspondingly, the present research aims to investigate workplace efficiency with the aid of ML. As architectural drawings have entered the digital realm, a variety of files progressively accumulates in local and global servers. These files are often unstructured and unsystematic, forcing engineers and designers to sort and retrieve them manually and repetitively. With ML coming into place, engineers can be off-loaded of laborious duties, while intelligent alternatives can be developed.

2. Research Aims

Challenging traditional approaches to architecture, engineering and design, the present research aims to investigate the potential of ML in optimising workplace efficiency by constructing a predictive model that can differentiate between typologies of architectural drawings (i.e. plans and sections). The initial objective is to master our understanding of ML concepts and principles, while determining what algorithm is best suited to solve the problem at hand. The second objective is to construct a model that effectively recognises and categorises given images, and to do so under optimal hyperparameters.

3. Research Question

Ultimately, the research project revolves around the following question: *"How can drawing classification be automated within the built environment discipline using machine learning?"*

Subsequently, several sub-questions emerge from the iterative nature of the investigative process, such as *"How effective is the convolutional neural network algorithm for the given problem?"*; and *"What are the differences between 'training', 'validation' and 'prediction', and how are they indicative of a ML model's performance?"*; and *"How can the adjustment of CNN hyperparameters - user controlled variables - affect the model's accuracy?"*.

4. Methodology

An action research approach is held to carry out the research. Action research, as per D. Gabel's definition (1995), involves a heuristic cycle, which iteratively progresses through the conceptualisation of a problem (exploratory stance), the action towards its resolution (action), and an evaluation of that action (observation) (Khean et al., 2018). In the first stage (exploratory stance), the impact of AI and ML on the architectural, engineering and construction (AEC) industry are investigated to highlight the need of ML for an intelligent and informed approached to problem-solving. In the second stage (action), ML fundamentals are explored to identify the best algorithmic approach for the current

investigation. Subsequently, a predictive model is constructed. In the third stage (observation), the predictive model is tested, quantitative performance feedbacks are collated, and observations are produced in concert with an industry partner (Arup Engineering), academic supervisors, and colleagues. Lastly, the process is iteratively repeated until the desired outcome is achieved. Observations and feedbacks are directed to always reflect the following questions: Can the model be adapted to different drawing style? Can the model differentiate between line thicknesses, colours and texts? Finally, can the model be implemented to accommodate different applications inside and outside the discipline of built environment?

5. Background Research

EVOLUTIONAL CHANGE IN ARCHITECTURAL DESIGN PROCESSES Since the historical shift between the Renaissance master builder and the modern architectural profession, design processes have continued to evolve with the fast progression of technological advancements. Novel computational tools have emerged that have allowed for exploring uncharted territories, where manual drawings have been progressively replaced by digitally-aided methods. According to Wirz's *"revolutionary cycle"* (2016), this metamorphosis has yet to reach full completion. However, an interesting trend has already risen. Designers and researchers have not only rapidly engaged in the exploration of advanced solutions for complex designs, but they have also increasingly shared their experience and knowledge through open-source platforms. With novel computational methods and approaches being more and more accessible to the wider community, students have been provided with the opportunity to rapidly understand this fundamental change in the design paradigm, where complexity and performance are explored not as separate aspects from their application in a specific form, but rather as complex interrelations between materials, structure and behaviour. In 1987, the architect Peter Eisenman was appointed by the Goethe University of Frankfurt for the design and construction of the Biozentrum, namely a biological centre which included biotechnology, molecular biology, and biochemistry research laboratories and support spaces. Eisenman's design inspiration came from the complexity of biological processes such as the human DNA, which he wished to embed, embody and celebrate within a long-lasting monument. The apparently aesthetic direction of Eisenman's design concept shouldn't, however, deceive the reader. Biological theories and procedures were mainly employed to optimise the distribution, dimension and form of the centre's innumerable spaces. To address such complexity of interrelations, Eisenman turned to computing, and initiated the development of "a procedural modelling tool capable of drafting predefined figures at varying alignments" (Zardini, 2013). The resulting geometrical pattern reflected a fractal distribution of individual laboratories, where varying scales and oblique orientations served to generate cantilevered spaces for cafeteria, library and meeting functions. As we briefly delineated with Eisenman's example, the increasing variation in computational methods has proved to be invaluable not only to achieve purely aesthetic outputs but also to optimise functionality and technicality of complex designs. A fruitful

cointegration between aestheticism and functionalism requires, however, a certain cross-disciplinary approach, where disciplines such as engineering, architecture, biology, and computer science cohesively contribute to the design process. With consideration for the aforementioned, the current research aims to refine and enhance a specific design process (i.e. files' sorting and identification) through the exploration and validation of a novel cross-disciplinary approach. Ultimately, we hope to encourage experimentation outside the box and further optimisation of design solution where form is informed by performance.

ML AND THE CHANGING PARADIGM Entering the lexicon in 1959, the term "machine learning" has continuously evolved, still failing to reach an agreed upon definition today. However, Professor Tom M. Mitchell of Carnegie Mellon University eloquently describes that "a machine learns with respect to a particular task, performance metric, and type of experience, if the system reliably improves its performance at that task, following experience" (Broussard, 2018). Within this paradigm, artificial neural networks (ANNs), a subcategory of ML algorithms, have been successfully applied to recognising patterns and trends within a specific dataset. Originally inspired by the human neurological system, ANNs can mimic our brain's information processing and knowledge acquisition - initially starting at a randomised state, and improving its performance over time through experience. In 2000, Basheer and Hajmeer published the article *Artificial Neural Networks: Fundamentals, Computing, Design, and Application*, where the juxtaposition between ANN approaches and traditionally held techniques was analysed. While highlighting the higher degree of robustness and rapidity of ANNs, the authors also introduced the idea of automation of design practices with the goal of expanding design opportunities, within and outside the design realm. A variation of the ANN algorithm is the convolutional neural network (CNN). CNNs differ from the ANN architecture due to its inherent ability to comprehend spatial relationships. There have been several instances wherein CNNs have been implemented into processes involving image recognition, semantic segmentation, and even image manipulation and generation. In 2015, Gatys, Ecker and Bethge investigated the potential of style transferring between several pictures. As such, they first dismantled the images in hierarchical layers. Subsequently, they identified specific features in each image that could reveal and transpose the styles from one another. With the overarching objective of developing a computational framework for recognising and categorising architectural drawings, we believe that an ANN, and in particular a CNN, would suit the present research. However, before constructing a model, we thought necessary to obtain a comprehensive understanding of how CNNs behave and what is their fundamental structure. In 1980, Fukushima published a paper titled Neocognitron: A Self-Organising Neural Network Model for a Mechanism of Pattern Recognition Unaffected by Shifts in Position. The article focused on the improvement of a model's ability to recognize patterns, namely neocognitron, which required an extended self-organizing multi-layered neural network. The structure proposed by Fukushima resembled the hierarchical model of the visual nervous system developed by Hubel and Wiesel between 1962 and 1965, where information flowed from simple cells to complex cells. In Fukushima's proposal,

the to-be-improved network was aimed to implement position variations within input data. Previous research had demonstrated the sensitivity of such data to normalisation. Fukushima implemented a position-invariant pattern recognition, where the network's structure consisted of C and S cell layers sub-grouped into "cell-planes". Each cell would have fields receptive of the same function independent of their position, and with the layers receiving the same set of input synapses, parameter alternations would provide the model with the determinants for differentiating between patterns similarities and distortion. Fukushima's network progressively acquired the ability to correctly distinguish between different inputs with similar features. However, when prompted to increase the number of cell-planes with the goal of increasing the steadiness and accuracy of the model's prediction, the network failed to perform due to a computer's memory deficiency. To achieve the overarching aim of the present research, the authors believe in employing Fukushima's network and method for position-invariant recognition. Since Fukushima's research, computers' memory has increased exponentially, allowing us to progress from where he left.

6. Case Study

In collaboration with Arup Engineering, an independent firm of multidisciplinary consultants in the field of Built Environment, this research aims to develop, train and validate a neural network model that can recognise and categorise different drawings systematically. To do so, an application-based approach is pursued. A CNN model is implemented with the goal of identifying the spatial relationship between pixels of the same image, the structure and behaviour of which we delineate below.

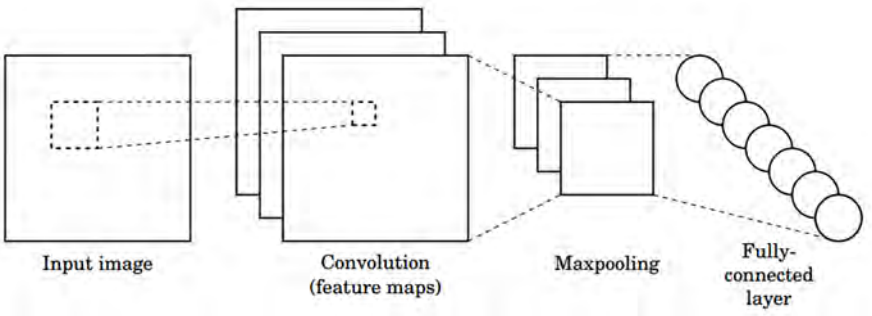


Figure 1. Diagram of Convolutional Neural Network (Pavlovsky, 2017).

INPUT LAYER In the first stage, images of the same category (either plans or sections) are fed to the model for training and validation. Each image is broken down by the algorithm into a matrix of input values, where each value corresponds to a pixel or, more specifically, to a combination of the pixel's RGB codes. In the process, 800 images are inputted for training and 200 images for validation.

CONVOLUTIONAL LAYERS In the second stage, each pixel is analysed by a set of filters, known as *kernels*. Each kernel, initialised randomly, moves along the

input matrix of pixels by *n* strife steps. At each step, the kernel overlaps a portion of the image's pixels, which are multiplied and summed, returning a single value. As the kernel moves along the input image, a single value is returned, leading to a new matrix for the next layer.

MAXPOOLING Following the generation of the new matrix, the image size is reduced in the third stage. Observing a portion of the matrix at a time, the largest value in the portion is kept and relatively insignificant details are ignored, subsequently reducing training time and preventing overfitting.

FULLY CONNECTED LAYERS In the last stage of the model, the matrix is flattened, while every value previously calculated is connected with the scope of training, validating and predicting the output data. The aim of the previous layers were to extract the features of the image, while the fully-connected layer is designed to map the correlation between these extracted features and the image's classification.

TRAINING AND VALIDATION The results from the training and validation process, indicated by the model's accuracy, indicates how best to modify the CNN's hyperparameters. The goal of this iterative adjustment is to increase the model's ability to generalise the correlation between features and image classes, which in turn increases the model's robustness. As a result, many iterations are generated, of which three are selected and evaluated in detail in this paper. Hence in the following we are changing the hyperparameters.

```
Number of Convolutional Layers: 1
Number of Filters: 32
Filter Size: (3, 3)
Dropout Percentage: 0.2
Learning Rate: 0.001
Epooch: 128
Batch Size: 8
```

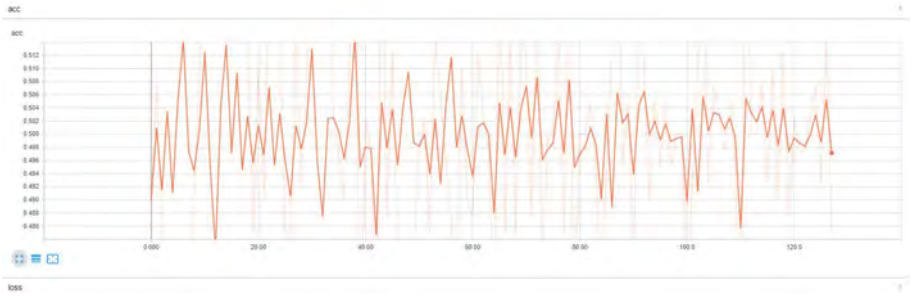


Figure 2. Iteration 1, Training Accuracy.

The performance of the model can be evaluated through the model's accuracy, calculated by comparing the number of correctly classified images against those classified incorrectly. For this research, the objective was to achieve an accuracy of over 90%. In theory, as the model continues to train, its accuracy should improve. However, poorly chosen hyperparameters will

manifest as excessive fluctuations or even a decrease in accuracy, also known as "overfitting". Overfitting is an undesirable consequence of a model with ill-fitting hyperparameters and can be intuitively described as the memorisation of the training data instead of the generalisation of the underlying patterns and trends. There are loose guidelines for selecting optimal hyperparameters, however each problem requires some level of hyperparameter tuning. Below are the hyperparameters of Iteration 1:

Analysing the Iteration 1 training graphs (Figure 2), we can observe that the model's accuracy reached a peak accuracy of 52%. Considering the task is a binary classification task, where a purely random classifier would typically get 50% accuracy, a 2% improvement does not indicate effective learning. However, it is the sporadic nature of the graphs are more telling. Changes this severe aren't typical of effective training. A likely reason for this is because the model is not recognising enough features from the input images. To improve the learning process, two additional layers are added to the convolutional network, and Iteration 2 is initiated. Below are the hyperparameters of Iteration 2:

```
Number of Convolutional Layers: 3
Number of Filters: 32
Filter Size: (3, 3)
Dropout Percentage: 0.2
Learning Rate: 0.001
Epooch: 128
Batch Size: 8
```

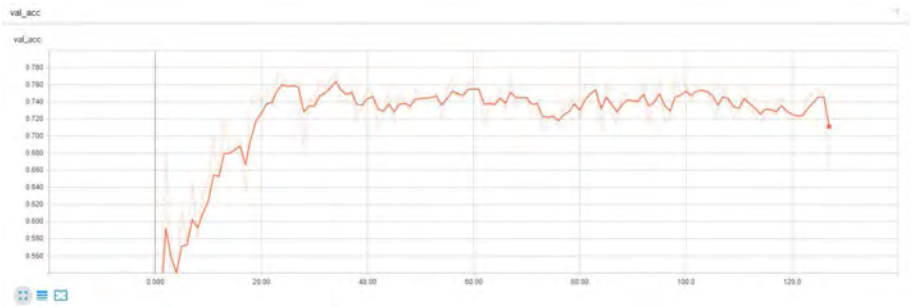


Figure 3. Iteration 2, Validation Accuracy.

Increasing the number of convolutional layers, which increases the complexity of extracted features, greatly reduced the extreme changes in accuracy. This smoother change is indicative of gradual improvement, thus more effective learning. Iteration 2 is a step in the right direction, however still shows larger fluctuations near the end of the 128 epochs - potential signs of overfitting. Accordingly, the model's learning rate is lowered in the following iteration. Below are the hyperparameters of Iteration 3:

```
Number of Convolutional Layers: 3
Number of Filters: 32
Filter Size: (3, 3)
```

```
Dropout Percentage: 0.2
Learning Rate: 0.0001
Epooch: 128
Batch Size: 8
```



Figure 4. Iteration 3, Validation Accuracy.

In Iteration 3, the model achieves a semblance of stability, indicated by more modest increases in accuracy. Despite our initial aim for a model with greater than 90% accuracy, the state of the model at its peak accuracy of 82% would suffice. It is this model that is held for prediction.

PREDICTION Following a dual-sample testing approach, the model's robustness is tested against new images that the model was not trained with. Because of the unicity of the architectural form, six Sydney Opera House plans and sections were used to assess if the trained model has truly learnt to extract the characteristics of what makes a plan and section. The model successfully classified all of these images (Figure 5), however, failed to achieve this same accuracy when tested on further inputs. As such, we recommend further adjustment of the model's hyperparameters before its implementation within a practice-based scenario.

7. Significance of Research

The present research aimed to investigate the development of a artificially intelligent system, capable of identifying and categorising a wide set of AEC files. The project was developed to encourage greater efficiency in the workplace by offloading employees of time-consuming and laborious tasks, such as the manual sorting of architectural drawings. A CNN model was developed and trained to process an abundance of imagery files and successfully classifyed them into their respective categories with an accuracy of 82%. The immediate next steps would involve further iterations of hyperparameter adjustment (with longer training times), in an attempt to achieve the desired 90% accuracy. This would be greatly aided with a larger training dataset of pre-classified drawings, as well as explorations of new CNN architectures - such as highway networks (Srivastava et al. 2015), residual networks (He et al. 2016), and dense networks (Huang et al. 2017) - that have been shown to yield superior performance. Assuming a trained model with acceptable levels of accuracy, the final steps required before deploying the tool would involve the development of an interface accessible to non-experts. This could take the form of a program or an executable file (py2exe),

which professionals can run locally. Alternatively, the trained model can be added to a backend server and uploaded to the cloud as a web application.

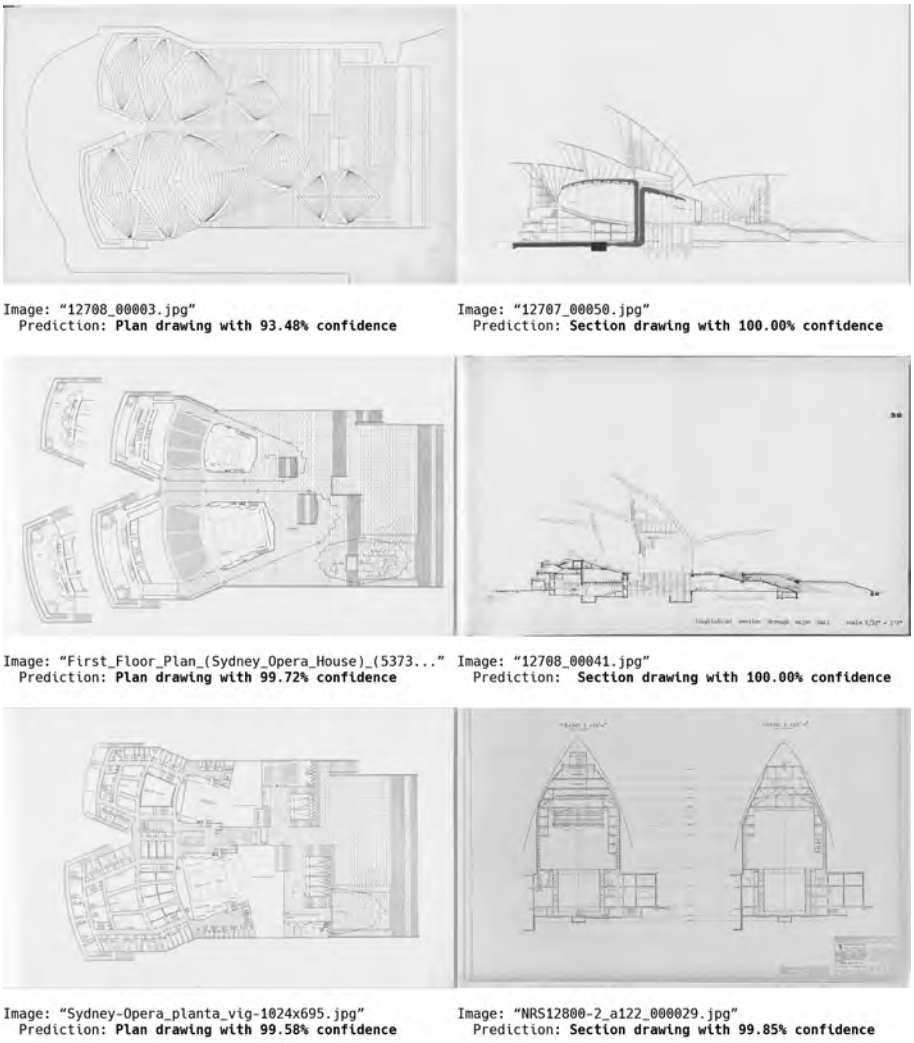


Figure 5. Original Sydney Opera House Drawings and Predictions.

8. Conclusions

Workplace efficiency can and should be addressed with the use of algorithmic solutions such as the one proposed in the present paper. Clearly, we aim to encourage a better communication between professionals of the AEC industry through an enriched organisation of resources libraries, and to increase their

productivity. The model presented in this paper could be further implemented to orderly categorise digital or hand-drawn archival files which might be currently forgotten in the companies' storage, and which could still inspire knowledge and innovation. Moreover, the model shows potential for identifying more specific features such as abstract drawings, texts and renders, to eventually differentiate between real pictures and architectural visualisations of the same building.

References

"A simple way to understand machine learning vs deep learning" : 2018. Available from Zendesk<https://www.zendesk.com/blog/machine-learning-and-deep-learning/> (accessed 22 September 2018).

Basheer, I. and Hajmeer, M.: 2000, Artificial neural networks: fundamentals, computing, design, and application, *Journal of Microbiological Methods*, **43**(1), 3-31.

Broussard, M.: 2018, *Artificial Unintelligence: How Computers Misunderstand the World*, The MIT Press, United States of America.

Fukushima, K.: 1980, Neocognitron: A Self-organizing Neural Network Model for a Mechanism of Pattern Recognition Unaffected by Shift in Position, *Biological Cybernetics*, **36**, 193 - 202.

Gatys, L. A., Ecker, A. S. and Bethge, M.: 2015, A Neural Algorithm of Artistic Style, *CoRR*, **1**, 1 - 16.

He, K., Zhang, X., Ren, S. and Sun, J.: 2016, Deep Residual Learning for Image Recognition, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, Las Vegas, 770-778.

Huang, G., Liu, Z., van der Maaten, L. and Weinberger, K.Q.: 2017, Densely Connected Convolutional Networks, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, Las Vegas, 4700-4708.

Khean, N., Kim, L., Martinez, J., Doherty, B., Fabbri, A., Gardner, N. and Haeusler, M. H.: 2018, The Introspection of Deep Neural Networks - Towards Illuminating the Black Box, *Proceedings of CAADRIA 2018*, Beijing, 237 - 246.

Pavlovsky, V.: 2017, "Introduction To Convolutional Neural Networks" . Available from <https://www.vaetas.cz/posts/intro-convolutional-neural-networks/> (accessed 9th December 2018).

Phelan, N.: 2016, "Designing with Machine Learning" . Available from <https://www.wework.com/blog/posts/designing-with-machine-learning> (accessed 1st November 2018).

Shah, D.: 2018, "AI, Machine Learning, & Deep Learning Explained in 5 Minutes." . Available from Becoming Human: Artificial Intelligence Magazine.<https://becominghuman.ai/ai-machine-learning-deep-learning-explained-in-5-minutes-b88b6ee65846> (accessed 20 September 2018).

Sharma, A.: 2017, "Convolutional Neural Networks in Python." . Available from DataCamp Community<https://www.datacamp.com/community/tutorials/convolutional-neural-networks-python> (accessed 22 September 2018).

Srivastava, R.K., Greff, K. and Schmidhuber, J.: 2015, Training Very Deep Networks, *Proceedings of Advances in Neural Information Processing Systems*, Montréal, 2377-2385.

Wirz, F. 2016, Introduction, *in* A. Tedeschi (ed.), *AAD Algorithms-Aided Design. Parametric strategies using Grasshopper.*, Le Penseur, Brienza, 10 - 11.

Zulkifli, H.: 2018, "Understanding Learning Rates and How It Improves Performance in Deep Learning." . Available from <https://towardsdatascience.com/understanding-learning-rates-and-how-it-improves-performance-in-deep-learning-d0d4059c1c10> (accessed 9th December 2018).

IDENTIFYING HIGHLY DENSE AREAS FROM RAW LOCATION DATA

ELIAS JAKOBUS WILLEMSE[1], BIGE TUNCER[2] and ROLAND BOUFFANAIS[3]
[1]*Singapore University of Technology and Design, and University of Pretoria, South Africa*
[1]*ejwillemse@gmail.com*
[2,3]*Singapore University of Technology and Design*
[2,3]*{bige_tuncer|bouffanais}@sutd.edu.sg*

Abstract. In this paper we show how very high-volumes of raw WiFi-based location data of individuals can be used to identify dense activity locations within a neighbourhood. Key to our methods is the inference of the size of the area directly from the data, without having to use additional geographical information. To extract the density information, data-mining and machine learning techniques form activity-based transportation modelling are applied. These techniques are demonstrated on data from a large-scale experiment conducted in Singapore in which tens of thousands of school children carried a multi-sensor device for five consecutive days. By applying the techniques we were able to identify expected high-density areas of school pupils, specifically their school locations, using only the raw data, demonstrating the general applicability of the methods.

Keywords. ; Machine Learning, Big-data, Location-analysis.

1. Introduction

The large-scale adoption of location-tracking capable devices, such as cell phones and some whereables, have given researchers access to large volumes of human mobility and activity data. In this paper, we demonstrate how such big data can be leveraged to identify high-density common-locations within urban areas. Such information provides key insight into locations that are close to saturation and may be in need of re-design and expansion to cater for forecasted population growth. Another potential use is in identifying formal communal locations with low densities which are likely in disuse. Such locations can then be directly studied and the cause of their disuse, such as an inconvenient location or poor design, can be investigated and corrected, or at the least avoided in future developments.

To extract the density information, we apply data-mining and machine learning techniques, commonly used in activity-based transportation modelling (Schuessler and Axhausen, 2009), on high volumes of time-stamped location data. The techniques are applied in four steps. First, velocity and proximity rules are applied to distinguish between travel point-sequences and activity point-sequences.

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 805-814. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Next, a commonly used machine-learning clustering algorithm, is applied over the activity sequence-points to identify potential commonly used, thereby dense areas. The convex hull of the cluster points is then calculated and used to approximate the physical size of the areas. Thereafter, the number of unique visitors and total time spent in them is calculated, which in turn, is used to calculate the densities. An important benefit of this approach is that no external information on the location area is required to calculate densities. The density calculations can be repeated at different times of the day while keeping the size of the area constant. The calculated time-based densities can then be used to find and compare dense common areas, and analyse the typical density experienced during non-transport activities over the course of a day.

2. Related research

Within the urban and transportation planning communities there has been a variety of models to study human and city dynamics and mobility patterns (Gonzalez et al., 2008; Liao et al., 2007). Among them, and especially in transportation planning, activity-based models are considered as the state-of-the-art whereby travel demand is seen as a direct result of people wanting to participate in and conduct activities in certain places at given times (Jiang et al., 2017; Pinjari and Bhat, 2011). The uptake of activity-based modelling is a direct result of the large volumes of human activity location data now readily available to planners. Such big data can be indirectly obtained through mobile call data (Chen et al., 2017; Zheng, 2015) or more directly through GPS-enabled devices (Schuessler and Axhausen, 2009). More recently, the movement of people has been successfully traced by triangulating their location through the proximity of their mobile phones to known WiFi access points (Fakhreddine et al., 2018). The data generated by all the above methods give a detailed view of people's movement over time which can be processed to identify the timing, location and duration of their key activities.

Similar to the aim of this paper, Vieira et al. (2010) deal with the problem of dense areas detection where individuals concentrate within a specific geographical region and time period. The authors develop the Dense Area Discovery (DAD-MST) algorithm to automatically detect dense areas in cell phone antenna networks using Call Detail Records. A benefit of their approach is that the underlying shape of dense-areas is directly inferred from antenna networks. Their approach is demonstrated in a non-disclosed city and used to identify dense areas that are insufficiently covered by the public transport network.

Huang et al. (2017) follow an even more detailed approach to track visitors' movement through the Vanke Songhua Lake Resort, located in Jilin City, northeast of China. The authors make use of WiFi Indoor Position System and track the spatial distribution of visitors through time, and infer the peak-times of specific shops and streets within the resort. For their study, detailed information on the underlying geographical area of the resort and points-of-interest are known beforehand. There is thus a research gap to identify dense locations using detailed location information, but in cases with little information on the underlying geographical areas. For such a scenario, points of interest will have to be inferred directly and solely from detailed location data.

Identifying points of interest from raw GPS records is a common first step in activity-based transportation modelling. Schuessler and Axhausen (2009) develop rule-based methods that split locations of individuals into activity and transport based records. The authors demonstrate the effectiveness of their methods using location data from a sample of residents in Switzerland. In a second step, the transportation mode-choices between activities are analysed (Montini et al., 2014). Similar studies have been conducted in Singapore on large volumes of location data of students (Monnot et al., 2016; Tan et al., 2018; Wilhelm et al., 2017). It should be noted that in these studies, the research focus is on analysing the travel behaviour of individuals. Understandably, little attention is given to the geospatial overlap between activities of residents.

Joubert and Axhausen (2013) follow the activity-extraction approach, specifically to study the overlap of locations of commercial freight vehicles in South Africa. Their aim is to use commonly visited areas to identify formal links between different freight carriers. Commonly visited areas are identified using density-based clustering methods, and formal links are established between vehicles when they visit the same location. Joubert and Meintjes (2015) show that these locations coincide with transportation and delivery hubs, as well as high-density freight demand points, such as shopping centres. A benefit of their approach is that locations are inferred without using additional information.

With our aim to use raw location data of people to identify highly-dense areas, the reviewed approaches can be adapted and applied as follows. The methods of Schuessler and Axhausen (2009) can be used directly to extract activity locations. Thereafter, key statistics for the activities, such as the duration, can be extracted. Commonly visited activity locations can then be determined using density-based clustering methods, and the cumulative time spent at these locations can be calculated. Lastly, the physical shape of the commonly visited locations can be inferred based on the convex-hull of original activity location points associated with them. The physical size of the activity space and cumulative time spend within it then can be converted to the number of visitors per time-period per m^2.

3. Study area and data

The techniques of the previous section were adapted and tested on a large-scale real-world dataset consisting of 133 million records, collected as part of the National Science Experiment (NSE) project in Singapore. The data has been used by a large number of researchers and public agencies to improve their understanding of complex urban systems, mostly from transport, environmental and sensor technology perspectives (Happle et al., 2017; Monnot et al., 2016; Tan et al., 2018; Wilhelm et al., 2017). The dataset was generated through the deployment of 50,000 wearable sensors to Singaporean school children. Students would collect the devices on a Monday and wear it until Friday. On the following Monday, the devices were distributed to new school children. Thereby each week's data capture activities of different students. The data that we used was captured over 8 weeks between April and August of 2016.

When carried, the device continuously measured environmental data, such

as temperature, and importantly for our study, its location. When the device was completely stationary it recorded at a 1-hour frequency. Otherwise, it recorded at a 14-second frequency. The location of the device was localised through surrounding WiFi access points and reported to be accurate to around 20 meters (Wilhelm et al., 2016). Weekends, as well as Mondays and Fridays, were not considered during the analysis since the devices were not in constant use on these days. Furthermore, for demonstration purposes and to limit the computational burden of the analysis, device records were considered for consecutive Wednesdays only, reducing the dataset from 133 to 33 million records. Since a new set of students was tracked in each week, the combined records represent a large sample of the activities of students on a typical weekday. Activities were extracted for active devices. For validation purposes, the clustering and density analysis were performed on three neighbourhoods, namely Toa Payoh, Jurong East and Punggol. The available records cover between 5% and 10% the school going population within each area, and between 0.5% and 1.8% of the total population.

There are some important limitations to the data which we acknowledge. First, the data only represents school children, therefore their activities mainly consist of home and school activity anchor-points, with some minor activities occurring elsewhere. Dense locations are expected to be dominated by areas in and around the schools through which the devices were distributed. Second, the proportion of students covered is small, especially when estimating absolute totals, such as density. The totals can be inflated based on the sample proportion, but care must be taken due to bias in the data. Third, the data is limited to weekdays, and we expect dense locations to be different on weekends. Lastly, activities may take place over different floors within buildings, as investigated by Tuncer et al. (2017). Any calculations of density must be interpreted with caution as the participants may be spread over multiple floor-levels. Despite these limitations, the data still allows for the demonstration of the techniques and the results give some insight to the density experienced by school children over the course of the day.

4. Methodology

In this section, we describe in detail the methods used to estimate the density of high-use common areas. The input required for the methods is time-stamped location coordinates for a large sample of people, with a unique identifier for each person's records. From here on, a record refers to a single time-stamped location-reading of a person participating wearing the device. The extraction and analysis proceeds in three main steps described in the rest of the section. All the methods were implemented in Python 3.7 with the scikit-learn package (Pedregosa et al., 2011) used for the clustering step.

The methods that we applied to identify activities is based on the approach of Schuessler and Axhausen (2009), which was designed for raw data from global positioning systems, without additional information. The methods takes as input each participant's time-ordered set of location records, $R = \{r_1, \ldots, r_n\}$, where n is the total number of records of the participant. Each record, $r_i = \{(x_i, y_i), t_i\}$, consists of the coordinate pair, (x_i, y_i), which we assume is in meters, of the

participant's location at time t_i. Depending on the format of the input data, the location may need to be converted from geographic coordinate system to a projected coordinate system, making it possible to directly calculate Euclidian distances in meters between points, without having to use the Haversine-formula. As a preliminary filtering step, points falling outside the geographical borders of the area being considered can already be removed.

To account for location inaccuracies, which are unavoidable with location tracking devices, a Gauss kernel smoothing function with a kernel bandwidth of 10 seconds is applied to all the location positions. Two rules are then used to identify activity sequences, consisting of consecutive points i to j. In rule 1, a sequence of points is flagged as stationary activity points when the speed between the points is lower than 0.01 m/s and their total duration is at least 120 seconds. For rule 2, a sequence of points is flagged as dense activity points when they occur spatially close to each other.

Once the activities have been identified, the next step is to cluster activities that occur relatively close to each other, while discarding those the occur in isolation. The Density-Based Spatial Clustering with Applications of Noise (DBSCAN) (Ester et al., 1996) was ultimately chosen for our application. The algorithm has two input parameters, namely, ϵ, which is the maximum distance between points to be considered as part of the same cluster, and p_{min}, the number of points required to form a cluster. For our application, both were set equal to ten.

Once the activities are clustered, the final step is to calculate the number of unique visitors, the number of activities, and the total time spent by participants on their activities within the clusters. Doing so is straight-forward using the calculated attributes of the activity clusters. Using the start-and-end times of activities, the number of activities occurring in specific time-interval can be also calculated, which translates to the number of people within the cluster area for the time interval under consideration. Proportional allocations can be made for the time intervals in which activities start and end. The only metric that still needs to be calculated to estimate the density of the activity-cluster is its physical size in m^2. To do so, we revert back to the original activity location points and calculate the convex hull of the points. The area of the convex hull of the points represent a rough physical boundary in which the activities took place, and the area of the convex hull is used as a proxy for the cluster's area. The size of the common activity location is then used to measure its density in people per m^2.

5. Results

In this section, we present full results for activity extraction over all participants records, as well as clustering and density calculations for the three study areas. As mentioned, the data used to test the methods consisted of 33 million records, recorded over consecutive Wednesdays. During the activity extraction phase, a total of 441,438 thousand activities were identified from 53,251 active participants. Key distributions for the activities are shown in Figure 1. The median number of activities per person was seventeen, whereas the median duration of activities was 9 minutes. Both distributions are right skewed, with durations being more

so. This reflects the difference between short bursts of activities occurring during the day while the participants are more active, and long home activities when the participants are inactive during the night.

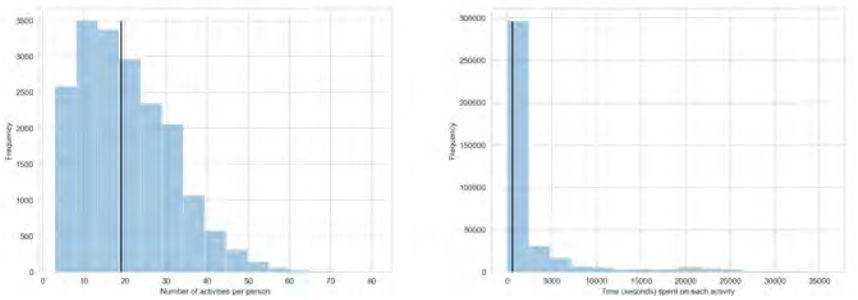


Figure 1. Distribution and median for the total number of activities extracted per participant and the total duration of each activity.

The next step was to cluster the activities using the DBSCAN algorithm on the three study towns. We first evaluated the impact of the input parameters of the algorithm, namely ϵ, the maximum distance in meters between points to be considered as part of the same cluster, and p_{min}, the number of points required to form a cluster. Both were ranged from 5-50 at intervals of 5 units and the resulting number of clusters produced and the fraction of points clustered, with the rest considered as outliers, were captured for the 25 parameter combinations. Results for the experiments are shown in Figure 2.

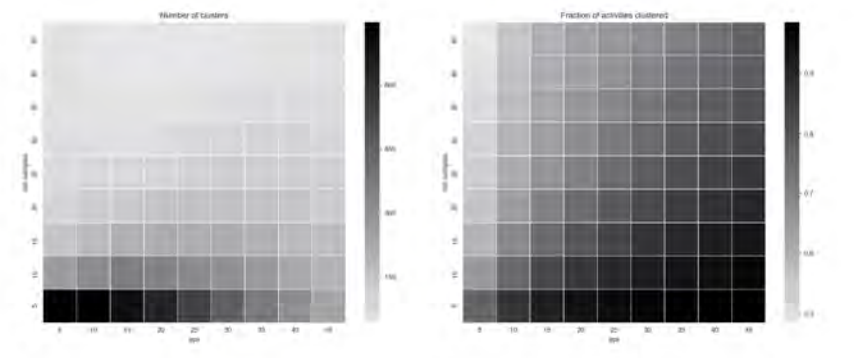


Figure 2. Number of clusters and fraction of points clustered at different levels of epsilon and p min.

At $p_{\text{min}} \geq 15$, the algorithm becomes insensitive to the parameter values, while still finding the same limited number of clusters. The only change is in the fraction of activities that are included in the clusters. In conjunction with lower values of ϵ,

more activities are considered as outliers, which were expected. The experiment shows that the clustering outcome is more sensitive towards p_{min}. The minimum number of activities to justify a common-location depends on the density of the area being considered, as well the proportion of participants included in the study. It, therefore, has to be critically evaluated when applied in semi-similar settings.

Since the data only considers a small fraction of participants, relatively small values of $\epsilon = 10$ and $p_{\text{min}} = 10$ were used to extract clusters for the final analysis. The clusters still totalled well over 300. Prior to identifying high-density locations, all clusters with less than ten unique visitors were removed. Our reasoning was that locations with less than 10 visitors cannot be considered as commonly visited, and in a preceding round of experiments it was observed that they have very low densities. Of the 300 clusters, only 33 met this criterion and where further analysed. Another round of clustering with $\epsilon = 10$ and $p_{\text{min}} = 10$ was applied to original activity points of the clusters to remove outliers, thereafter the area of the convex-hull of remaining points was calculated. The total duration, in days, of the activity durations was calculated. Since the analysis focussed on a single day, the total duration in person-days can interpreted as the number of people throughout the day within the cluster. This value together with the convex hull of the area was used to calculate density. The first four graphs in Figure 3 shows distributions for the number of unique visitors for the clusters, the total duration, in days, of all activities within them, their final area size in m^2, and finally their density in people per m^2.

As expected, the number if unique visitors in the clusters were quite high, with a median of just under eighty. The ten clusters with more than 100 visitors all match schools that participated in the study. Although not explicitly showed, the total duration of the activities per cluster is directly correlated with the number of unique visitors. The cluster areas were also quite small with a median value of less than 1000 m^2, representing a 50-by-20 meter areas. The large clusters again coincide with areas within participating schools. The density of the locations was also quite small, with the largest being 0.08 people per m^2. The median density is only about 0.005. Where the values coincide with school locations we deem them to be accurate, which includes the highest observed density. For other locations, adjustments can be made to account for the less than 2% sample size included in the analysis. At the very least, the analysis results show potentially dense areas which can be further investigated through direct observation or using more representative data.

The last analysis conducted was to measure the density per hour-of-day. Results for the 33 clusters are shown in the bottom of Figure 3. As expected, there is a rise in the density of the locations from 07:00 as participants gather in either respective schools, thereafter the density stays fairly consistent until 14:00 at which point it decreases as students move to other less student-dense location. There is another minor spike later in the evening, indicating another batch of activities. Coinciding with the thick-right tail of the original density distribution, there are two locations within schools with high-density levels throughout the course of the day, including the very early morning hours. These points coincided with small areas with a few continuously active devices, indicating that the

ten-unique visitor limit was too lax. Despite these limitations, the results show to the expected density trends, allowing us to recommend with caution, and subject to further parameter analysis, that they can applied to larger and more representative datasets.

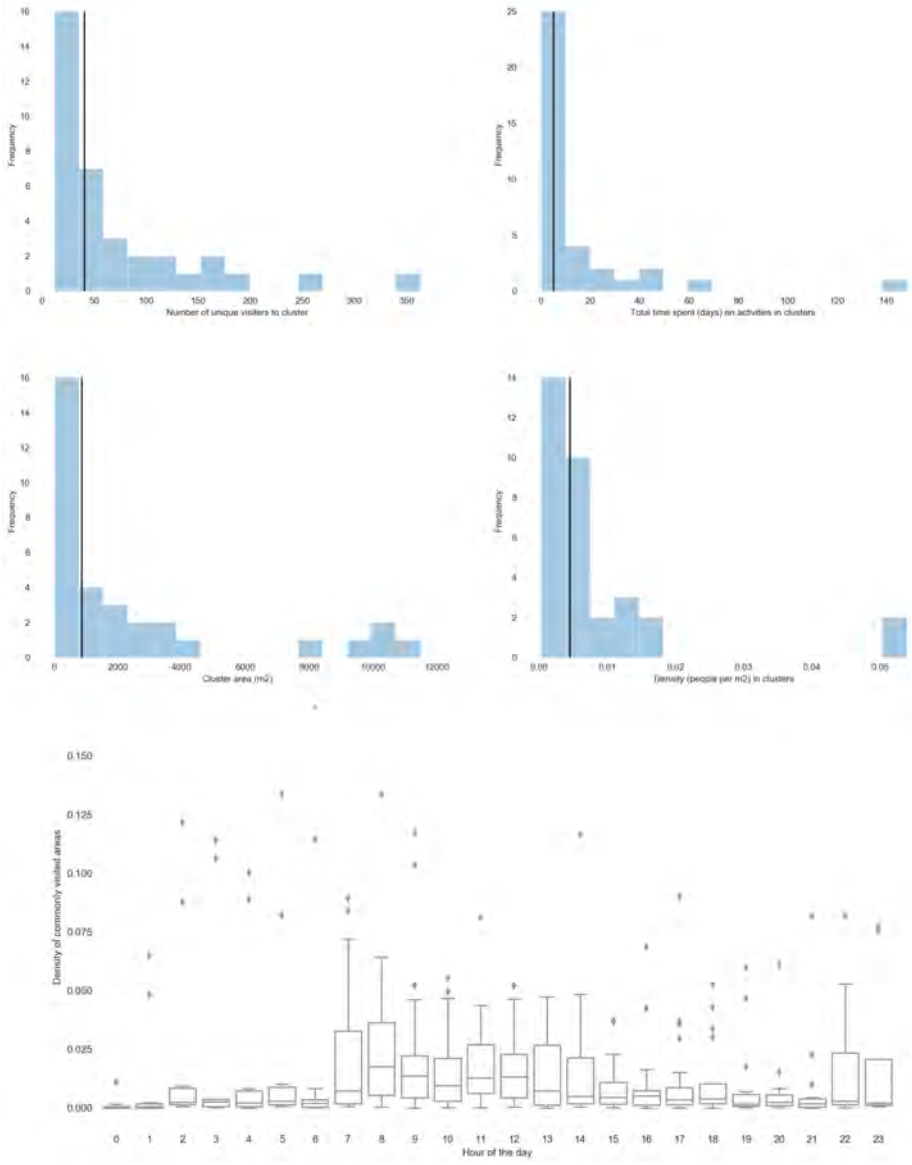


Figure 3. Distributions for the number of unique visitors per cluster, the duration of activities within it, the size of the clusters, and the density of the clusters (top four figures), and distribution of the density of clusters over the course of a day (bottom figure).

6. Conclusion

Our aim with the study was to investigate whether commonly applied techniques from activity-based transportation modelling could be used to identify high-density activity locations, and further to quantify the density levels. The methods were applied to raw data from school pupils in Singapore, and the initial results showed that high-density areas can be extracted and analysed over the course of a day. The methods consisted of a rule-based activity extraction step, followed by clustering using the DBSCAN algorithm. Thereafter the convex-hulls of the activity points associated with commonly visited clusters were calculated to estimate the size of the areas. A benefit of the methods is that they are relatively straight-forward to implement with intuitive parameters that can be tuned for specific application areas. In terms of generality, the scale of the data obtained through study does limit the generality of the techniques. Still, the techniques may be of use in other settings, specifically where similarly high-volumes are obtained through cellphone devices. As is usually the case with an initial investigation of this type, there exist many opportunities for improvement. First, the activity extraction parameters were taken directly from literature and better values and more advanced methods can be investigated. Second, the methods were tested on a small subset of the available data, and the observed results may be indicative of random fluctuations in the travel behaviour of participants. A full application on the whole dataset and all areas in Singapore will produce more robust results. Lastly, the methods can be applied to more comprehensive datasets with ground-truth data to validate that they are effective. The actual floor-space of known popular areas can also be compared against the calculated convex-hull area to analyse its accuracy.

Acknowledgement

This research is supported by the Singapore Ministry of National Development and the National Research Foundation, Prime Minister's Office under the Land and Liveability National Innovation Challenge (L2 NIC) Research Programme (L2 NIC Award No. L2NICTDF1-2017-4). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of the Singapore Ministry of National Development and National Research Foundation, Prime Minister's Office, Singapore.

References

Chen, N., Xie, J., Tinn, P., Nagakura, T. and Larson, K.: 2017, Data Mining Tourism Patterns - Call Detail Records asComplementary Tools for Urban Decision Making, *Protocols, Flows, and Glitches: Proceedings of the22nd International Conference on Computer-AidedArchitectural Design Research in Asia (CAADRIA 2017)*, 685-694.

Ester, M., Kriegel, H.P.a. and Xu, X.: 1996, A density-based algorithm for discovering clusters inlarge spatial databases with noise, *Proceedings of the Second International Conference onKnowledge Discovery and Data Mining (KDD-96)*, 226-231.

Fakhreddine, A. and Tippenhauer, N.O.a.: 2018, Design and Large-Scale Evaluation of WiFi ProximityMetrics, *European Wireless 2018; 24th European WirelessConference*, 1-6.

Gonz'alez, M.C. and Hidalgo, C.A.a.: 2008, Understanding individual human mobility patterns, *Nature*, **453**(7196), 779.

Happle, G., Wilhelm, E. and Schlueter, A.: 2017, Determining air-conditioning usage patterns in Singapore from distributed, portable sensors, *Energy Procedia*, **122**, 313-318.

Huang, W., Lin, Y. and Wu, M.: 2017, Spatial-Temporal Behavior Analysis Using Big DataAcquired by Wi-Fi Indoor Positioning System, *Protocols, Flows, and Glitches: Proceedings of the22nd International Conference on Computer-AidedArchitectural Design Research in Asia (CAADRIA 2017)*, 745-754.

Jiang, S. and Ferreira, J.a.: 2017, Activity-based human mobility patterns inferred frommobile phone data: A case study of Singapore, *IEEE Transactions on Big Data*, **3**(2), 208-219.

Joubert, J.W. and Meintjes, S.: 2015, Repeatability \& reproducibility: Implications ofusing GPS data for freight activity chains, *Transportation Research Part B: Methodological*, **76**, 81-92.

Liao, L., Patterson, D.J. and Fox, D.a.: 2007, Learning and inferring transportation routines, *Artificial Intelligence*, **171**(5-6), 311-331.

Monnot, B., Wilhelm, E.a., Zhou, Y.a., Lu, H.Y. and Jin, W.: 2016, Inferring Activities and Optimal Trips: Lessons FromSingapore's National Science Experiment, *Complex Systems Design \& Management Asia*, Cham, 247-264.

Montini, L., Rieser-Sch"ussler, N.a. and Axhausen, K.W.: 2014, Trip purpose identification from GPS tracks, *Transportation Research Record*, **2405**(1), 16-23.

Pedregosa, F., Varoquaux, G., Gramfort, A.a., Thirion, B., Grisel, O.a., Prettenhofer, P., Weiss, R.a., Vanderplas, J., Passos, A.a., Brucher, M. and Perrot, M.a.: 2011, Scikit-learn: Machine Learning in Python, *Journal of Machine Learning Research*, **12**, 2825-2830.

Pinjari, A.R. and Bhat, C.R. 2011, Activity-based travel demand analysis, *in* R.L. Andr'e de Palma (ed.), *A Handbook of Transport Economics*, Edward Elgar Publishing, 1-36.

Schuessler, N. and Axhausen, K.: 2009, Processing raw data from global positioning systemswithout additional information, *Transportation Research Record: Journal of theTransportation Research Board*, **2105**, 28-36.

Tan, S.B., Zegras, P.C.a. and Arcaya, M.C.: 2018, Evaluating the effects of active morning commutes onstudents' overall daily walking activity inSingapore: Do walkers walk more?, *Journal of Transport \& Health*, **8**, 220-243.

Tuncer, B., Benita, F. and Tay, H.: 2017, Identification of building floors in a 3D citymodel, *Smart Cities: Improving Quality of Life Using ICT \&IoT (HONET-ICT), 2017 14th International Conferenceon*, 16-20.

Vieira, M.R., Frias-Martinez, V.a. and Frias-Martinez, E.: 2010, Characterizing dense urban areas from mobilephone-call data: Discovery and social dynamics, *2010 IEEE Second International Conference on SocialComputing (SocialCom)*, 241-248.

Wilhelm, E., MacKenzie, D., Zhou, Y.a. and Tippenhauer, N.O.: 2017, Evaluation of transport mode using wearable sensordata from thousands of students, *Proceedings of Annual Meeting of the TransportationResearch Board (TRB)*, 1-18.

Wilhelm, E., Siby, S., Zhou, Y.a., Jayasuriya, M.a., Kee, J.a. and Tippenhauer, N.O.: 2016, Wearable environmental sensors and infrastructure formobile large-scale urban deployment, *IEEE Sensors Journal*, **16**(22), 8111-8123.

Zheng, Y.: 2015, Trajectory data mining: an overview, *ACM Transactions on Intelligent Systems andTechnology (TIST)*, **6**(3), 29.

IDENTIFYING THE LANDSCAPE OF MACHINE LEARNING-AIDED ARCHITECTURAL DESIGN

A Term Clustering and Scientometrics Study

TANIA PAPASOTIRIOU
[1]*School of Architecture and Built Environment, Faculty of Engineering and Built Environment, The University of Newcastle (UON)*
[1]*Soultana.papasotiriou@uon.edu.au*

Abstract. Recent advances in Machine Learning and Deep Learning revolutionise many industry disciplines and underpin new ways of problem-solving. This paradigm shift hasn't left Architecture unaffected. To investigate the impact on architectural design, this study utilises two approaches. First, a text mining method for content analysis is employed, to perform a robust review of the field's literature. This allows identifying and discussing current trends and possible future directions of this research domain in a systematic manner. Second, a Scientometrics study based on bibliometric reviews is employed to obtain quantitative measures of the global research activity in the described domain. Insights on research trends and identification of the most influential networks in this dataset were acquired by analysing terms co-occurrence, scientific collaborations, geographic distribution, and co-citation analysis. The paper concludes with a discussion on the limitations, opportunities and future research directions in the field of Machine Learning-aided architectural design.

Keywords. Machine Learning; Text mining; Scientometrics.

1. Introduction

An increasing number of architects is seeking proof that their designs will meet future expectations via quantitative, data-intense methods, which are necessary to understand in depth the increasing complexity of contemporary designs. It has already been argued that there are more data available to us than we need (Carpo, 2017), and the primary challenge is to convert generated or retrieved data into meaningful information.

New strategies for data collection and processing and, most importantly, new techniques for understanding and automatically extracting information are necessary to overcome the limitations of traditional parametric design approaches. The advocators of parametricism argue that increasing the number of design parameters will allow linking all kinds of information, towards more automated design processes. However parametric models are rule-based models that allow

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 815-824. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

for the coding of human reasoning, and require intervention from an analyst able to observe the steps of every condition of intelligent behaviour; therefore, large workflows of human flux cannot be fully automated(Andia, 2013). The computer science community as early as in the 1960's "abandoned" systems that had a structure directly related to the designer and not the task, and focused on artificial intelligence (Winograd, Flores, & Flores, 1986)

An efficient and cost-effective automatic technique employed when manual programming is failing to perform is Machine Learning (L'heureux, Grolinger, Elyamany, & Capretz, 2017). It is a computer-based approach imitating human cognitive abilities for problem-solving, and one of - if not the -main applications of artificial intelligence (Fogg, 2018) that is extensively used in computer science, and many other fields. Machine Learning algorithms are trained by identifying patterns in data and build probabilistic or predictive models that can perform specific tasks, by generalising from examples. However, the fundamental goal of learning algorithms is to go beyond generalisation of training sets, because it is extremely unlikely to meet the exact same data set again(Le, 2018). When overpassing dependencies on initial input data and parameters, including singularities, algorithms develop the capacity to perform out of idealized set-ups. Moreover, learning models allow identifying patterns from data and important aspects relevant to interactions between systems, between the environment and its inhabitants, as well as between disciplines, through observing recursive events.

In order to identify research trends and measure global research activity in the field of Machine Learning-aided architectural design, Scientometrics (Nalimov & Mul□chenko, 1971) is employed in this study to quantify research trends and impact via measuring citations, mapping scientific fields, and using indicators in research policy and management (Mingers & Leydesdorff, 2015)A bibliometric review based on bibliographic coupling and co-citation analysis is also used to provide a coherent overview of theoretical cornerstones along with recent research trends and uncover hidden links between the two distinct areas of study at hand.

The remaining of this paper is organized as follows: Section II describes the methodology that was used for data extraction and presents the structure of the selected dataset. Section III is comprising two parts. First, a co-occurrence analysis reveals the main areas of focus within the research area and second, a Scientometrics study identifies and describes networks and connections; as well as citation, bibliographic coupling, co-citation, and co-authorship relations. The mentioned tasks are performed and visualized with the help of VOSviewer (N. van Eck & Waltman, 2009) Finally, Section IV aggregates the findings and discusses limitations of the current study as well as future research directions.

2. Dataset

The Scopus database was last accessed on 20/11/18 to build the required dataset. A two-stage search was performed to collect the sought data. First, publications containing terms relevant to computer-aided architectural design and architectural terminology were retrieved. This resulted in 11,573 documents, published between 1970 and 2019. Within those results, 4,038 documents referred to

machine learning processes, while it is worth noting that 330 of them were published as open access. In order to separate these documents, the following database query was used: (((ALL ("computer-aided architectural design" OR "architectural design" OR "algorithmic design" OR "algorithmic architecture") AND ALL ("build environment" OR "urban environment" OR "urban space" OR "design process" OR "design cognition" OR landscape OR geometry OR form OR "form finding")))) AND ("machine learning" OR "deep learning" OR "neural networks" OR "supervised learning" OR "unsupervised learning" OR "artificial intelligence")

Figure 1 presents the distribution of the retrieved publications per year. Notice that there is an exponential increase in the number of publications since early 2000s. Most papers appeared on 2017 (400, 9.91%), followed by 2016 and 2018 when 8.79% and 8.77% of total papers were published respectively. The number of total scientific publications in the field almost doubled in 2008 (from 143 to 277) due to the large number of papers (78) appearing in the 2007 Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007. However, a clear decline in the number of publications followed the next three years between 2008-2011. This could be attributed to lack of funding due to the global financial crisis, as the specific research field requires access to costly computational sources. The distribution of findings per subject area suggests that 35,35% of the publications were published by authors whose main area was computer science, followed by engineering (27,12%). This is due to the interdisciplinary nature of the topic and was taken into account in the analysis that follows.

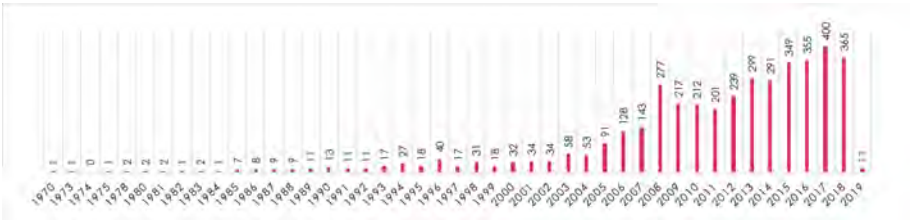


Figure 1. Distribution of publications on Machine Learning in Architectural Design per year.

3. Analysis

The first part of the analysis focuses on exploring in depth the topics of interest, with the aid of VOSviewer. This comprises a term co-occurrence analysis of title and abstract contents, to pinpoint key research areas and their evolution over time. The second part of the analysis deals with developing keyword co-occurrence, co-authorship, and co-citation density maps, to provide a visual representation of networks, collaboration, and future directions.

3.1. TERM CO-OCCURRENCE

In order to gain insights on trends in the dataset, and due to the interdisciplinary nature of this area of research, a term co-occurrence analysis was performed. This approach is a novel text mining method for content analysis, which allows identifying main topics and trends in key research areas, and their evolution over time (Demeter, Szász, & Kő, 2018). The dataset, including title and abstracts of each publication, was exported in .csv format and imported to VOSviewer for further processing, noting that VOSviewer does not include keywords in terms co-occurrence analysis. Specifically, the automatic text mining option is used via incorporating part-of-speech tagging (i.e., identification of verbs, nouns, adjectives, etc.) and applying a linguistic filter. In simpler words, the software identifies noun phrases (i.e. words or word sequences that consist exclusively of nouns, or adjectives followed by a noun) and creates an extensive list of terms that potentially describe the research topics of the field(N. J. Van Eck & Waltman, 2011). The default threshold of occurrences was increased in this study from 10 to 20 to limit results to more relevant information (i.e. selected terms must occur at least 20 times in the relevant documents to be further considered). In the 4038 publications that were analysed 66011 terms were identified, and 958 met the above criteria. A "full counting" method, where the occurrences metric corresponds to the total number of occurrences of a term in all documents, provides a complete list, preventing missing important information; as equal weighting is assigned to terms with different frequency of occurrence.

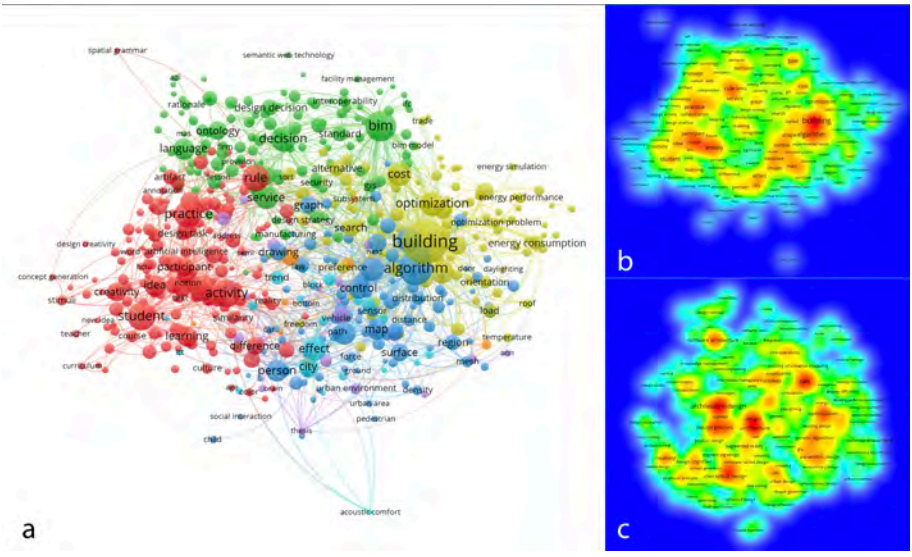


Figure 2. a. Distance-based term map. b. Density map of term co-occurrence c. Density map of keywords co-occurrences identified from authors .

A distance-based term map (Fig.2.a) was created from the final term set and was used to identify clusters of related items. The distance between any two items

reflects the strength of the relation between them (N. van Eck & Waltman, 2009). VOSviewer calculates a relevance score for each noun phrase. A low relevance score indicates a random pattern in co-occurrences with other noun phrases and a high relevance score suggests that the terms co-occur mainly with a limited set of other noun phrases((N. J. Van Eck & Waltman, 2014).

Based on relevance scores 575 terms (60%) were selected. Seven term clusters were identified (Waltman, Van Eck, & Noyons, 2010)and the most frequently appearing terms in these clusters are listed in Table 1. The terms that identified and clustered via this procedure are the potential descriptors of certain subject areas and provide the designated labels. Moreover, the weighted average age in Table 1 corresponds to the date when the specific collection of keywords emerged as a standalone cluster and provides an indication of research trends. Interestingly, education appears to be one of the earlier areas where Machine Learning invaded architectural research.

A density map (Fig.2.b) can be used to depict the occurrences of terms that frequently appear together in the same or in relevant publications. Thus, the most important terms with relatively higher relevance scores (red areas) form the center of main clusters, which are encircled by yellow, green, cyan and blue areas, corresponding to lower scores. This process resulted in the formation of two major group of clusters (Fig. 2). Terms like building (frequency: N = (1330), algorithm (N=741), control (N=271), map (N=266), city (N=271), are located in the “hot” areas and form the first group, while for the second group a more fragmented shape is formed by terms like activity (N=503), practice (N=472), rule (N=461). In areas of smaller density, we can find terms like BIM (N=634) and cost (N=363).

3.2. BIBLIOGRAPHIC MAPPING

Next, the dataset was used for bibliographic mapping in VOSviewer. The first part of the analysis was based on the co-occurrence of keywords that were used by the authors to describe their publications, again in “full counting” (see above). After a series of pilot runs, it was found that setting the number of occurrences to 8 provided optimal (i.e. less fragmented) results. As such, out of the 8651 keywords, 181 were found to meet the criteria and were selected for further processing. In the resulting density map (Fig.2.c) one can observe that more groups appeared around terms like architectural design, design process, design, architecture, BIM, conceptual design, optimization. These terms are frequently used in computer science and other disciplines, and that fact weakens the use of keywords for the identification of relevant publications.

Next, a citation analysis was performed to identify the most influential dissemination forums in the field. Out of 1618 sources 120 had published more than 5 documents in this field. The top 10 based on the total link strength (which is related to the number of commonly cited references appearing in these sources) are presented in (Table 2).

Table 1. Cluster labeling for areas within the architectural realm that Machine Learning processes were explored in the literature.

Cluster number / colour	Cluster label	Most frequent terms	Total number of terms	Weighted average age
1 / Red	Inventory of architectural education	Student, activity, practice, rule, theory, idea, learning, reasoning, creativity, participant	178	2010.71
2 / Green	Inventory of information flow	BIM, decision, service, language, industry, ontology, design, decision, standard, software architecture, decision making	121	2011.96
3 / Blue	Inventory of modelling processes	Algorithm, geometry, shape, image, person, control, map, layout, surface, accuracy	111	2012.47
4 / Yellow	Inventory of sustainability	Building, optimization, cost Parameter, genetic algorithm, building design, search, energy, alternative, energy consumption	110	2013.04
5 / Purple	Inventory of research	Database, practitioner, measurement, proposal, output, urban environment, motivation, discovery, evolutionary, algorithm, hardware, artificial neural network	26	2011.83
6 / Cyan	Inventory of urban planning	Effect, city, influence Trend, landscape, participation, market, block, strength, plant, urban planning	20	2013.13
7 / Orange	Inventory of feasibility	Survey, intelligence, feasibility, office, building, subsystem, absence, efficacy, premise, empirical evidence	9	2010.92

Table 2. Most influential forums in the field of Machine Learning aided Architectural Design.

Source Title	Total ling strength	Citations
Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)	16070	1531
Design Studies	15660	3384
Automation in Construction	11423	3342
Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics)	7944	2166
Advanced engineering informatics	6200	1370
Energy and buildings	5111	924
Computer aided design	5010	1413
Renewable and sustainable energy reviews	4714	814
Communications in computer and information science	4241	74
Proceedings of the ASME design engineering technical conference	4007	139

Analysis of results of scientific collaboration data from countries over 49 years suggests that 9 clusters correspond to established collaborations between groups

in different countries (Table 3) with United States, United Kingdom, Canada, Germany, Australia, and China appearing as the countries that have attracted the largest number of citations. Furthermore, the study revealed 64 collaboration clusters between Universities, with only 5 of these clusters forming a network with more than of 3 institutes (Table 4) With the School of Mechanical Engineering from Purdue University, United States with 390 citations emerging as more influential among them followed from University of California, Berkeley with 326 citations.

Table 3. Clusters of scientific collaboration between countries.

C1	Canada, Italy, Belgium, Greece, Israel, Finland, Portugal, New Zealand, Poland, Romania, Cyprus, Russian, Federation
C2	Singapore, Spain, Brazil, Sweden, Mexico, Argentina, Norway, Chile, Luxembourg, Colombia
C3	Denmark, Austria, India, Ireland, Malaysia, Slovenia, Saudi Arabia, Serbia, Indonesia, Croatia
C4	Australia, China, Hong Kong, South Korea, Taiwan, Thailand, Pakistan
C5	Germany, France, Venezuela, Czech Republic, Algeria
C6	United States, Iran, Egypt, Lithuania
C7	Netherlands, Japan, Turkey, Hungary
C8	United Arab Emirates, South Africa
C9	United Kingdom, Sri Lanka

Table 4. Clusters of scientific collaboration between institutions.

I1	Kyung Hee University, South Korea; New York University, United States; University of Newcastle, Australia; Curtin University, Australia; University of Sydney, Australia;
I2	Carnegie Mellon University, United States; Georgia Institute of Technology, United States; University of California, Berkeley, United States; University of Michigan, United States;
I3	Delft University of Technology, Netherlands; Department of Computer Science, University of Toronto, Canada; Eindhoven University of Technology, Netherlands; University of Toronto, Canada;
I4	Aristotle university of Thessaloniki, Greece; Massachusetts Institute of Technology, United States; Singapore University of Technology and Design;
I5	Kaist, South Korea; Open University, United Kingdom; University of Strathclyde, United Kingdom;

4. Discussion

4.1. MAIN FINDINGS

The most important findings from the analysis of the dataset can be summarised into the following:

- There is an exponential increase in the number of publications in the field

since the early 2000's, which the maximum number of publications being 400 in 2017. Certainly, there is no indication of saturation of the particular field, which continues to attract an ever-increasing number of researchers.

- The main areas of research within the field can be described by 7 clusters/inventories: Architectural education, Information flow, Modelling processes, Sustainability, Research, Urban planning, Feasibility. The breadth of these clusters is indicative of the interdisciplinary nature of the topic, which spans across practically all fields of Architecture. It is interesting though to mention that education appears to attract considerable interest, which underlines the momentum of Machine Learning, and its future role in architectural design.
- United States of America is the world leader in the area and serve as a pivotal node that connects a large cluster of researchers from 58 countries.
- A shift towards sustainability and urban planning is noticeable is research trends, which is in line with developments in other sciences.
- Implementation of Machine Learning procedures requires costly computational power, and declines in funding may affect advances in the field.

4.2. LIMITATIONS AND CHALLENGES

Two main challenges were faced during this study. The first one is the potential omission of relevant publications, after the fine-tuning of the search query. The initial search query (computer-aided architectural design; architectural design; algorithmic design; algorithmic architecture) resulted in 62,573 publications. Search within those results with the addition of machine learning, artificial intelligence, and neural networks reduced the number to 11,144 documents (SEARCH A, Fig. 3). The common use of key phrases among different disciplines resulted in the inclusion in the dataset of a large number of publications with very low to no relevance. That can be explained if we consider that most of the publications (7,902) originated from computer science, where terms like architecture, design, architectural design, computer-aided design are used to describe software engineering concepts. Therefore, additional key phrases relevant to build environment, urban environment, urban space, design process, design cognition, landscape, geometry, form, and form-finding i.e. more common in Architecture, were included to the query in order to limit the results to the most relevant ones. Moreover, to minimise the loss of important and relevant studies deep learning, supervised learning, unsupervised learning added to the search within the results (SEARCH B, Fig. 3). Still, it must be stated that mining of relevant publications is not a fully robust procedure.

The second limitation is relevant to the text analysis algorithms used. VOSviewer provides information regarding the structure of a field through algorithms based on distribution or frequency of terms. However, such algorithms cannot consider the contextual meaning of words e.g. Architecture as discipline and architecture as structure of a processor. Moreover, the software offers limited customisation options for term selection and clustering. Nevertheless, the use of a wide variety of terms to customise the research query prevented omitting results

with significant impact.

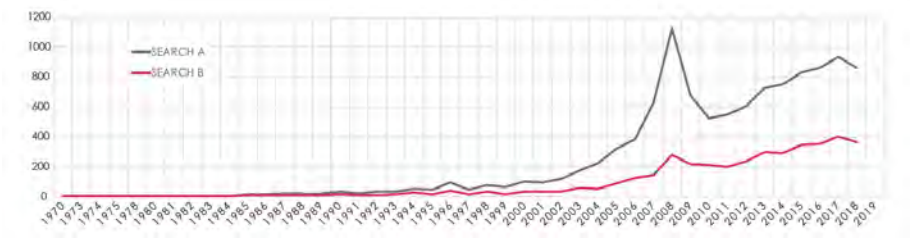


Figure 3. Comparison between search queries.

4.3. CONCLUDING REMARKS

The study presented in this paper is the first, to the authors' knowledge, attempt to provide a coherent and comprehensive overview of advances over the past 50 years in the field of Machine Learning-aided architectural design and, through a text mining technique, cluster and classify the main areas of research focus in this interdisciplinary field. In addition, a Scientometrics study was employed to shed some light on the most influential sources, formed collaborative networks and significant institutions operating in the field.

It was found that this field is experiencing exponential growth since the 2000's, perhaps triggered by easy access to ample computational power and massive labelled datasets, which revolutionise the fields of Machine and Deep learning. Since the 2012 breakthrough (Beam, 2017), the field moves fast, and new developments perhaps become obsolete in a timescale of months. It is important to note that Machine Learning has infiltrated architectural education, suggesting a bold move from research to practice in the near future. It is therefore important to incorporate in a future update of this study resources from non-traditional research dissemination platforms, such as online learning platforms, open repositories and social media, in order to evaluate how deep learning technologies will shape Architecture in the years to come. Definition of a robust set of sampling criteria compatible with such information sources is challenging, and part of ongoing research in the field.

References

Andia, A.: 2013, Automated Architecture: Why CAD, Parametrics and Fabrication are Really Old News, *Blucher Design Proceedings*.

Beam, A.: 2017, "github.io" . Available from <https://beamandrew.github.io/deeplearning/2017/02/23/deep_learning_101_part1.html> (accessed 3/12/2018).

Carpo, M.: 2017, *The Second Digital Turn: Design Beyond Intelligence*, MIT Press.

Demeter, K., Szász, L. and Kő, A.: 2018, A text mining based overview of inventory research in the ISIR special issues 1994–2016, *International Journal of Production Economics*, **in press** , in press .

Van Eck, N.J. and Waltman, L.: 2009, Software survey: VOSviewer, a computer program for bibliometric mapping, *Scientometrics*, **84**, 2.

Van Eck, N.J. and Waltman, L.: 2011, Text mining and visualization using VOSviewer, *arXiv*,

preprint(1109.2058), arXiv.
Van Eck, N.J. and Waltman, L. 2014, Visualizing bibliometric networks, *in* Y. Ding, R. Rousseau and D. Wolfram (eds.), *Measuring scholarly impact*, Springer, 285-320.
Fogg, A.: 2018, "import.io" . Available from <https://www.import.io/post/history-of-deep-learning/> (accessed 2/12/2018).
Le, J.: 2018, "A Medium Corporation" . Available from <https://medium.com/cracking-the-data-science-interview/12-useful-things-to-know-about-machine-learning-c599be92c98d> (accessed 10/11/2018).
L'heureux, A., Grolinger, K., Elyamany, H. and Capretz, M.: 2017, Machine learning with big data: Challenges and approaches, *IEEE Access*, **5**, 777-797.
Mingers, J. and Leydesdorff, L.: 2015, A review of theory and practice in scientometrics, *European Journal of Operational Research*, **246 issue 1**, 1-19.
Nalimov, V. V. and Mulchenko, Z. M.: 1971, *Measurement of Science. Study of the Development of Science as an Information Process,*, FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON AFB, OHIO.
Waltman, L., Van Eck, N.J. and Noyons, E.C.M.: 2010, A unified approach to mapping and clustering of bibliometric networks, *Journal of Informetrics*, **4**, 629-635.
Winograd, T., Flores, F. and Flores, F. F.: 1986, *Understanding computers and cognition: A new foundation for design*, Intellect Books.

Index of Authors

A

Aghaei Meibodi, Mania 1-133
Ahrens, Chandler 1-433
Alva, Pradeep 2-11
van Ameijde, Jeroen 2-241
Amorim, Pedro 2-421
Anderson, T. N. 1-705
Asher, Rob 1-775

B

Bai, Nan 2-41
Bamborough, Chris 2-343
Banon, Carlos 1-113
Barnstorff, Adam 1-433
Beattie, Hamish 1-737
Beaudry Marchand, Emmanuel 2-141
Behmanesh, Hossein 2-211
Bekele, Mafkereseb Kassahun 2-675
Belém, Catarina 1-685
Bernhard, Mathias 1-123
Beza, Beau B. 2-737
Binder, Alexander 1-805
Bogosian, Biayna 1-573
Boonstra, Sjonnie 1-205
Borunda, Luis 2-333
Boudhraâ, Sana 2-141
Bouffanais, Roland 2-805
Boychenko, Kristina 2-381
Brandao, Filipe JS 2-101
Bratoev, Ivan 1-583
Brell-Cokcan, Sigrid 1-163
Brisbin, Chris 1-361
Brown, André G.P. 2-211
Brown, Daniel 1-737
Burry, Jane 1-715
Butler, Andrew 1-775
Byrne, Daragh 2-333

C

Caetano, Inês 1-645
Cai, Chenyi 1-291
Calixto, Victor 2-685
Camacho, Daniel 1-563
del Campo, Matias 2-767
Cao, Rui 2-623
Castelo-Branco, Renata 1-655
Celani, Gabriela 2-685
Cha, Shao-Yu 2-121
Chai, Hua 1-183
Chamberlain, Roger 1-433
Champion, Erik 2-675, 2-695
Chan, Zion 1-23
Chang, Jiahui 1-515
Chang, Teng-Wen 2-91
Chang, Zhuming 1-245
Cheddadi, Mohammed Aqil 2-181
Chen, Kian Wee 2-665
Chen, Zhewen 1-143, 2-451
Cheng, Bingyu 1-301
Cheng, Chi-Li 1-193
Chernyavsky, Michael 1-371
Choi, Minkyu 1-695, 1-767
Chung, Wang Leung Thomas 2-313
Claessens, Dennis 1-205
Clemenson, Dane 1-573
Cochran Hameen, Erica 1-785
Cristie, Verina 2-491
Crolla, Kristof 1-23, 1-93, 2-481
Cui, Weiwen 2-561

D

Dai, Rushi 1-163
Darweesh, Barrak 2-253
Davidová, Marie 2-151
Deng, Nachuan 1-301
Deniz Kiraz, Leyla 1-215
Dias-da-Costa, Daniel 2-401
Dillenburger, Benjamin 1-123, 1-133
Dillon, Brittney 2-571
Dobbs, Tiara 1-475, 1-563, 2-643
Doherty, Ben 2-653
Donn, Michael 1-815
Dorta, Tomás 2-141
Dounas, Theodoros 2-293
Dritsas, Stylianos 1-13, 2-263, 2-323
Duarte, Jose 2-391
Dwi Pranata Putra, Bima 2-161

Dwivedi, Urvashi 1-245

E

Engholt, Jon 1-53

F

Fabbri, Alessandra 1-371, 1-475, 1-563, 2-603, 2-653, 2-795
Fernandez, Javier G. 2-263, 2-441
Ficca, Jeremy 2-333
Finch, Gerard 1-153
Fingrut, Adam 1-93
Fischer, Thomas 2-541, 2-551
Fitriawijaya, Adam 2-411
Forren, James 2-705
Freitas, José 1-173
Fujii, Haruyuki 1-463
Fukuda, Tomohiro 1-423, 2-71, 2-623

G

G. Belém, Catarina 1-453
Gao, Weizhe 1-73
Gao, Yuan 1-83
Gardner, Nicole 1-371, 1-475, 1-563, 1-775, 2-603, 2-653, 2-795
Gaudilliere, Nadja 2-581
Gelbard, Joshua 1-433
Giesecke, Rena 1-133
Gjerde, Morten 1-153
Globa, Anastasia 2-737
Gomes, M. Glória 1-685
Grau, Michael 2-551
Green, Stephen 2-603
Grewal, Neil 2-571
Gu, Mengjie 1-331
Gu, Ning 1-321, 1-361, 2-685
Gu, Zhuoxing 1-225
Guo, Zhe 1-63
Gupta, Sachin Sean 2-441
Gursoy, Benay 2-391

H

Ha, Gloria 2-431
Hack, Norman 2-363
Haeusler, M. Hank 1-371, 1-475, 1-563, 1-775, 2-31, 2-603, 2-653, 2-795
Hahm, Soomeen 1-553
Haiqing, Li 1-665
Halim, Samuel 2-263
Han, Dongchen 2-561
Han, Li 1-183
Han, Yunsong 2-613
Hannouch, Adam 1-403
Hasler, Stephanie 2-747
He, Peijun 2-747
Herr, Christiane M. 2-541, 2-551
Herthogs, Pieter 2-747
Hirasawa, Gakuhito 2-501
Hirschberg, Urs 2-757
Ho, Samuel Yu De 1-13
Hofmeyer, Hèrm 1-205
Holohan, Donn 1-103
Holth, James 2-373
Holzer, Dominik 2-715
Hong, Sukjoo 1-245
Hotta, Akito 1-281
Hotta, Kensuke 1-281, 1-341, 2-181
Hou, June-Hao 1-193
Houda, Maryam 2-401
Hramyka, Alina 2-571
Hsin-Hsuan, Tsai 2-411
Hsu, Pei-Hsien 1-311
Huang, Chenyu 2-633
Huang, Jeffrey 2-421
Huang, Jie 2-561
Huang, Weixin 1-301, 2-231
Huangfu, Wenzhi 2-313
Hyejin, Park 1-747
Hyeongmo, Gu 1-747

I

Ikeda, Yasushi 1-281, 1-341, 2-181
Ilha Pereira, Bianca 2-51
Imani, Marzieh 1-815
Indraprastha, Aswin 2-161
Inhan, Kim 1-747

J
Janssen, Patrick 1-383, 2-11, 2-593, 2-665
Jayashankar, Dhileep Kumar 2-441
Jeng, Tay-Sheng 2-121
Ji, Guohua 1-383, 2-593
Jiaxin, Zhang 1-665
Jin, Jinxi 1-63, 1-73, 1-183
Jin, Mingyu 2-471
Johan, Ryan 1-371
Johns, Ryan Luke 1-33
Joyce, Sam Condrad 2-491

K
Kado, Keita 2-501
Karoji, Gen 1-281
Kasseb, Zeynab 1-255
Kato, Yuri 2-81
Keisen, U 1-463
Kerber, Ethan 1-163
Khean, Nariddh 2-795
Khoo, Chin Koi 2-131
Kim, Jinsung 1-795, 2-785
Kim, Meereh 1-695, 1-767
Kindon, Sara 1-737
King, Geoff 2-603
Kladeftira, Marirena 1-123
Kloft, Harald 2-363
Knecht, Katja 2-221
Kobayashi, Yuki 1-463
Kocaturk, Tuba 1-215
Koenig, Reinhard 2-221
Koh, Immanuel 2-421
Konieva, Kateryna 2-221
Koosha, Rasool 1-615
Krishnamurti, Ramesh 2-333
Kummamuru, Bhargava Ram 1-443

L
Lacroix, Igor 1-635
Ladron de Guevara, Manuel 2-333
Lai, Po Yan 1-695
Lange, Christian 1-103
Lau, Darwin 1-93
Lee, Chae-Seok 1-695
Lee, Heewon 2-253
Lee, Hyunsoo 1-351
Lee, Jaejong 1-341
Lee, Ji-Hyun 1-245, 1-695, 1-767
Lee, Jin-Kook 1-795, 2-785
Lee, Jisun 1-351
Lee, Tat Lin 1-43
Leggett, David 2-521
Leitão, António 1-173, 1-453, 1-645, 1-655, 1-685
Lertsithichai, Surapong 2-353
Leung, Emily 1-775
Li, Biao 1-263, 1-291, 1-625
Li, Xintian 1-331
Li, Yunqin 1-271
Liang, Jing 1-725
Liao, Pan 1-361
Lie, T. T. 1-705
Lin, Xuhui 1-413
Lin, Yuqiong 2-633
Lindemann, Hendrik 2-363
Liu, Jie 1-515
Liu, Quan 1-331
Lo, Tian Tian 1-545
Loh, Paul 2-521
Lombardi, Davide 2-293
Loonen, Roel 1-685
Lopez Rodriguez, Alvaro 1-553
Low, Rebekah 2-323
Lu, Siliang 1-785
Luo, Chuanwen 2-471
Luo, Dan 1-83
Luo, Lin 1-725
Luo, Youyuan 1-73

M
Ma, Chenlong 1-675
Ma, Hongtao 1-515
Maciel, Abel 1-553
Macken, Marian 1-505
Madden, David 2-795
Makki, Mohammad 2-571
Manninger, Sandra 2-767
Mao, Ming 1-331
Marriage, Guy 1-153

Marschall, Max 1-715
Martinho, Helena 1-685
Matsubayashi, Michio 2-21
Matsukawa, Shohei 2-81
McGinley, Tim 1-321
McMeel, Dermott 2-61
Meekings, Scott 2-373
Mitchell, Scott 1-433
Moleta, Tane Jacob 1-485, 1-525, 1-535, 2-373, 2-727
Motamedi, Ali 2-191
Mulla, Sarosh 1-505
Müller, Johannes 2-747
Mun, Kristine 1-573
Muslimin, Rizal 1-413, 2-431

N

Nam, Hyunjae 2-273
Nandavar, Anirudh 1-595
Natephra, Worawan 2-191
Ng, Jennifer Mei Yee 2-795
Ng, Jonathan Ming-En 1-13
Ng, Truman Wei Cheng 1-13
Nguyen, Binh Vinh Duc 1-235
Nguyen, Duong 1-485

O

Ochoa Paniagua, Jorge 1-321

P

Pachi, Maria 1-123
Paio, Alexandra 2-101
Pan, Yongjie 2-613
Pang, Yun Jie 2-323
Paoletti, Ingrid 1-443
Papanikolaou, Dimitris 2-511
Papasotiriou, Tania 2-815
Park, Hyoung-June 2-303
Paterson, Aaron 1-505
Pelosi, Antony 1-153
Peng, Chengzhi 1-235
Petzold, Frank 1-583, 1-595
Pigram, Dave 1-53
Pokhrel, M. K. 1-705
Porcellini, Valentin 1-245, 1-695
Poustinchi, Ebrahim 2-531
Prohasky, Daniel 2-521
Pung, Derek 2-665

Q

Qian, Kaijie 1-495
Qureshi, Cyrus 1-525

R

Rahaman, Hafizur 2-695
Ramos, Cristina 1-475
Raspall, Felix 1-113, 2-283
Ratchakitprakarn, Pheeraphat 2-323
Rofe, Matthew 1-361
Rogers, Jessie 2-727
Rosenberg, Daniel 2-171

S

Safin, Stéphane 2-141
Sammer, Maria 1-645
Sanandiya, Naresh 2-263
Sanandiya, Naresh D 2-441
Sanche, Marianne 2-767
Sandstrom, Alice 2-303
Santos, Guilherme 1-655
Sayah, Iman 1-815, 2-773
Schnabel, Marc Aurel 1-485, 1-525, 1-535, 2-373, 2-727, 2-773
Schubert, Gerhard 1-583, 1-595
Schumann, Kyle 1-33
Scott, Sophie 2-653
Seungyeon, Choo 1-747
Shahsavari, Fatemeh 1-615
Shammas, Demetris 1-123
Sheldon, Aron 1-475
Shi, Jie 1-785
Shi, Xing 1-757
Silva, Daniela 2-463
Silva, Lilian 1-635
Silva, Neander 1-635
Sivam, Alpana 1-321
Soh, Jia Ying 1-13
Soltani, Sahar 1-321, 1-361
Song, Jaeyeol 1-795, 2-785
Steenblik, Ralph Spencer 2-111
Stouffs, Rudi 1-605, 2-11
Strelchenko, Vadym 1-583
Su, Junbang 1-73

Subramanian, Ramanathan 1-805
Sumitiomo, Eri 1-553
Sun, Cheng 2-613

T

Tan, Ying Yi 1-43
Tang, Peng 1-291, 1-757
Tauscher, Helga 1-605
Tay, Jenn Chong 1-113
Taysheng, jeng 2-411
Teo, Elizabeth 2-323
Teo, Ryan 2-263
Tomarchio, Ludovica 2-747
Tong, Hanshuang 2-231
Tracy, Kenneth 2-441
Tsamis, Alexandros 2-171
Tuncer, Bige 1-805, 2-805
Tunçer, Bige 2-747
Tung, Hong-Cing 1-311

V

Vale, Brenda 1-815
Vazquez, Elena 2-391
Vijay, Yadunund 2-263
de Vries, Bauke 1-205

W

Wang, Brandon 1-535
Wang, Chunxing 2-613
Wang, Leetee 2-767
WANG, Likai 1-383
Wang, Likai 2-593
Wang, Lu 2-41
Wang, Rui 2-737
Wang, Shihan 1-785
Wang, Sihan 2-283
Wang, Sining 2-481
Wang, Tsung-Hsien 1-235
Wang, Will 2-111
Wang, Xiang 1-63, 1-73, 1-143
Wang, Xiao 1-757
Wee, H. Koon 2-131
White, Michael 2-31
Willemse, Elias Jakobus 2-805
Woojun, Lee 1-747
Wu, Yi-Sin 2-91

X

Xia, Ye 1-73
Xiang, Ke 1-675
Xiao, ZuoPeng 1-545
Xie, Yu 2-323
Xu, Jianan 1-263, 1-625
Xu, Qingqing 1-515
Xu, Weiguo 1-83, 1-515
Xueqiang, Wang 1-665
Xuereb Conti, Zack 2-283

Y

Yabuki, Nobuyoshi 1-423, 2-71, 2-623
Yan, Liang 1-423
Yan, Wei 1-615
Yang, Chunxia 1-225
Yang, Li 2-253
Yang, Lijing 1-301
Yao, Jiawei 2-633
Yao, Ziying 1-225
Yap, Sarah 2-431
Ye, Qingfeng 1-331
Yi, Taeha 1-695, 1-767
Yin, Lu 2-471
Youssef, Elie 1-595
Yu, Chuanfei 1-271
Yu, Henry 1-545
Yuan, Philip F. 1-63, 1-73, 1-143, 1-183, 1-255, 1-393, 2-451, 2-633
Yunqin, Li 1-665

Z

Zarzycki, Andrzej 2-201
Zavoleas, Yannis 1-371, 1-475, 1-563, 2-31, 2-603, 2-795
Zhang, Hong 2-561
Zhang, Jiaxin 1-271
Zhang, Liming 1-143, 2-451
Zhang, Runzhou 2-231
Zhang, Ruocheng 2-231
Zhang, Xiao 1-63, 1-73, 1-183
Zhao, Bing 1-255
Zhao, Tianyu 2-613

Zhao, Yao 1-393
Zheliazkova, Maia 1-443
Zheng, Hao 2-253
Zhou, Yifan 1-143
Zhou, Zhi 1-301
Zhu, Shuyan 1-675
Zhu, Weiran 1-393
Zhu, Yuehan 2-71
Zou, Yue 1-785



INTELLIGENT & INFORMED

April 15-18 2019
Faculty of Architecture and Design
Victoria University of Wellington, New Zealand

This volume contains the double-blind peer-reviewed papers accepted for the 24th Annual Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, held at the Faculty of Architecture and Design, Victoria University of Wellington, New Zealand. They provide a snapshot of leading research in the field by researchers around the world.

© 2019 All rights reserved and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, China

ISBN 978-988-78917-2-7

9 789887 891727