CAADRIA 2021 - Hong Kong

'PROJECTIONS'

Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia

Edited by:
Anastasia Globa
Jeroen van Ameijde
Adam Fingrut
Nayeon Kim
Tian Tian Sky Lo

t | 301 | Secret Whispers & Transmogrifications: A Case Study in Online Teaching of Augmented Reality Technology for Collaborative Design Production
oxel-Based 3D Modelling Approach
of Real-Time Virtual Engines in the Architectural Design Studio
104 | Quantification and Typology Methods for Spatial Regionalism: From Traditional Residence to Modern Chinese-Style House Design
n the Posthumanist Discourses
tions in Building Information Modelling (BIM) Systems
ng Parametric Design Exploration in a Collaborative Environment: A Study Case of Versioning for Parametric Design
Design Acts | 376 | Topology Generated Non-Fungible Tokens: Blockchain as Infrastructure for a Circular Economy in Architectural Design

esign Participation | 127 | Expanding the Methods of Human-VR Interaction (HVRI) for Architectural Design Process
cision Making for Automated Building Access Systems
uman Senses to Create Virtual Atmospheric Qualities
phy, Sonic Art, Creative Writing Collide at "in the Forest with the Trees We Made"
on | 143 | AR Digi-Component: AR-Assisted, Real-Time, Immersive Design and Robotic Fabrication Workflow for Parametric Architectural Structures
sional Modelling Using Sketching Interface
e Engines as a Quantitative Daylighting Simulation Tool
Exhibitions | 101 | An Augmented-Reality-Based Experiment of Multiple Building Performance in Design Curriculums
amework for Emotional Tactile Interaction Design
omputer Interface within VRAD by the Active and Two-Way Employment of Our Visual Senses

ace Syntax in the Study of Urban Texture: Considering the Street System and Property Right Plots
he Accuracy of Generating Horizontal Building Mask Images for Deep Learning in Urban Planning and Design
Data-Driven Analysis and Generative Design for Public Housing Estate Layouts
erpret the Performance of the Urban Form
of Measurement and Envi-Met Simulation of Winter Night in NanPing Village Under Wet and Cold Microclimate Based on Urban Roughness
istribution on Land Surface Temperature in Mid-Size Cities of Poland
044 | 3D Space Resilience Analysis of Commercial Complex: Beijing APM as an Example
ties | 274 | Urban Space Simulation System for Townscape Ordinance
ni Evacuation Behavior Simulation System for Selection of Evacuation Sites
chibase: A City-Scale Spatial Database for Architectural Research
ration of Human Activity and Mobility Infrastructure
s in Shanghai CAZ
n Pedestrian Flow through Machine Learning
d | 311 | SECTIONMATRIX: Mapping Urban Form through Urban Sections
ublic Spaces | 448 | Optimising Harbour Typology in the Form Finding Process Using Computational Design: A Case Study of a Greenfield Port Facility
w on Its Application towards Urban Planning
s of Urban Design Processes
ng Mechanical Devices
nts for Responsive Urban Design by Non-Programmers: Melding Real-Time ABM Pedestrian Simulation and Form Modelling in Unity 3D
ent in Reaction to COVID-19 Pandemic
ng Crowd Safety: Agent-Based Pedestrian Simulations in the Early, Collaborative Design Stages

VOLUME 2

PROJECTIONS

Proceedings of the 26th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2021)

Volume 2

Edited by

Anastasia Globa
University of Sydney

Jeroen van Ameijde
The Chinese University of Hong Kong

Adam Fingrut
The Chinese University of Hong Kong

Nayeon Kim
Yonsei University

Sky Lo Tian Tian
Harbin Institute of Technology (Shenzhen)

Projections
26th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2021)

29 March – 1 April 2021
School of Architecture
The Chinese University of Hong Kong

The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong

ISBN: 978-988-78917-6-5
ISSN: 2710-4257 (print)
2710-4265 (online)

Printed in Hong Kong

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 proceedings have two volumes containing the research papers that were accepted for presentation at the Projections – 26th International CAADRIA Conference, hosted and organised by the Faculty of Architecture at Chinese University of Hong Kong. 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 CAADRIA's international Academic Review Committee.

Within the context of continued challenges and restrictions imposed by the ongoing world-wide pandemic, our CAADRIA community have shown its resilience and strength. Initial calls for papers in July 2020 resulted in a round number of 400 abstract submissions. These abstracts were assessed by the Paper Selection Committee and were a subject to a double-blind peer review performed by a team of 151 international reviewers. 250 papers were invited to proceed to the next stage - the full-length paper submission. Those manuscripts went through another series of double-blind reviews, with two-to-four for each paper. As a result, 152 submissions were accepted and 149 of these were ultimately published in the CAADRIA 2021 proceedings. We congratulate the authors for their accomplishment.

Next to the authors, the reviewers, who volunteered their valuable time and effort, deserve our sincere thanks and acknowledgements. We thank the Organising Team at The Chinese University of Hong Kong for hosting the 26th International CAADRIA Conference online.

We extend our special thanks to the ProceeDings team, and in particular Gabriel Wurzer, for his support with customizing the submission and review system to the needs of CAADRIA from the full-paper submission to the production stage. 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 *Projections, the 26th International CAADRIA Conference 2021.*

Anastasia Globa	*University of Sydney (Chair)*
Jeroen van Ameijde	*The Chinese University of Hong Kong*
Adam Fingrut	*The Chinese University of Hong Kong*
Nayeon Kim	*Yonsei University*
Sky Lo Tian Tian	*Harbin Institute of Technology (Shenzhen)*

CAADRIA 2021

Theme: ***'Projections'***

In a time of unprecedented global challenges, the need for researchers and designers to reflect on our changing society has rarely been more obvious. As the pandemic highlights the precariousness of our fragile climate, limited resources and unequitable urban areas, there is a new mandate for research and innovation, searching for new technology-enabled processes that positively impact our profession, communities, and planet.

The advancement and adoption of new technologies in all aspects of our society have started to profoundly change the nature of architectural design and materialisation processes, bridging between the digital and the physical worlds. Fluid communication allows for unprecedented new levels of complexity, control and feedback between design and the built environment. Large quantities of information allow us to forecast how architectural and urban structures perform over time, against a detailed understanding of their contexts.

'Projections' focuses on the implementation of our work, asking us to reflect upon the different ways innovation will impact the future of our industry. We will invite conversations and debate around the status of computational research and design, reflecting on recent challenges and opportunities, and how these translate into futures that are different from what was previously predicted. As we assess our projects within the context of our shared realities, we position our work as prototypes for alternative futures in our collective field.

The 2021 annual conference for Computer-Aided Architectural Design Research in Asia (CAADRIA), will bring together academics, researchers and practitioners involved in innovating, disrupting or revolutionising processes for the conceptualisation, evaluation and materialisation of the built environment. By inviting participants from universities and practices throughout Asia, we aim to create a platform for shared moments of inspiration, reflection, and projection.

Conference Organisers & Hosts,

Kristof Crolla — *The University of Hong Kong*
Adam Fingrut — *The Chinese University of Hong Kong*
Jeroen van Ameijde — *The Chinese University of Hong Kong*

{https://caadria2021.org}

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, 25 conferences have been held in Australia, China, Hong Kong, India, Japan, Korea, Malaysia, New Zealand, Singapore, Taiwan, and Thailand. The annual CAADRIA conferences provide an opportunity to meet, to learn about the latest research, and to continue the discourse in the field. The 26th conference, in 2021, is held at The Chinese University of Hong Kong. CAADRIA 2021 is held as a virtual conference for the second time in the history of the Association to bring together researchers, practitioners and schools of the pacific region even at a time of continued global Covid-19 related travel restrictions.

CAADRIA is one of the four founding organizations of the *International Journal of Architectural Computing* (IJAC), and typically 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: Urvi Sheth
CEPT University, India

Treasurer: Hyoung-June Park
University of Hawaii, USA

Membership Officer: Immanuel Koh
Singapore University of Technology and Design, Singapore

Web Master: Kyung Hoon Hyun
Hanyang University, Korea

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

CAADRIA 2021 Conference Committees

Hosting Institution:
The Chinese University of Hong Kong

Organising Committee:

Kristof Crolla
The University of Hong Kong — *Conference Co-Chair*

Adam Fingrut
The Chinese University of Hong Kong — *Conference Co-Chair*

Jeroen van Ameijde
The Chinese University of Hong Kong — *Conference Co-Chair*

Donn Holohan
The University of Hong Kong — *Workshop Coordinator*

Hoi Lam Melody
The Chinese University of Hong Kong — *Tour Coordinator*

Garvin Goepel
The Chinese University of Hong Kong — *Technical Coordinator*

Lidia Ratoi
The University of Hong Kong — *Exhibition Coordinator*

Paper Selection Committee:

Anastasia Globa
University of Sydney — *Chair*

Jeroen van Ameijde
The Chinese University of Hong Kong

Adam Fingrut
The Chinese University of Hong Kong

Nayeon Kim
Yonsei University

Sky Lo Tian Tian
Harbin Institute of Technology (Shenzhen)

Post Graduate Students Consortium:

Dagmar Reinhardt — *Co-Chair*

Sky Lo Tian Tian — *Co-Chair*

Christiane M. Herr

Sasada Prize Committee:

Tom Kvan — *Chair*

Christiane M. Herr

Atsuko Karga

Young CAADRIA Award Committee:

Sky Lo Tian Tian — *Chair*

Christiane M. Herr

Rudi Stouffs

Jeroen van Ameijde

International Review Committee

Mona Ghandi
Washington State University
Anastasia Globa
The University of Sydney
Meng Gu
Harbin Institute of Technology
Zhuoxing Gu
Tongji University
Qi Guo
Harbin Institute of Technology
Benay Gursoy
The Pennsylvania State University
M. Hank Haeusler
University of New South Wales
Yoojin Han
Yonsei University
Christiane M. Herr
Xi'an Jiaotong-Liverpool University
Pablo C. Herrera
Peruvian University of Applied Sciences
Wei Hu
Tongji University
Xiaoran Huang
Swinburne University of Technology
North China University of Technology
Kyung Hoon Hyun
Hanyang University
Aswin Indraprastha
Institut Teknologi Bandung
Sylvie Jancart
The University of Liège
Krystyna Januszkiewicz
West Pomeranian University of Technology
Taysheng Jeng
National Cheng Kung University
Mads Brath Jensen
Aalborg University
Guohua Ji
Nanjing University
Lenka Kabošová
Technical University of Košice
Yuval Kahlon
Tokyo Institute of Technology
Ammar Kalo
American University of Sharjah
Chin Koi Khoo
Deakin University
Daiki Kido
Kajima Corporation
Sung-Ah Kim
Sungkyunkwan University
Nayeon Kim
Yonsei University
Geoff Kimm
Swinburne University of Technology
Seow Jin Koh
Defence Science & Technology Agency
Immanuel Koh
SUTD
Dennis Lagemann
ETH Zurich
Ih-Cheng Lai
Tamkang University
Hyunsoo Lee
Yonsei University
António Leitão
INESC-ID/IST, University of Lisbon
Surapong Lertsithichai
Chulalongkorn University
Andrew Li
Kyoto Institute of Technology
Bin Li
South China University of Technology
Mengting Li
Tongji University
Chieh-Jen Lin
Tainan University of Technology
Yuezhong Liu
Nanyang Technological University
Jie Liu
Tsinghua University
Tian Tian Lo
Harbin Institute of Technology, Shenzhen
Paul Loh
University of Melbourne
Davide Lombardi
Xi'an Jiaotong-Liverpool University
Thorsten Lomker
Zayed University
Werner Lonsing
Independent Researcher
Mauricio Loyola
University of Chile

Shuai Lu
The University of Sydney
Yao Lu
University of Pennsylvania
Bob Martens
TU Wien
Rodrigo Martin Iglesias
University of Buenos Aires
Michio Matsubayashi
KOSEN, Kushiro College
Samim Mehdizadeh
TU Darmstadt
Virginia Melnyk
Tongji University
Olga Mesa
Roger Williams University
Joy Mondal
WEsearch lab
Hugo Mulder
The University of Southern Denmark
Rizal Muslimin
The University of Sydney
Walaiporn Nakapan
Rangsit University
Farzaneh Oghazian
The Pennsylvania State University
Mine Özkar
Istanbul Technical University
Hyoung-June Park
University of Hawaii at Manoa
Jungeun Park
Yonsei University
Trevor Ryan Patt
Carnegie Mellon University
Wanyu Pei
Harbin Institute of Technology, Shenzhen
Inês Pereira
INESC-ID/IST, University of Lisbon
Hendro Trieddiantoro Putro
Universitas Teknologi Yogyakarta
Ahmad Rafi
Multimedia University
Mina Rahimian
Deluxe Modular
Jinmo Rhee
Carnegie Mellon University
Manuel Rodriguez Ladron de Guevara
Carnegie Mellon University
Luís Romão
University of Lisbon
Marc Aurel Schnabel
Victoria University of Wellington
Gerhard Schubert
Technical University of Munich
Krishnendra Shekhawat
BITS Pilani
Urvi Sheth
Craft Quest
Sahar Soltani
University of South Australia
Ralph Spencer Steenblik
Wenzhou-Kean University
Vladeta Stojanovic
Hasso Plattner Institute
Djordje Stojanovic
University of Melbourne
Rudi Stouffs
National University of Singapore
Marcin Strzala
Warsaw University of Technology
Salma Tabi
Keio University
Ying Yi Tan
SUTD
Teng Teng
Cornell University
Ziyu Tong
Nanjing University
Elena Vazquez
The Pennsylvania State University
Tomas Vivanco
PUC Chile
Tongji University
Likai Wang
Nanjing University
Shih-Yuan Wang
National Chiao Tung University
Sihan Wang
SUTD
Glen Wash Ivanovic
Xi'an Jiaotong-Liverpool University
Claudia Westermann
Xi'an Jiaotong-Liverpool University
Bastian Wibranek
TU Darmstadt
Albert Wiltsche
Graz University of Technology

Andrew Wit
Temple University
Thomas Wortmann
University of Stuttgart
Yen-Liang Wu
NTCUST
Xinchang Xiong
Tsinghua University
Chao Yan
Tongji University
Lijing Yang
Tsinghua University
Jiawei Yao
Tongji University
Hatzav Yoffe
Technion-Israel Institute of Technology
Jungwon Yoon
University of Seoul
Rongrong Yu
Griffith University
Hao Zheng
University of Pennsylvania
Jianjia Zhou
Tongji University
Guanqi Zhu
The University of Queensland

Keynote Lectures

Worlds Less Travelled

Liam Young
Coordinator, MA in Fiction and Entertainment, SCI-Arc
Founder, Tomorrows Thoughts Today
Co-director, Unknown Fields Division

Our perception of the world is largely shaped through the mediums of fiction. Through film we have always imagined alternative worlds as a way of understanding our own world in new ways. A critical role of Science Fiction is to provide a counterbalance to the prevailing media narratives around emerging urban technologies. Typically, our imagined futures are based on a solutionist view of technology and are marketed to us as simplified worlds of better and brighter often ignoring the complexities, subcultures and unintended consequences that result when technologies are democratized and rolled out at scale. In this talk, Liam Young will narrate a series of stories from these worlds less travelled, just small glimpses, fragments, vignettes and snapshots from a series of his films that will come together to create a portrait of an alternative future of technology, urbanisation and automation.

BIOGRAPHY

Liam Young is a speculative architect and director who operates in the spaces between design, fiction and futures. He is cofounder of Tomorrows Thoughts Today, an urban futures think tank, exploring the local and global implications of new technologies and Unknown Fields, a nomadic research studio that travels on expeditions to chronicle these emerging conditions as they occur on the ground.

Described by the BBC as ‘the man designing our futures’, his visionary films and speculative worlds are both extraordinary images of tomorrow and urgent examinations of the environmental questions facing us today. As a concept designer he visualizes the cities, spaces and props of our imaginary futures including work on the forthcoming features Swan Song, starring Mahershala Ali and Awkwafina for Apple TV and Folding City for Chinese Production company Wanda in addition to production designing an unannounced new sci fi series for eOne. With his own films he is a BAFTA nominated producer and has premiered with platforms ranging from Channel 4, SxSW, the New York Metropolitan Museum, The Royal Academy, the BBC and the Guardian.

His fictional work is informed by his academic research and he has held guest professorships at Princeton University, MIT, and Cambridge and now runs the ground-breaking Masters in Fiction and Entertainment at SCI Arc in Los Angeles. He has published several books including the recent Machine Landscapes: Architectures of the Post Anthropocene and Planet City, a story of a fictional city for the entire population of the earth.

Leveling-up our Design Methodologies

Ben van Berkel
Professor, AA Dipl. (Hons), (F)RIBA, Hon. FAIA
Founder / Principal Architect, UNStudio
Founder, UNSense

In light of the challenges society is facing, UNStudio's founder Ben van Berkel will present on the integral and human centric approach to health, flexibility and technology in their work. Leveling-up our built environment requires thinking about the relation between different scales. UNStudio has produced a wide range of work, from public buildings to infrastructure, offices to residential as well as interiors and products to urban master plans. With their focus distinctly placed on the future, in 2018 the practice founded a sister company, UNSense, an arch tech company that aims to create impact by developing technology and innovative solutions that improve quality of life for individuals, communities and the planet.

BIOGRAPHY

Ben van Berkel studied architecture at the Rietveld Academy in Amsterdam and at the Architectural Association in London, receiving the AA Diploma with Honours in 1987. In 1988 he and Caroline Bos set up UNStudio, an architectural practice in Amsterdam. Current projects include the Southbank mixed-use development in Melbourne, 'Four' a large-scale mixed-use project in Frankfurt and the Wasl Tower in Dubai.

With UNStudio, he realised amongst others the Mercedes-Benz Museum in Stuttgart, Arnhem central Station in the Netherlands, the Raffles City mixed-use development in Hangzhou, the Canaletto Tower in London, a private villa upstate New York and the Singapore University of Technology and Design. In 2018 Ben van Berkel founded UNSense, an Arch Tech company that designs and integrates human-centric tech solutions for the built environment.

Ben van Berkel has lectured and taught at many architectural schools around the world. From 2011 to 2018 he held the Kenzo Tange Visiting Professor's Chair at Harvard University Graduate School of Design, where he led a studio on health and architecture. In 2017, Ben van Berkel also gave a TEDx presentation about health and architecture. In addition, he is a member of the Taskforce Team / Advisory Board Construction Industry for the Dutch Ministry of Economic Affairs.

Planetary Reticulum: Considerations for Global Multi-Modal Connectivity in the Post-COVID Era

Cristiano Ceccato
FRAeS FRSA
Director, Zaha Hadid Architects, London

In today's globalised economy, multi-transport nodes bind cities together as part of an ever-growing, singular planetary network of complex urban environments. In the post-COVID world, we are confronted with the question of how to fill the intangible space between them and create a new balance across cultural boundaries, geographical barriers and growing political divides. This 'infrastructural glue', combined with new forms of travel, communication and decentralised collaborative work environments, is rapidly becoming the major catalyst for societal transformation in a 21st century tempered by pandemic and its politics.

Touching on examples from ZHA, this presentation will reflect on how multimodal infrastructure projects of increasing complexity are designed and constructed to provide the innervation for cities around the world – the connective tissue for a truly global meta-urban condition. These excursions into transport design provide a thematic and functional counterpoints of nodes and connectors, and speculates on an architectural vision of inter-urban development on a worldwide scale.

BIOGRAPHY

Cristiano Ceccato is a Director at Zaha Hadid Architects (ZHA) in London, having previously worked for Frank O. Gehry Partners in Los Angeles. Trained as an architect and computer scientist, he engages across all levels of design and technical development, with worldwide project delivery experience on a wide range of typologies. Cristiano is also an accomplished software developer, having previously co-founded the BIM company Gehry Technologies in California.

Cristiano has spearheaded ZHA's entrance into the aviation market since 2010. He is the Project Director for the Beijing Daxing Airport in China completed 2019; the Navi Mumbai International Airport in India; and the Western Sydney Airport under construction in Australia. Cristiano is a graduate of the Architectural Association and Imperial College in London. He is a Fellow of the Royal Society of Arts and a Fellow of the Royal Aeronautical Society, where he sits on the Air Transport Specialist Group board.

Senseable Cities

Carlo Ratti
Director, MIT Senseable City Lab
Founding Partner, Carlo Ratti Associati

The way we live, work, and play is very different today than it was just a few decades ago, thanks in large part to a network of connectivity that now encompasses most people on the planet. In a similar way, today we are at the beginning of a new technological revolution: the Internet is entering the physical space – the traditional domain of architecture and design – becoming an "Internet of Things" or IoT. As such, it is opening the door to a variety of applications that – in a similar way to what happened with the first wave of the Internet – can encompass many domains: from energy to mobility, from production to citizen participation. The contribution from Prof. Carlo Ratti will address these issues from a critical point of view through projects by the Senseable City Laboratory, a research initiative at the Massachusetts Institute of Technology, and the design office Carlo Ratti Associati.

BIOGRAPHY

An architect and engineer by training, Professor Carlo Ratti teaches at the Massachusetts Institute of Technology (MIT), where he directs the MIT Senseable City Lab, and is a founding partner of the international design and innovation office Carlo Ratti Associati. He graduated from the Politecnico di Torino and the École Nationale des Ponts et Chaussées in Paris, and later earned his MPhil and PhD at the University of Cambridge, UK.

A leading voice in the debate on new technologies' impact on urban life and design, Carlo has co-authored over 500 publications, including "The City of Tomorrow" (Yale University Press, with Matthew Claudel), and holds several technical patents. His articles and interviews have appeared on international media including The New York Times, The Wall Street Journal, The Washington Post, Financial Times, Scientific American, BBC, Project Syndicate, Corriere della Sera, Il Sole 24 Ore, Domus. His work has been exhibited worldwide at venues such as the Venice Biennale, the Design Museum Barcelona, the Science Museum in London, MAXXI in Rome, and MoMA in New York City.

Carlo has been a presenter at TED (in 2011 and 2015), program director at the Strelka Institute for Media, Architecture and Design in Moscow, curator of the BMW Guggenheim Pavilion in Berlin, and was named Inaugural Innovator in Residence by the Queensland Government. He was the curator of the Future Food District pavilion for the 2015 World Expo in Milan and chief curator of the "Eyes of the City" section at the 2019 UABB Biennale of Architecture and Urbanism of Shenzhen. He is currently serving as co-chair of the World Economic Forum's Global Future Council on Cities and Urbanization.

Roundtable Conversations

Projections on Automation and Architecture

Recent tendencies in architecture have moved on from an obsession with continuous form to develop a more critical understanding of the disciplines' relation to "the Digital". Part of this shift is a variegated group of practitioners and theorists that interrogate the notion of automation as an alternative angle to understand the relation between architecture and digital technologies.

Framing architecture's engagement with digital technologies as a form of automation opens up a vast territory of investigation, ranging from robotics and fabrication, to platform economics, the politics of the digital, and planetary issues such as climate change. While this is a welcome departure from the often-isolated viewpoint of the early digital experiments in architecture, the question arises how this reflects back on core issues architecture itself – space, form and experience. Returning from these vast territories of automation, have we lost the desire to formulate a position on space and form?

This panel of experts will debate how automation has impacted our understanding of design and architecture itself. Covering the politics of automation and its repercussions on architecture, the discussion will project possible architectural attitudes, ideas and positions.

Gilles Retsin (convenor)

Programme Director, M.Arch Architectural Design, the Bartlett School of Architecture, UCL
Co-founder, UCL AUAR Labs (Automated Architecture Labs)
Co-founder, AUAR ltd (Automated Architecture)

Originally from Belgium, Gilles Retsin is an architect and designer living in London. He studied architecture in Belgium, Chile and the UK, where he graduated from the Architectural Association. His design work and critical discourse has been internationally recognised through awards, lectures and exhibitions at major cultural institutions such as the Museum of Art and Design in New York, the Royal Academy in London and the Centre Pompidou in Paris. He recently edited an issue of Architectural Design (AD) on the Discrete and has co-edited Robotic Building: Architecture in the Age of Automation, with Detail Verlag.

Gilles Retsin is Programme Director of the M.Arch Architectural Design at UCL, the Bartlett School of Architecture. He is also co-founder of the UCL Design Computation Lab, which does high profile research into new design and fabrication technologies. He is also co-founder of AUAR ltd (Automated Architecture), a start-up working towards an automated platform for affordable housing.

Marina Otero Verzier
Head of the Social Design MA, Design Academy Eindhoven

Marina Otero Verzier is an architect based in Rotterdam. She is Director of Research at Het Nieuwe Instituut (HNI) and head of the Social Design MA at Design Academy Eindhoven. At HNI, Otero works to give visibility to research projects, practices, and initiatives that depart from established modes of thinking. Examples include Automated Landscapes (focusing on emerging architectures of automated labour) and BURN-OUT. Exhaustion on a planetary scale (instigating other forms of coexistence and care for multispecies, collective bodies). She was previously Director of Global Network Programming at Studio-X in New York. Otero was a member of the Artistic Team for Manifesta 13, and Curator of WORK, BODY, LEISURE, the Dutch Pavilion at the 16th Venice International Architecture Biennale in 2018. With the After Belonging Agency, she was Chief Curator of the Oslo Architecture Triennale 2016. Currently, she is one of the curators of the 13th Shanghai Art Biennial. Otero studied at TU Delft and ETSA Madrid and Columbia University GSAPP. In 2016, she received her PhD at ETSA Madrid.

Deborah Lopez & Hadin Charbel
Lecturers, the Bartlett School of Architecture, UCL
Co-founders, Pareid Office

Deborah Lopez and Hadin Charbel are architects and founders of Pareid; an interdisciplinary design and research studio currently located in London. Their works adopt approaches from various fields and contexts, addressing topics related to climate, ecology, human perception, machine sentience, and their capacity for altering current modes of existence through iminent fictions (if) believing that disruptions to existing norms can be useful in generating alternate versions of future realities. They have been recently awarded with the Arquia Innova Award in the VII Arquia Próxima Awards by Fundación Arquia and their work has been presented in different international institutions and exhibitions such as Royal Academy of Arts, Centre Pompidou, Seoul Biennale or Venice Biennale.

They are both Lecturers (Teaching) at The Bartlett School of Architecture UCL in the B-Pro program where they run the cross-Research Cluster (1+20) in Architectural Design and Urban Design entitled “Monumental Wastelands”, By using climate fiction as a vehicle, speculations are put forward that engage various ecologies via sentient machines and automated landscapes, through which current economically profitable models are challenged.

Jelle Feringa
Chief Technology Officer, Aectual

Jelle Feringa is an architecture and robotics specialist and as CTO of Aectual responsible for the development and production of tailor-made building products at scale. While developing his PhD thesis at TU Delft, Jelle established a full robotics lab in the docks of Rotterdam. Here he developed the technical underpinnings for Odico formwork robotics, the first publicly traded architectural robotics company which he co-founded in 2012. Technologies that Jelle developed, include hotwire, hotblade, diamond wire cutting and large scale 3d printing and are applied in high-profile construction projects.

Jelle has taught & lectured internationally at the Bartlett, Architectural Association, Paris-Malaquias, IAAC, ETH Zürich, TU Delft and Aarhus School of Architecture. He is a founding partner of EZCT Architecture & Design Research. The work of the office is widely exhibited, exhibitions include the Mori Art Museum, Tokyo, Archilab, Orléans, Barbican Gallery Design Miami/Basel. Projects by the office are part of Pompidou Center permanent collection and the FRAC Centre Orléans. Jelle is a long-term contributor of the PythonOCC project, and some of his fascinations include levelsets, stereotomy and powertools.

Innovation Re-Origination

This panel will be discussing how the displacement of the origins of existing contexts can constitute new, future origins. Innovation is not always what's new and what is next; it may be directly in front of us. This is an increasingly important consideration for architectural education and the profession; one which foregrounds the reuse of buildings, building systems, materials, infrastructures, trades, craftsmanship, and landscapes as a viable arena for scholarly research, design development and technical innovation. Within the context of CAADRIA, the importance of this subject lies in the numerous technological promises that come with the hybrid, mixed systems and which contradict and complicate the clean, singularity of 20th century, holistic, ground-up construction. In focusing on this area of research, the smooth streamlined mythology of BIM software might be reconsidered and expose latent technical horizons.

The scope of research on "re-origination" and its requisite praxes locates itself on the fringes of architecture discourse. Existing research on this subject has been limited due to the fact that the majority of architecture schools and practices largely see solutions to sustainability as tethered to the continued necessity for new, novel construction systems, materials and tradecrafts. This panel will explore ways in which research in this area emphasises and explores the robust space between social and environmental justice afforded by the primary lens of "alteration." Through this framework, small-scale, highly attenuated, design moves that draw concisely from their context, minimize displacement, limit resources, and capitalize on obsolete square footage and/or practices will be discussed as having the capacity to innovate and re-originate.

David Erdman (convenor)
Chairperson, Graduate Architecture and Urban Design, Pratt Institute's School of Architecture

David Erdman is the chairperson of Graduate Architecture and Urban Design at Pratt Institute's School of Architecture in Brooklyn, NY. He was a co-founding partner of the design collaborative servo where he designed and completed numerous projects exhibited in museums in North America and Europe. Erdman co-founded davidclovers (now plusClover) with former partner Clover Lee where from 2006-2016 he designed and completed over twenty built projects in Hong Kong, China and North America. In addition to the receipt of numerous awards and having work from both firms exhibited and collected in museums, Erdman was awarded the prestigious Rome Prize in 2008-2009.

In addition to Pratt, Erdman has taught at UCLA and HKU and held visiting positions at various universities including Yale, UC Berkeley and Rice University. He is the author of Introducing (AR+D 2021), Pratt Sessions Volumes 1 and

2 (ORO 2018, 2020) and co-author of Future Real (Yale SoA 2018). He has lectured throughout Asia, North America and Europe. Erdman is currently working on several books and a series of collaborative design research projects with government organizations in New York City and Hong Kong.

Debora Mesa Molina
Principal, Ensamble Studio
Ventulett Chair, Georgia Tech

Débora Mesa Molina, (Madrid, 1981) is European Licensed Architect and principal of Ensamble Studio, a cross-functional team she leads with her partner Antón García-Abril, based in Madrid and Boston. Balancing imagination and reality, art and science, their work innovates typologies, technologies and methodologies. From their early works – Hemeroscopium House or The Truffle- to their most recent – Ca'n Terra and Ensamble Fabrica -, every project makes space for experimentation aiming to advance their field. Currently, through their startup WoHo, they are developing ways to increase quality and affordability in architecture through the integration of offsite technologies.

Debora is committed to sharing ideas and cultivating synergies between professional and academic worlds through teaching, lecturing and researching: she is Ventulett Chair in Architectural Design at Georgia Tech since 2018 and previously served as research scientist at MIT where she co-founded the POPlab – Prototypes of Prefabrication – in 2012. Above all, she is a doer, committed to making poetic ideas happen.

Elora Hardy
Founder, IBUKU

Elora is the Founder and Creative Director of IBUKU. The team of designers, architects and engineers that is exploring ground-breaking ways of using bamboo to build homes, hotels, schools, and event spaces in Bali, Indonesia. Creating a new design vocabulary based on this one material and exploring the way sustainable architecture and design can redefine luxury. The traditional skills of Balinese craftsmen, combined with their design ideas and modern engineering enable them to create original bamboo structures that meet the needs of a diverse clientele. "IBUKU's goal is to provide spaces in which people can live in an authentic relationship with nature. IBUKU is creating spaces where living in nature is living in style. IBUKU has built over 72 bamboo structures in Bali, Indonesia, and 5 internationally. Completed key projects include the Green School, Green Village, Sharma Springs, and Bambu Indah Eco Resort, which have appeared in international publications like Architectural Digest, Elle Decor, Vogue and the Huffington Post.

Philip Yuan
Associate Dean and Professor, College of Architecture and Urban Planning (CAUP), Tongji University

Philip F. Yuan Associate Dean, tenured professor of the College of Architecture and Urban Planning (CAUP) at Tongji University, Council Member of Architects Sector, Virtual and Automated Construction Sector as well as Academic Committee of Computational Design Sector at Architectural Society of China; Director of Academic Committee of Shanghai Digital Fabrication Engineering Technology Center; Co-Chair of DigitalFUTURES Association. He founded Shanghai based firms: Archi-Union Architects and Fab-Union Technology. Yuan is also a member in the Scientific Committee of The International Association on Spatial Structures (IASS) and the International Conference on 3D Printing and Transportation3D Printing and Transportation (3DTRB).

His research mainly focuses on the field of performance-based architectural tectonics, the application of robotic fabrication equipment as weak as developments of robotic fabrication technologies and is able to realize many of his research theories in architectural practices.

Jing Liu
Co-Founding Principal, SO-IL
Visiting Professor, Pratt Institute

Jing Liu has been practicing for more than 15 years working on a wide range of projects both in the US and abroad. Through building practice and interdisciplinary research projects, Liu has led SO–IL in the engagement with the socio-political issues of contemporary cities — in projects like the Artists Loft North Omaha and the Martin Luther King, Jr. Library in Cleveland. Her projects range from artistic collaborations with contemporary choreographers and visual artists to master plan and major public realm design in cities like Melbourne and Indianapolis.

Liu brings an intellectually open, globally aware, and locally sensitive perspective to architecture. Her intellectual curiosity and artistic imagination allow her to bring a more nuanced cultural perspective to the table. Her keen skills in combining digital technology with traditional craft and firm belief in design's ability to re-engage people with the physical world around them allow the buildings she designs to become places of exchange that welcome interpretation and transformation.

FUTURE PRACTICE: Challenges and Opportunities of Technology Integration in Building Engineering

Moore's law predicts the number of transistors in a dense integrated circuit to double approximately every two years. This means that every 24 months, computational devices can perform their tasks twice as fast. For over 50 years, this theory has held up. In the meantime, while our industry still considers decade-old BIM technology to be "new", Automation, Machine Learning, and Artificial intelligence are increasingly taking over the laborious and repetitive tasks that are part of our design and engineering work.

Designers will in the future interface with machines through AI assistants and use human qualities, such as creativity, emotion, inter-human relationships, experience, and common sense to make decisions. At Arup Group we are currently developing a design automation platform called "Total Design Automation" (TDA) which will make it easy to both develop automated workflows and use them across projects around the world. Through cloud technologies, automated design tasks are linked together by the data they produce and subsequently consume, orchestrating entire design workflows from start to end. In doing so, a gap has been exposed between what is theoretically possible and what is needed now. The biggest industry challenge is hardly ever the design and delivery of complex, iconic architecture, but to provide sufficient housing and places to work for the exponentially growing world population.

By touching on issues related to standardisation, industry skills, business strategies, and future design and delivery methodologies, this roundtable panel of experts in computational design engineering and construction will discuss how our industry can (prepare itself to) utilise future computation and automation to improve the quality of our built environment.

Ramon van der Heijden (convenor)
Digital Design Leader, Arup East Asia

Ramon is Digital Design Leader at Arup East Asia. His work in Research and development, Building Information Modeling and Building Data Management has allowed him to develop a deep understanding of the technology that drives innovation in construction data management and design. Specializing in the generation of large, data rich building models has enabled him to create the Elefront add-in for Grasshopper. He is currently the Programme Director of the development of a cloud-based design automation platform that allows anyone to develop and use automated design solutions through the web.

Ramon has taught computational design at Eindhoven University of Technology, and Construction Communication and Architectural Design at The University of Hong Kong. He has hosted seminars on Elefront at The Chinese University

Hong Kong, The University of Hong Kong and for the AA Visiting School, Hong Kong. Leading the Digital Design Team, his work focuses on optimizing and digitizing existing design and engineering processes as well as exploring new business opportunities using digital design technologies.

Emidio Piermarini
Associate, Buro Happold Asia

Emidio is an Associate with Buro Happold Asia, where he is the lead for their new Computational Consulting offering. He works with clients in all stages of the real estate life cycle to help clients realize solutions to their most complex problems using big data and analytics. He is an early contributor to the open-source Buildings and Urban Habitat Object Model (BHoM) and believes the open-source era of AEC represents the future of our industry–design professionals who can communicate and design using code.

Susanne Knorr
Global Client Development Lead Data & Analytics, Arcadis

Susanne is managing the Global Client Development of Arcadis' Data Analytics services, with a focus on driving sustainability. She is responsible for identifying opportunities to apply advanced statistical methods and solutions for key-clients, helping them to address their challenges and enhance the performance. Therefor Susanne and her team partner with the technical engineering team, focusing on analytics key methods like Data Management & Engineering, Data Visualization, Data Science & Machine Learning, NLP, Computer Vision and IoT, and the client development community across all sectors and solutions.

In 2017 Susanne was selected as an Arcadis Global Shaper, in 2018 she was awarded the Start- up Digital Award. She is a mentor of Techstars X Arcadis City Accelerator 2019. In 2020 Susanne was selected for the W50 Emerging Leaders Programme by the London School of Economics and Political Science supported by the Becas Santander Scholarship.

Lai, Man Kit Thomson
Executive Director of Innovative Solutions,
Digital Transformation Lead, Greater China, AECOM

Thomson Lai is a technology veteran with over 20 years of experience in the geospatial industry and is an expert in a wide variety of digital technology. He is a chartered surveyor, CIC Certified BIM Manager, and a Project Management Professional (PMP) certified project manager. Thomson's involvement has been integral to many large- scale civil infrastructure projects, and he's responsible for many digital solutions, including BIM processes and workflows. His recent projects include the Hong Kong International Airport Three-runway System, pilot study on underground space development for the HKSAR Civil Engineering and Development Department, study on integration of BIM & 3D spatial data for the HKSAR Lands Department, and APAC datacenter BIM managed service for multinational technology company.

As an experienced technology practitioner, Thomson is a pioneer who integrates technologies — including BIM, GIS, photogrammetry, IoT, and immersive technology — for civil and infrastructure projects. He is also the Asia Digital leader of AECOM and is currently leading the digital business in Asia, pushing the adoption of digital technology across the region.

Nick Williams
Principal, Computational Design & Automation Leader, Aurecon

Nick Williams is a Principal at Aurecon and leads digital modelling, computational design and automation across the firm. In this role Nick has created both a distributed network of practitioners across regional teams, and a central software and business transition team. These two streams enable both a nimble response to specific project needs, and the creation of standards and tools to reshape engineering and design services at scale.

Prior to joining Aurecon, Nick trained as an architect and practiced in Australia and Europe. He has a Master's degree from The Architectural Association, London, and a PhD from RMIT University, Melbourne. In academic roles, Nick has led various applied research around digital design and construction, prototyping data-driven approaches across multiple scales, materials and types of performance. He has also authored over 20 peer-reviewed journal and conference papers and remains a regular contributor to several academic forums.

FROM LAB TO SITE: Promises of Disruptive Technology Implementations in AEC

Having overcome the debate of the transition between the digital and the physical, architectural design faces a challenge about applying lab research into real-life scenarios to produce a true impact in our society. Whereas technology keeps driving definitive changes in architecture education and research, the demand for disruptive technological solutions addressing humanity's future challenges, behest a clear position on how to move beyond 'the lab' in the short, mid, and long term.

From the development of discrete 'chunky' architectures based on the mass production of building components, to the proposition of smart architectures from a material perspective that can self-assemble into complex objects and spaces, to the final realization of a digital continuum from the 3d model to the physical environment using robots collaborating in a coordinated dance, lab research is under scrutiny. The proposition of building systems and narrow applications representing the state-of-the-art research faces questions about their real impact in our society in the short, mid, and long term. Can architecture – through computational design – drive the necessary changes in the light of the challenges humanity will face in the next 30 to 50 years? Furthermore, what are the necessary steps that could lead to a disruptive implementation of the promising research that lays in lab setups' boundaries?

Diego Pinochet (convenor)
Professor, School of Design, UAI Chile
PhD Researcher, MIT

Diego Pinochet is a PhD student at the Design and Computation group at MIT, researcher at the Encoded elements lab in the International Design Center at MIT, a visiting Ph.D. Student at the Human-computer interaction group at MIT CSAIL, and a Professor at the School of Design at UAI Chile. Diego Pinochet holds a B.Arch and a M.Arch in the Pontifical Catholic University of Chile (PUC) and a Master of Science in Architectural Studies (SMArchS) from MIT.

His research is focused on computational design and interactive fabrication methodologies, Artificial Intelligence, Robotic Fabrication, Building Information Modelling BIM, and Interactive Applications for creative purposes. His research is focused on advanced computational design and interactive fabrication methodologies using Artificial Intelligence. He is pursuing his PhD degree in Design and Computation at MIT with a major in Human-Computer Interaction and a minor in Machine Learning. He seeks to bridge robotic fabrication with design methodologies to push innovation in architecture and construction through his research.

Stefana Parascho
Assistant Professor, Director creAte Laboratory, Princeton University

Stefana Parascho is a researcher, architect, and educator whose work lies at the intersection of architecture, digital fabrication and computational design. She is currently an Assistant Professor at Princeton University where she founded the CREATE Laboratory Princeton and is co-leading the PhD program in Technology of Princeton's School of Architecture. Through her research, she has explored multi-robotic fabrication methods and their relationship to architectural design. Stefana investigated computational design techniques ranging from agent-based systems to sequential design and optimisation methods. Her goal is to strengthen the connection between design, structure, and fabrication, and boost the interdisciplinary nature of architecture through the development of accessible computational tools and robotic fabrication methods.

Stefana completed her doctorate in 2019 at ETH Zurich, Gramazio Kohler Research. Previously, she received her Diploma in Architectural Engineering in 2012 from the University of Stuttgart and worked with DesignToProduction Stuttgart and Knippers Helbig Advanced Engineering.

Skylar Tibits
Associate Professor of Design Research, MIT
Co-director and Founder, MIT Self-Assembly Lab

Skylar Tibbits is a designer and computer scientist whose research focuses on developing self-assembly and programmable materials within the built environment. Tibbits is the founder and co-director of the Self-Assembly Lab at MIT, and Associate Professor of Design Research in the Department of Architecture.

He is the author of the book Self-Assembly Lab: Experiments in Programming Matter (Routledge, 2016), Active Matter (MIT Press, 2017), co-editor of Being Material (MIT Press 2019) and the Editor-In-Chief of the journal 3D Printing and Additive Manufacturing. He has exhibited installations in galleries around the world, including the Centre Pompidou, Philadelphia Museum of Art, Cooper Hewitt Smithsonian Design Museum, Victoria and Albert Museum and various others.

Awards include LinkedIn's Next Wave Award for Top Professionals under 35 (2016), R&D Innovator of the Year (2015), National Geographic Emerging Explorer (2015), an Inaugural WIRED Fellowship (2014), the Architectural League Prize (2013), Ars Electronica Next Idea Award (2013), TED Senior Fellow (2012) and 2008 he was named a Revolutionary Mind by SEED magazine.

Kevin Saey
Tutor, The Bartlett School of Architecture, UCL
Architect and Researcher, Automated Architecture (AUAR) Ltd.

Kevin Saey is a London based architect and researcher at design and technology consultancy Automated Architecture (AUAR) and Automated Architecture Labs at The Bartlett. He is invested in automation, digital fabrication and computational design. With his background in both architecture, game design and digital arts, he combines various interdisciplinary techniques to develop new and innovative systems, with a focus on innovative timber construction. Currently, he is an architectural design tutor in the B-Pro Program at the Bartlett.

He studied Digital Arts and Entertainment and Architecture in Belgium and obtained a post-professional masters from UCL The Bartlett, where he was awarded the Gold Price for his final project. His collaborative work with Gilles Retsin Architecture has been exhibited at the Tallinn Architecture Biennial in Estonia, the Royal Academy of Arts in London and Digital Futures in Shanghai.

Victor Leung
PhD Candidate, Gramazio Kohler Research, ETH Zurich

Victor Leung received his Bachelor of Arts in Architectural Studies from HKU in 2011 and Master of Science in Architectural Studies (Design and Computation) from MIT in 2016. Victor is currently a PhD candidate in ETH Zurich, working on robotic assembly methods of timber structures with integral timber joints. Victor is obsessed with designing and making custom robots/machines/end effectors for various types of fabrication. He is the technical co-founder of AWAWA timber research, which focuses on the design-to-production cycle of freeform timber joinery. From 2016 to 2018, Victor worked as a technical consultant for digital artist and architects in the realization of kinetic installation and digitally fabricated bespoke components. He has taught digital fabrication and computational design courses in MIT (Boston), ETH (Zurich), HKU (Hong Kong), SUTD (Singapore) and AA Visiting School (Hong Kong).

Encoding and Decoding Patterns of Planetary Urbanization

In 1986 the Earth System Sciences Committee from NASA Advisory Council raised the importance of an understanding of Earth Systems, and how the complex interactions among Earth's components affect its history and evolution. It emphasized humanity's new role as an active participant in the Earth's evolution and, therefore, the need to understand the consequences of human economic and technological activity on the Earth's biochemical cycles. This planetary perspective is rising among the academic community, bringing back epistemological questions that challenge a city-centric approach to the urban phenomenon. The alternative is the concept of "Planetary Urbanization" to describe the extensive, uneven urban fabric shaped in a neoliberal global context.

35 years after NASA's report, the Covid-19 Pandemic demonstrates how unsuccessful humanity is in facing global challenges. Similarly, the disciplines of the built environment seem to be poorly equipped to engage with this Planetary condition. This panel will discuss the positions and approaches that urban designers can adopt to take advantage of the advances in global observations, information systems, and computational methods for the analysis and planning of landscapes, urban and infrastructural systems in the context of Planetary Urbanization. How can we challenge the negative externalities and consequences of a capital-driven Earth System in which a large variety of agents interact in a non-linear way, returning different levels of organization and hierarchies, each of them ruled by their own laws?

This roundtable will bring together researchers with different areas of expertise around the analysis and modelling of natural and urban environments as complex adaptive systems, enquiring how global indicators and changes occurring at the Planetary scale require the incorporation of emerging disciplines. It will explore how the incorporation of decision-making and behaviour might help to inform design scenarios, in the context of a non-linear Planetary Urbanization.

Enriqueta Llabres-Valls (convenor)
Lecturer, the Bartlett School of Architecture, UCL
Mittelsten Scheid Guest Professor, Wuppertal University

Enriqueta Llabres-Valls is a Lecturer in Architecture and Urbanism at the Bartlett School of Architecture, University College London, and Mittelsten Scheid Guest Professor in the Faculty of Architecture and Engineering at Wuppertal University. She holds a degree in Architecture from UPC, Barcelona, and Local Economic Development from the London School of Economics. Her research interest expands from the studies of the built environment to local development concepts such as environmental policy and regulation, globalization, and inequalities.

In her career, she has focused on integrating the concept of Relational Capital in the design process. She leads with Zach Fluker Research Cluster 18 in the MArch Urban Design BPro at the Bartlett. Her career in the practice has been awarded on numerous occasions since she co-founded Relational Urbanism in 2009. In 2017 she co-founded LlabresTabony Architects; Relational Urbanism continues its mission as Relational Urbanism Lab under the umbrella of LlabresTabony Architects.

Michael Weinstock

Chair of Academic Committee,
Founding Director, Emergent Technologies and Design Programme, The Architectural Association School of Architecture

Dr Michael Weinstock is an Architect and a Fellow of the Royal Society of Arts. He is the Founder and Director of the Emergent Technologies and Design program and Director of Research and Development at the Architectural Association. Whilst his principal research and teaching have been conducted at the Architectural Association, he has published and lectured widely at many other schools of architecture worldwide.

His long-term interdisciplinary research agenda, *The Evolution of Sentient Cities*, focuses on the development of 'metabolic' and intelligent urban infrastructures that interconnect buildings, cities and conurbations with a special focus on the evolution of adaptive and responsive systems of existing cities and on developing new paradigms for sentient cities in extreme climates and ecological contexts. His upcoming book is titled "The Architecture of Intelligence: The Evolution of Sentience and the City" (Wiley Academy).

Ying Jin

Reader in Architecture and Urbanism,
Director, Martin Centre for Architectural and Urban Studies, University of Cambridge

Dr Ying Jin lectures on city planning, urban design, and urban modelling. He is particularly interested in understanding how technology, policy and human behaviour affect the development of cities and their infrastructure, and in using this knowledge to create new design solutions. At the Department of Architecture, he leads the Cities and Transport Research Group, which is one of the world's leading centres in the creation and use of conceptual and practical models for cities and city-regions. Among a wide range of research projects, Dr Jin leads the city-scale data science and urban modelling applications at the EPSRC Centre for Smart Infrastructure and Construction.

Dr Jin is the current Director of the Martin Centre for Architectural and Urban Studies, and is the lead convenor of the international symposia on Applied Urban Modelling. He currently leads the COVID-19 related modelling efforts in Cambridge within the Royal Society's Rapid Assistance in Modelling the Pandemic (RAMP) programme.

Rosalea Monacella
Design Critic in Landscape Architecture, Harvard GSD
Co-founder, OUTR Research Lab, RMIT

Rosalea Monacella is a registered Landscape Architect and has undertaken research on a number of cities around the world, and generated urban masterplans that explore design at the nexus of the urban and natural environments. She has been the recipient of a number of national and international awards and grants related to her practice-based research as co-founder of the OUTR Research Lab at RMIT University Melbourne, Australia.

Rosalea's expertise is in the transitioning of the urban environment through a careful indexing and shifting of dynamic resource flows that inform the landscape of contemporary cities. As Chief Editor for 10 years, she has led the development of Kerb Journal to become a significant publication in the discipline that engages and challenges the discourse of landscape architecture. She holds a PhD from RMIT University, a Master's in Landscape Urbanism from the AA School London, UK, and a Bachelor of Architecture from RMIT University.

TABLE OF CONTENTS

Computational Design Education, Theory and Methodology

A COMPARATIVE ANALYSIS OF THE TOOL-BASED VERSUS MATERIAL-BASED FABRICATION PEDAGOGY IN THE CONTEXT OF DIGITAL CRAFT

SAMMAR ALLAM[1] and SEMA ALAÇAM[2]
[1]*Modern Sciences and Arts University*
[1]*samar.allam@gmail.com*
[2]*Istanbul Technical University*
[2]*alacams@itu.edu.tr*

Abstract. This study presents the comparative analysis of two undergraduate courses which focus on introducing digital fabrication to design students. The duration of the compared courses are 5 weeks and 7 weeks respectively. The study employs action research methodology, while the theoretical lectures, weekly exercises, materials, fabrication tools and techniques, and students' outcomes were used as data sources. Particularly the material-based pedagogy and tool-based pedagogy of the compared courses are evaluated in relation with the tools, materials and techniques. The outcomes of the study is expected to provide insights for instructors and design students in the context of digital craft.

Keywords. Digital Craft; Fabrication Techniques; Design Pedagogy; Tool-Based Fabrication; Material-Based Fabrication.

1. Introduction

Over the last decades, there has been a growing interest in the integration of required skills for digital fabrication with design education. One of the challenges in digital fabrication pedagogy remained as how the skills might be introduced to undergraduate students while they have not gained enough experience in designing. Digital fabrication in architecture (Kolarevic, 2003) and architectural pedagogy (Duarte et al., 2012; Celani, 2012; Blikstein, 2013; Sharif & Gentry, 2015; Varinlioglu et al., 2016; Pitkanen et al, 2019) is not a new topic. Apart from the changing student profiles, the increase in access opportunities of architecture schools to digital fabrication tools, the diversification of techniques and methods used, and the material-based experimental approaches make it necessary to discuss the pedagogy of digital fabrication again and again. Adopting from Sheppard et al. (2008), Celani (2012) introduces three pedagogical models ranging from the most defined to open ended approaches called controlled experiments, semi-structure experiment, open experiments and projects. This paper focuses on open experiment models in architectural education with a special emphasis on two lenses conceptualized as tool-based and material-based fabrication pedagogies as delineated in Figure 1.

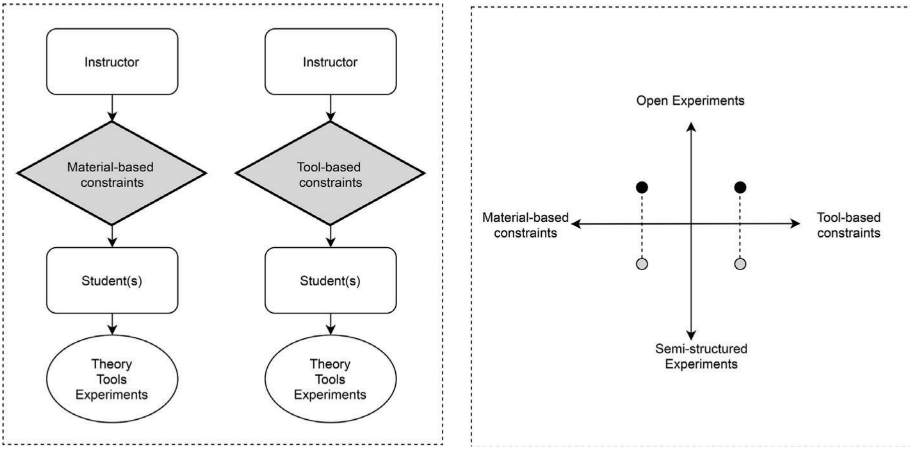


Figure 1. a: Adopted from Celani (2012:476). b: Experiment-constraint relationship.

2. Digital Fabrication Pedagogy

Design Pedagogies have been controversial for decades. Regarding the reflection of the digital fabrication tools, techniques, methodologies into architecture education, there can be listed three transformative factors that have been influential in shaping today's pedagogical models. Over the last two decades, it has been getting easier for architecture schools or architecture students to access tools for digital fabrication. The second factor is the change in the actions of designing and making with the transformation of the design-production flow into integrated processes such as file-to-factory, design-to-production. Relatedly the growingly body of knowledge and complexity of the processes in design and fabrication necessitated novel approaches. The third is the paradigm shift from "instructive" teaching to active learning approaches (Vrouwe et al., 2015), giving the due to students.

Further to the establishment of the Center of Bits and Atoms (CBA) in MIT Media Lab in 2001, institutionalization of digital fabrication laboratories continued with an increasing momentum (Url-01). This development affected the motivation to define a minimum common denominator for the tools that should be in the digital fabrication laboratories and also provide these production tools for architecture schools. Apart from the concrete tools available in FABLABs, this situation also led to the formation of an abstract maker culture and the spread of do-it-yourself (DIY) techniques.

Fabrication labs deal with several parameters in which a designer has to manifest and demonstrate an algorithmic design to the real world with multiple scales as a prototype or scale 1:1. Reflections of fabrication labs into academia have faced multiple challenges due to students' different hands-on design or algorithmic design skills. Oxman (2007) offered "fabrication-based" design and "digital craft" terms. Oxman's (2007) digital craft term suggests the design process, guided by fabrication rather than production as a result of design. Therefore, the reciprocal information flow between the designer and the design object, material and digital model, analog and digital, prototypes and their iterations enable a rich potentialities domain for designers. Celani (2012) provides a comprehensive overview on the reflections of digital fabrication on architectural curricula, underlining the challenges of introducing digital fabrication technologies to novice students who have limited knowledge of parametric/algorithmic/computational design methods and limited experience in design. In this case, existence of complementary courses or workshops on specific skills such as scripting, programming, parametric modelling; specific techniques on analog or digital ways of making such as folding, cutting, molding, etc.; and courses binding making processes and design would be also crucial factors affecting students' learning process. Hemsath (2010) discusses the potentials of didactic strategy of teaching digital fabrication in architecture education, while underlining the interconnected nature of the skills such as computational design logic, digital fabrication and programming. Agirbas (2015) approaches digital fabrication as a new mode of sketching in undergraduate level, through insertion of material-based design strategies. Considering the tacit dimensions of interaction between the designing subject and the material space, El-Zanfaly (2015) suggests the term I3 as an abbreviation of imitation, iteration and improvisation. In El-Zanfaly's (2015) proposition, human as a perceiving and experiencing subject is considered as a crucial part of a situated craftsmanship activity. Fabrication laboratories or FABLABs provide a collaboration ground for students, and teachers or instructors to investigate materials' potentials and different tools or machines throughout a design process. Considering the pendulum between open-ended design activities and structured exercises, Pitkänen et al. (2019) uses the term "scaffolding".

2.1. TOOLS AND TOOLING

The digital fabrication tools that can be used in a design are directly related to the materials selected and the desired production time depending on the budget of a project. Another constraint is available technology which covers not only the mechanical parts of a tool but also software, processes, operations and the flow of information. When we add the designer to this equation, topics such as the interaction between the designer and the tool, the creative use of the tools by the designer, and the designers discovering new tools needs to be discussed. Therefore, different than merely using a tool, tooling is a versatile and multifaceted concept that is not easy to unfold without appropriate contexts.

Computer numerical control (CNC), laser cutters, rapid prototyping and 3D printing machines, robotic arms can be listed as the most common digital fabrication tools. Apart from the digital fabrication tools, analog/conventional tools for trimming, cutting, filing or forming are widely used in model making processes. Modelling, prototyping and fabrication processes in architecture are conducted with concepts of computational design thinking. Gonenc Sorguc et al. (2019) underlines the priority of creating an awareness on emerging technologies instead of merely teaching the tools.

Communication with the different design models through an analog, mechanic, and digital processes is a cyclic and open-ended activity that provides insights to designers. Aranda and Lasch (2006) investigate the tooling concept through a series of design processes. In those projects “tooling” becomes a medium in which different techniques such as spiraling, packing, weaving, blending, cracking, flocking, and tiling (Aranda and Lasch, 2006) manifest themselves in geometry, form, material, and experiential representations.

Digital fabrication tools and processes necessitate relevant types of data, therefore the way information is coded as data matters. Translation from one mode of representation to another is required at every step of design and production process. In some tools, this conversion process is automated. There are many conversion processes including but not limited to conceptual model to design model, geometric model to topological model, digital model to production model, one scale to another; 3D CAD model to GCode, and vice versa. Regarding the rapidly changing nature of digital fabrication technologies the mechanical components of tools and their end effectors, soft components (graphical user interface, algorithms and software) and their versions, computer aided representations of design models, materials can be considered as active agents of a digital fabrication process, apart from the designing human subject. In this context, instead of defining a concrete body of knowledge in the architectural curricula, providing temporal scaffolds (Pitkänen et al., 2019) for introducing the tools becomes more crucial.

2.2. MATERIALS AND MATERIALITY

Oxman (2010) discusses materiality as a design driver in the context of new materialism. In this conception, material properties inform form and structure decisions in a bottom-up design strategy by incorporating physical form-finding strategies with digital analysis and fabrication (Oxman, 2007; Oxman, 2010).

Beorkrem (2007) introduces a wide range of material techniques and strategies with a specific focus on wood, metal, concrete/masonry, composites/plastics, and recycled/pre-cycled materials. The notion of materiality in the context of digital fabrication is closely connected to the affordances of tools and the interaction between the materials and the techniques applied. When it comes to digital fabrication pedagogy, exploring each material characteristics and potentials in fabrication and design is the first step to orient students into computational thinking design dependent on the used material. Designs have been formed and modeled using multiple substances while nourishing students‘ tactile sense to stimulate students’ sense of material perception and modelling capabilities. Each material varied from rigid to ductile, from porous to solid guides students to use different design techniques to avoid material failure or collapse. Materials with almost opposite characteristics have been imposed to test different modelling and design techniques through a material-based fabrication process.

2.3. FABRICATION STRATEGIES: TECHNICS AND ACTIONS

Aranda and Lash (2006) used a classification of a series of actions that ultimately elicited specific behaviors, namely spiraling, packing, weaving, blending, cracking, flocking, and tiling. Iwamoto (2013) directly focuses on the action and considers actions as a particular function of material. In other words, actions such as sectioning, tessellating, folding, contouring, and forming are considered as both material techniques and design strategies in Iwamoto's (2013) conception. Considering open-ended processes of design and fabrication, the list of the actions can be expanded by designers depending on the needs and feedback from experimental trials.

3. Methodology

Digital and analogue fabrication relies on multiple parameters and variables as illustrated earlier. The study employs action research methodology, while the theoretical lectures, weekly exercises, materials, fabrication tools and techniques, and students' outcomes were used as data sources. The students are expected to gain an understanding of a variety of tools, techniques, materials, and their use in architecture in the context of digital fabrication and gain insights into the workflow and data flow in CAM processes, as well as gain hands-on experience on representing and producing complex geometries by using digital modelling and fabrication tools in both of the courses as learning outcomes. Another common factor between both courses is the fabrication of both geometric and organic forms using multiple fabrication design-based techniques like contouring, repetition, recursion, rotation, folding, stacking and assembling. The main difference between the mentioned courses is the pedagogical strategies namely tool-based and material-based that were employed.

3.1. TOOL-BASED FABRICATION PEDAGOGY

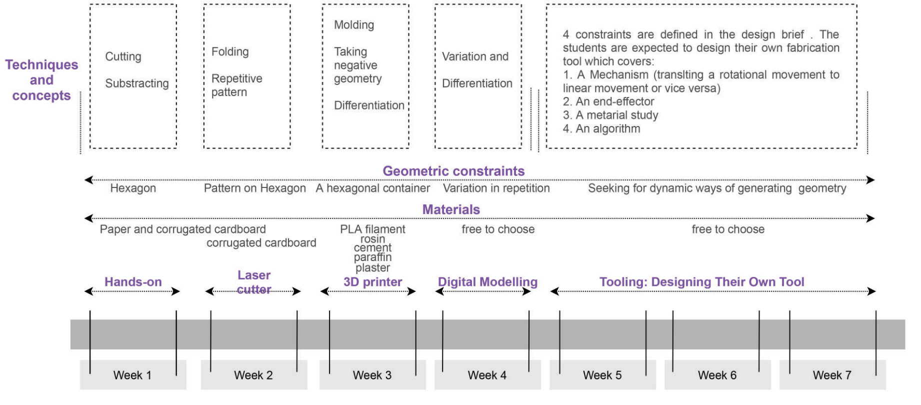


Figure 2. Weekly timeline analysis regarding technique , materials, lectures and concept in a tool-based course introduced to level 2 and 4.

Taught Courses on digital fabrication in undergraduate level aim to achieve new detail solutions for the known design problems, support students' exploring the limits of the material and fabrication strategies in terms of static and dynamic, and developing new and novel-material in the design and construction process, engaging the algorithms and the input collected from physical environmental, as well as test the limits of digital fabrication as shown in Figure 2

3.2. MATERIAL-BASED FABRICATION PEDAGOGY

3D visualization course has focused on developing students' skills through tackling with different materials then manipulating others through digital tools. Digital design has been extensive with metal sheets and paper boards through patterns generation, folding, cutting, and trimming while investigating subtractive fabrication. Then by the end of the course another massive design is modelled using a 3d printer to explore more fabrication. Free-form fabrication has been manifested at the beginning with prototypes using tactile senses on discarded materials, clay, and wire. At the end they follow the same fabrication techniques with scale 1:1 with wooden boards to visualize their designs while adding some textures with patterns using laser cutters.

This material-based course has encompassed three different fabrication techniques while blending digital with analog to fit a tight 5 weeks' schedule. Main sources of inspiration to students are nature (biomimicry), geometry and culture. Shifting their design skills from 2D to 3D forms has been mastered through different tactics include folding, contouring (one-way and two-way as waffle), stacking or packing, Assembling parts from subtraction, repetition of elements or recursion which are the distinctive patterns and strategies of parametric design as yielded in figure 3.

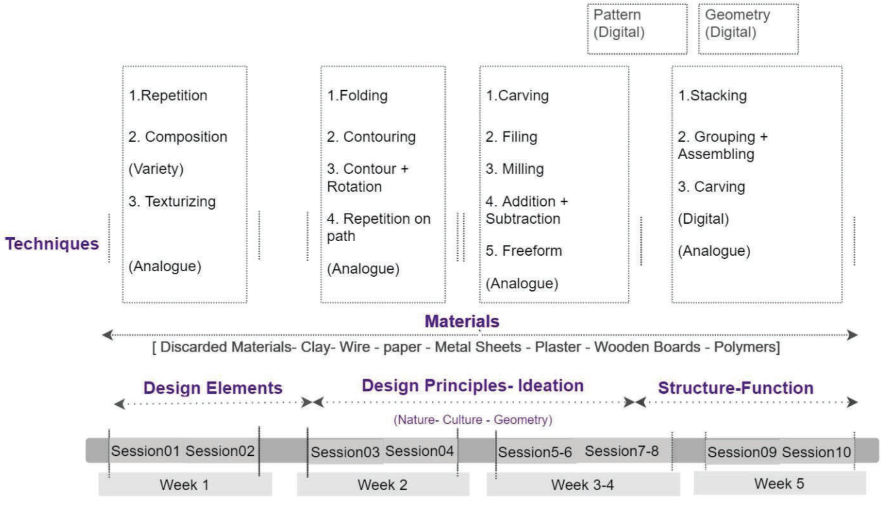


Figure 3. Weekly timeline analysis regarding techniques , materials, lectures and concept in a material-based course introduced to level 2 .

This emphasizes the analog form-finding by well establishing tactile sense with different materials' characteristics and intrinsic boundaries.

4. Case Study

The case study consists of comparison of two undergraduate courses which have been introduced to different student groups relying on their academic level- one is tool-based introduced to level 2 and 3 students - and another is material-based conducted to level 2 students. Each course investigates the current applications of digital fabrication methods in architecture with their theoretical foundations.

4.1. AIM AND SCOPE

The aim of this research is to share both courses experiences and interchange learnt lessons to enhance performance and upgrade digital fabrication pedagogy. Similarities and differences discussion between both curriculum has raised many creative approaches in which both suthers and readers can consider in academia.

4.2. ANALYSIS

Firstly, a material-based course conducted to level 2 students has conveyed multiple materials to stimulate students' tactile senses through exploring different materials characteristics and fabrication potentials as yielded in figure 4. Secondly, a tool-based course presented to level 2 and 3 students has investigated students ability to create their own fabrication tool based on subtractive, additive and free-form ones creating their own process. Design modeling in both courses has benefitted from computational design-based methodology that has oriented the entire fabrication process.

At last, both courses have triggered students' conceptual thinking through the realm of fabrication processes. Both have upgraded their CAM (Computer-aided manufacture) perception in both environments- analogue and digital.

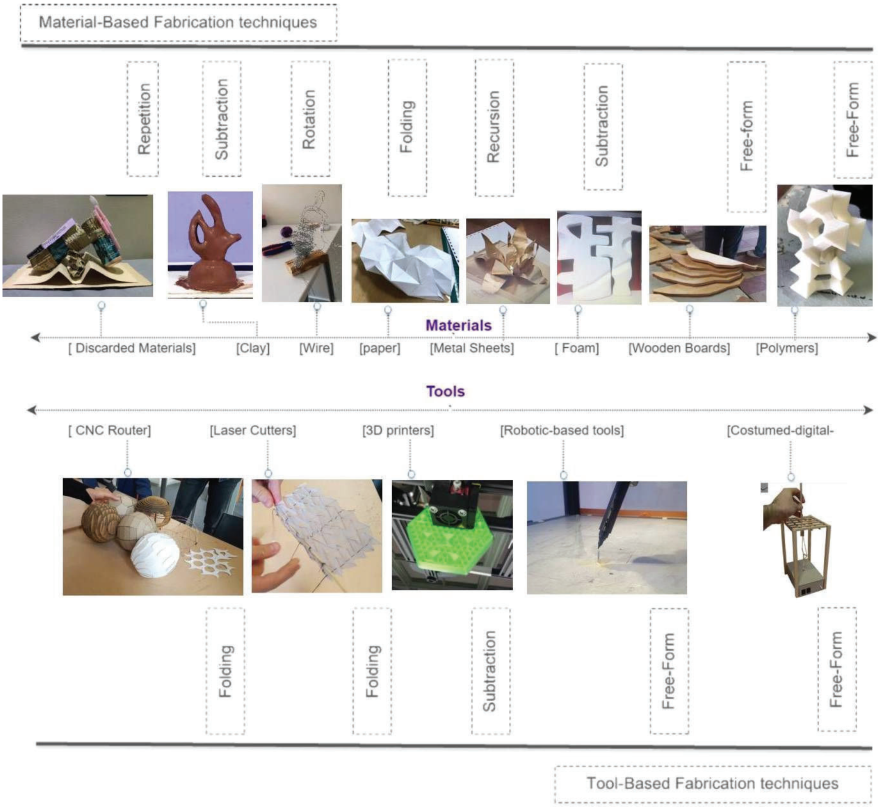


Figure 4. Material-Based fabrication Technique versus Tool-Based one regarding design methodologies; Two courses remarkable students output comparative analysis.

4.3. COMPARISON AND EVALUATION

Both courses attempt to manifest materials and tools manipulation skills of undergraduate students to implement and algorithmic design. Some students have developed a sophisticated mindset to manage digital tools after experimentation the potentials of each material through its physical and mechanical characteristics. However, combining multiple materials and tools together is rather an advanced process that requires more time. Such challenge can motivate students to pursue further exploration in advances courses, workshops, or classes as postgraduate.

Students of both courses tend to manipulate geometric patterns while adopting additive fabrication techniques. Their design potentials were attracted more through combined, morphed and transformed geometries as illustrated in Figure 5.

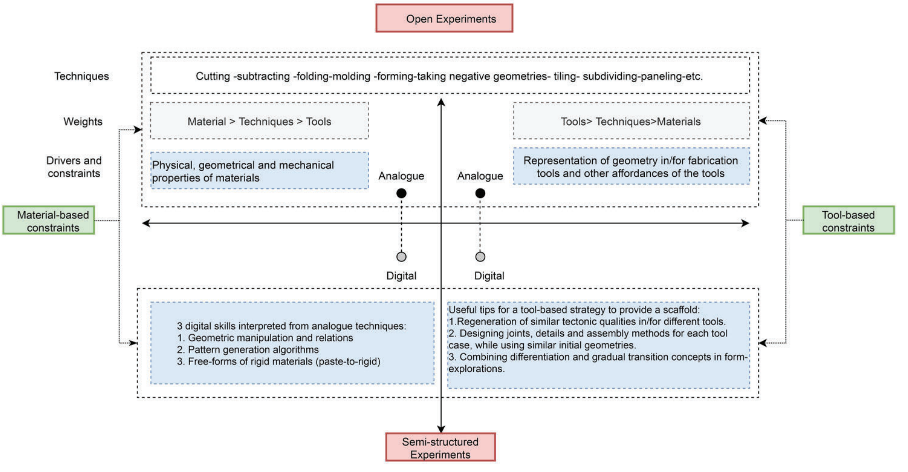


Figure 5. Mapping the pedagogical approaches.

5. Concluding Remarks

This study focuses on the comparison of two courses with similar learning outcomes, in which digital fabrication approaches are taught to undergraduate architecture students. An experiment-constraint relationship matrix, which covers a semi-structured and open experiment axis, as well as tool-based constraints and material based constraints axis was used to gain a better understanding about the teaching process and its evaluation. The main motivation of the study is to evaluate our own teaching methods and make inferences that will be useful for the teaching of the digital fabrication course in the following years.

Initial results show that translation of one form of design information to another, from one tool to another, from one technique to another, from one medium to another, in other words the process of translating the design information has potential to support students' engagement in both cases. In this sense, how to provide common ground and a sense of continuity among different exercises might become crucial. In the presented cases, the notion of scaffolding has contributed a traceable backbone throughout the semester.

Moreover, an open experiment might not be the best thing to start with novice students and get satisfactory results. In the observed cases, semi-structured experiments oriented students toward reliable results which makes them gain more self-confident and encourage them to push their boundaries. The results might be different in the cases where complementary courses focusing on algorithmic/computational thinking skills are available. It can be asserted that semi-structured exercises have potential to support novice students' engagement and motivation in the context of learning and teaching digital fabrication.

Acknowledgment

The authors would like to thank CDS-213 students of Modern Sciences and Arts University who participated to the course in the 2020 Summer Semester, and MIM418E Students of Istanbul Technical University who participated to the course in the 2019-2020 Fall Semester.

References

"Url-01" : 2021. Available from <https://www.fablabs.io/labs/map> (accessed 07th February 2021).

Agirbas, A.: 2015, The use of digital fabrication as a sketching tool in the architectural design process, *Real Time-Proceedings of the 33rd eCAADe Conference*, Vienna.

Aranda, B. and Lash, C.: 2006, *Tooling*, Princeton Architectural Press, New York.

Beorkrem, C.: 2017, *Material strategies in digital fabrication*, Routledge..

Blikstein, P. 2013, Digital fabrication and 'making'in education: The democratization of invention, *in* C. Büching and J. Walter-Herrmann (eds.), *FabLabs: Of machines, makers and inventors*, Transcript Publishers.

Celani, G.: 2012, Digital Fabrication Laboratories: Pedagogy and Impacts on Architectural Education, *Nexus Network Journal*, **14**, 469-482.

Duarte, J.P., Celani, G. and Pupo, R. 2012, Inserting Computational Technologies in Architectural Curricula, *in* N. Gu and X. Wang (eds.), *Computational Design Methods and Technologies Applications in CAD, CAM and CAE Education*, IGI Global Publisher , 390-411.

El-Zanfaly, D.: 2015, [I3] Imitation, iteration and improvisation: Embodied interaction in making and learning, *Design Studies*, **41**, 79-109.

GonencSorguc, A., Krusa, M. and Ozgenel, C.F.: 2019, A Computational Design Workshop Experience for 21 Century Architecture Education, *eCAADe 37 Sigradi 23*, Porto, 127-136.

Hemsath, T.L.: 2010, Searching for innovation through teaching digital fabrication, *28th eCAADe Conference Proceedings*, 21-30.

Iwamoto, L.: 2013, *Digital fabrications: architectural and material techniques*, Princeton Architectural Press.

Kolarevic, B.: 2003, *Architecture in the digital age: design and manufacturing*, Taylor & Francis..

Oxman, N.: 2007, Digital craft: fabrication based design in the age of digital production, *Workshop Proceedings for Ubicomp 2007: International Conference on Ubiquitous Computing*, 534-538.

Oxman, N.: 2010, Structuring materiality: design fabrication of heterogeneous materials, *Architectural Design*, **80**(4), 78-85.

Pitkanen, K., Iwata, M. and Laru, J.: 2019, "Supporting Fab Lab facilitators to develop pedagogical practices to improve learning in digital fabrication activities, *FabLearn Europe 2019*, Oulu.

Sharif, S. and Gentry, R.: 2015, Design cognition shift from craftsman to digital maker., *Emerging Experience in Past, Present and Future of Digital Architecture, Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2015)*, Daegu, Korea.

Sheppard, S.D., Macatangay, K., Colby, A. and Sullivan, W.M.: 2008, *Educating engineers: Designing for the future of the field*, Jossey-Bass, Stanford, CA.

Varinlioglu, G., Halici, S.M. and Alacam, S.: 2016, Computational Thinking and the Architectural Curriculum-Simple to Complex or Complex to Simple?, *eCAADe 2006*, Oulu.

Vrouwe, I., Luyten, L. and Pak, B.: 2015, Teaching and Learning CAAD and CAM in a Fluid Era, *eCAADe 2015-33rd Annual Conference*.

SECRET WHISPERS & TRANSMOGRIFICATIONS:

A case study in online teaching of Augmented Reality technology for collaborative design production.

GARVIN GOEPEL[1] and KRISTOF CROLLA[2]
[1]*The Chinese University of Hong Kong*
[1]*garvin.goepel@link.cuhk.edu.hk*
[2]*The University of Hong Kong*
[2]*kcrolla@hku.hk*

Abstract. This paper focusses on teaching the integration of Augmented (AR) and Mixed Reality (MR), combined referred to as Extended-Reality (XR), and photogrammetry technology into handicraft using an online-taught digital fabrication workshop as an educational case study. Set up in response to restrictions from Covid-19, workshop "Secret Whispers & Transmogrifications" had students and instructors around the world participate in a course that challenged our understanding of educating craft and technology without the necessity of physical presence. The integration of AR into craftsmanship enhances architectural design and fabrication processes as it overlays computation-driven information onto the hands of the end user. These computer-numerically-controlled workflows incorporate and rely on manual actions as an integral part of a process that is typified by inevitable, unpredictable, human error. In doing so, the workshop questions common infatuation with precision in digital fabrication and construction by striving for alternative approaches that embrace the inaccuracies and imprecisions innate to technologically-augmented human craftsmanship. Participants took part in a hands-on clay modelling "secret whispers" experiment that was designed to introduce theoretical concepts and applications of XR technology into the production workflows. This paper concludes by highlighting that the accessibility of today's technology enables AR-enhanced craftsmanship to be successfully taught remotely and online.

Keywords. Collaborative design; augmented-reality; mixed reality; human-computer interaction; tolerances and error.

1. Introduction

Workshop "Secret Whispers & Transmogrifications" had students and instructors around the world participate in a course that challenged our understanding of educating craft and technology without the necessity of physical presence as being set up in response to restrictions from Covid-19. An online taught digital

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 21-30.

fabrication workshop was used as an educational case study on teaching the integration of Augmented (AR) and Mixed Reality (MR), combined referred to as Extended-Reality (XR), and photogrammetry technology into handicraft.

1.1. COURSE FOCUS: INCREMENTAL SLIPPAGE

The workshop website describes how ”*[...] Augmented Reality (AR) integration into craftsmanship promises a radical overhaul of architecture and design production as it brings computational power directly to people's fingertips. Yet, with the hand becoming a key component in these computer-numerically-controlled workflows, innate and unpredictable human imprecision, inaccuracy, and error become an inevitable part of the equation.*” (Crolla et al., 2020). By seeking beauty in incremental slippage from technologically augmented human craftsmanship, ”Secret Whispers & Transmogrifications” challenged the ”Digital's” obsession with control and precision. Participants were exposed to both theoretical concepts and practical applications of AR technology integration in design and production workflows by participating in a hands-on ”secret whispers” experiment. Positioning itself in a ”Post-Digital” context, the work employs alternative notational systems in implementation methods that aim at humanising digital technologies through interplay between digital and analogue material systems (Crolla, 2018).

1.2. COURSE CONTEXT: AR AND CRAFTSMANSHIP

With the arrival of easily accessible AR/MR technology, opportunities present themselves for an increased and productive dialogue between collaborating designers and craftsmen, providing greater local agency and prospects for more diverse design output (Goepel and Crolla, 2020). Architects and engineers commonly use AR applications to facilitate information extraction from design information models to improve the efficiency and effectiveness of workers‘ tasks (Chi et al., 2013; Chu et al., 2018). These include onsite applications where AR can be seen implemented in Smart Helmets and Tablets, primarily for helping engineers to make more accurate and rapid judgments for construction review tasks (Ren et Al., 2017). In industrial settings, case studies of AR systems' user experiences have demonstrated their potential to reduce errors in assembly and improve the quality of maintenance work (Aromaa et al., 2018).

Showcases for the integration of AR into fabrication and design processes in architecture and the arts include work from peers that used MR for tasks such as bricklaying (Franco, 2019) plywood construction (Jahn, Wit and Pazzi, 2019) steel artwork production (Jahn et al. 2018), bamboo construction (Goepel and Crolla, 2020), and many more, indicating that a paradigm shift in manual production has been set in motion. Instead of surrendering human skill to automation in manufacturing, AR enhances the human capacities to participate in complex processes through simplified instructions (Goepel, 2019).

We foresee human-computer interaction as in AR/MR to become far more effective in a “Post-Digital” context than e.g. robotics or other forms of computer-numerically-controlled (CNC) production, because AR enables augmentation of onsite skill through the direct visual overlay of specific holographic instructions onto manual actions (Goepel and Crolla, 2020).

1.3. COURSE TASK: SCULPTING AND 3D REFERENCING

The workflow and methodology applied in this workshop relied on 3D referencing and 3D replication. This study builds up on prior research in which a series of AR-aided clay sculpting methods were developed and tested in a demonstrator case study and adds to this more elaborate AR-aided sculpting method for remote operation.

2. Method

2.1. SETUP

The workshop set out as an experiment in which a set of fourteen sculptures, of which digital model files were sourced online, was altered through several morphing cycles that oscillated between the analogue and the digital world. Each iteration began by hand-modelling a sculpture based on a given digital file through the aid of holographic instructions, displayed through an AR application on the participants‘ mobile devices. The result was then captured through multiple photographs, taken with these devices’ high-resolution cameras, that were then processed in a photogrammetry software. The resulting digital 3D geometry model files were then passed on to the next person for the following sculpting cycle until four iterations were achieved (see Figure 1, 2 and 3).

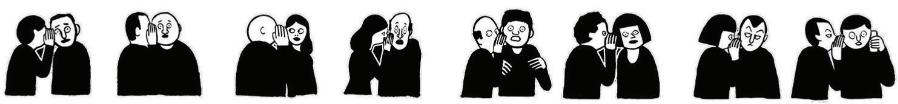


Figure 1. Workshop concept, based on “Chinese Whispers” (image by Jean Julien).

Figure 2. Left: Original sculpture. Middle left: Iteration 1 by Student X. Middle right: Iteration 2 by Student Y. Right: Iteration 3 by Student Z.

To speed up the start of the workshop, the instructors preselected fourteen figures from free access online libraries such as 3D warehouse. These figures were resized and trimmed to similar-scale sculptures using a Grasshopper® script in 3D modelling software Rhinoceros®. Mesh resolutions were automatically optimised to be suitable for seamless AR streaming, keeping sufficient detail for precise modelling. These models were distributed to each student for the first iteration of the secret whisper experiment. Throughout the process, these were gradually transmogrified in three further steps until they reached their final form (see Figure 2 and 3).

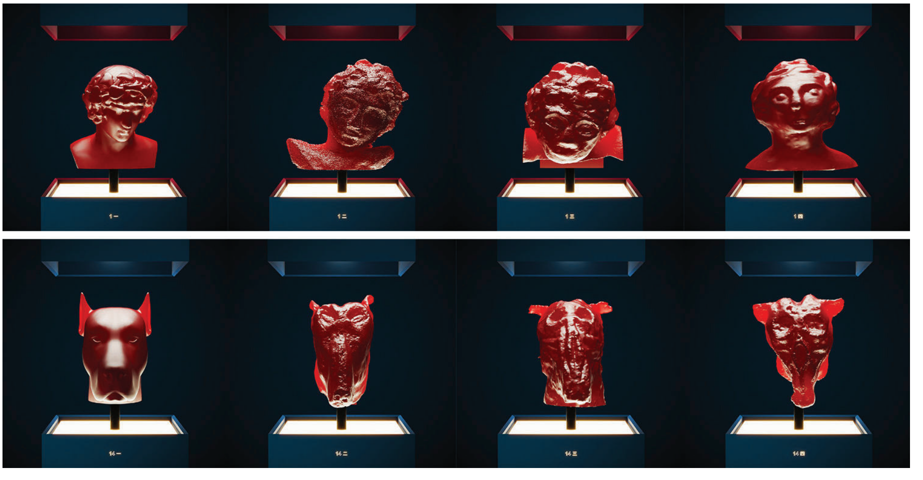


Figure 3. Sculpture transmogrifications.

2.2. BESPOKE AR-APP

Fologram®, a Grasshopper® software add-on, was used to stream model data through a custom developed AR application to the mobile handheld devices. The app references itself and the clay block in the real-world environment through an image target placed on the edge of the clay block (see Figure 4).

The custom AR application starts by using a digital bounding box which equals the size of the physical clay block with the to-be-modelled digital sculpture in its centre. The digital sculpture is intersected with several planes to identify and highlight its contouring profiles. An interactive parametric slider determines the spacing between each plane in X, Y, and Z direction. Intersection points are connected with a curve, resulting in several silhouettes in each direction. Using simple control buttons inside the app, users can switch between the X, Y, and Z axis, and through sliders one can decide which silhouette is shown.

Figure 4. View through smartphone of customised AR application, showcasing the overlay of holographic instructions on top of the physical clay model.

Figure 5. Analogue sculpting process informed by holographic instructions.

Augmented reality is then used to holographically overlay this digital information directly on top of the analogue sculpture. App controls give users the real-time ability to switch between the display of the predefined contours and silhouettes, allowing them to decide, as they sculpt, which necessary guides to access to inform their addition or removal of material. This process is repeated until an analogue interpretation of the digital file is accomplished (see Figure 5 and 6).

Figure 6. Top: View through mobile device with holographic instructions and view on clay model where mass is removed or added accordingly. Bottom: Sculpting while viewing through mobile device with holographic instructions. .

2.3. PHOTOGRAMMETRY

Photogrammetry software packages Meshroom® and ReCap® were then used to capture the analogue clay sculpture and bring it back into a digital modelling environment. A photo series taken by the participants was used as input to regenerate a digital 3D model approximation of the analogue model (see Figure 7). This digital model was then passed to the next participant for the next modelling iteration.

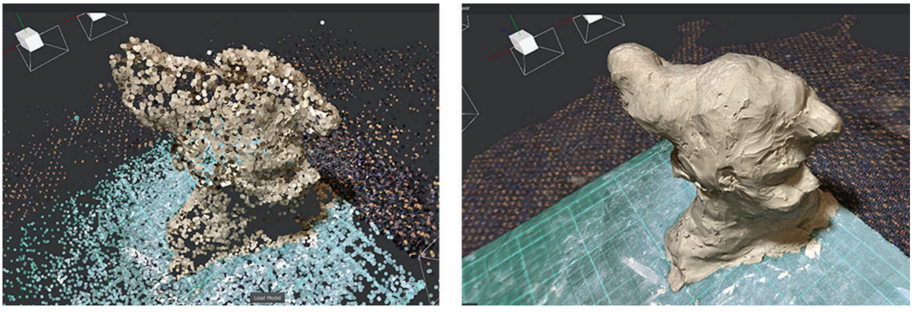


Figure 7. View of scanned clay model in Meshroom photogrammetry software.

Photogrammetry typically requires dozens of pictures of one object, a software setup, processing time to convert the images into a 3D model, and post-processing time for cleaning the mesh outcome in a 3D modelling software. This process can take up to a few hours, depending on the used photogrammetry software.

Good photography skills are crucial to achieve successful photogrammetry result. The object should be captured from all 360-degree angles and from the top, middle and bottom. Image quality and resolution also affects the scan results, with more recent handheld devices with better camera specifications typically producing better results. Artificial lighting can possibly unfavourably affect the scan outcome, whereas daylight conditions typically increase the quality of the final scan. Used computer's processing power also played an important role, as one might only see an unsuccessful result after hours of processing, impacting timelines. Clay properties also effected the scanning result: darker sculpting clays resulted in less detailed scans than light-coloured material, as shadows and highlights of the sculpted clay seemed to be less recognisable for the cameras on dark surfaces.

3. Outcome

Unique characteristics and qualities emerged as the transmogrifications by multiple authors accumulated with each step. Three cycles were completed, producing a total of 56 sculptures. Their digital models were rendered for display in an online exhibition presenting the collection in a virtual space visible by means of walkthroughs with 360-degree views (see Figure 8).

This exhibition and website was created with free online virtual tour creator Theasys®, a tool which allows for a series of digital renderings to be interconnected through a navigation system to create and publish a 360° Virtual Tour. The exhibition can be either experienced with virtual reality goggles as an immersive 3D environment or through web browsers where visitors can navigate through the exhibition space by clicking on arrows and using the mouse or finger to direct the view.

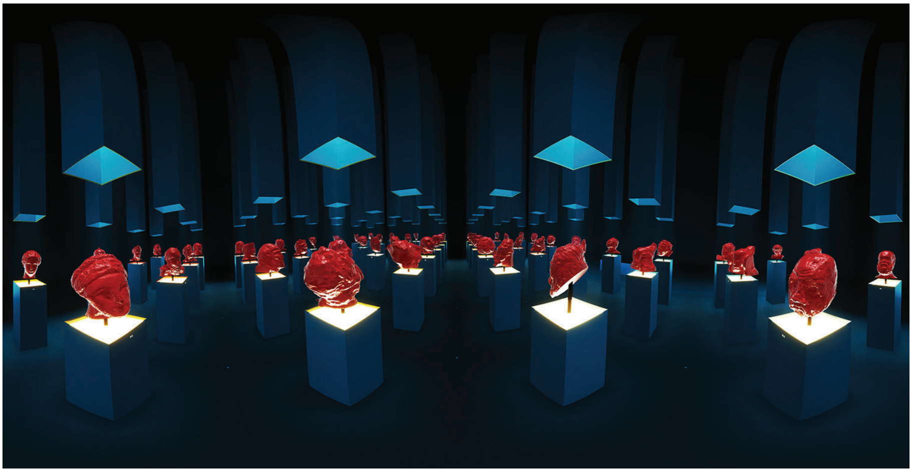


Figure 8. Virtual exhibition.

Exhibition visitors can observe and compare the sculpture transmogrifications which are highly informed by the incremental slippage in the translation of the sculptures. Rather than striving for accuracy in precise replication, the show highlights the emergent characteristics in each iteration, leaving within each sculpture a trace to the multiple co-authors' hands, making the overall a collective art piece.

The photogrammetric scan and the human sculpting hand became the two contradicting authors, placed in a bi-directional dialogue between accuracy and transgression throughout a modelling process centred around the holographic guidelines. A high-resolution scan, for example, will directly affect a following iteration's similarity far more than a low-resolution scan, and a precise replication of the holographic overlay will sway the following scan more favourably than an unprecise copy. The level of participants‘ prior sculpting skill also substantially differed within the group, which can be observed in the execution of the models. The participants' learning curve for working with holographic guides also affected the resolution of the outcomes. Each participant's first iteration can therefore be seen as a first prototype with the technique, rather than as a well-executed, holographically guided model which can be found the last iterations.

4. Discussion and future opportunities

The scanning technology used in this workshop relied on photogrammetry, which today can be accessed with free software and does not require additional hardware. The integration in latest mobile devices of LiDAR hardware, a technology found for example in the fourth generation Ipad Pro and the Iphone 12 Pro, presents an increase in usability and quality of 3D scanning technology. LiDAR stands for light detection and ranging. The LiDAR scanner measures how long it takes light to reflect back from objects, so it can create a depth map of any space you're in (Apple, 2020). LiDAR has been used for several years now, for example in self-driving cars, robotics and drones, but the integration into a mobile device opens up a whole new world of possibilities for 3D scanning and the use of AR. It allows devices to understand their surrounding space by mapping it in 3D, enabling the accurate placement and interaction with virtual AR objects. It also allows for the generation of 3D objects based on a quick scan with apps such as 3D Scanner App. Within a few minutes one can create a meshed-out 3D object. The quality of the 3D mesh scan is not as decent as the method presented in this paper yet, but considering the acceleration of the workflow, we can see a potential use of integration LiDAR mobile 3D scans for future applications.

XR integration today has become rather straightforward: workshop participants were able to quickly grasp the setup and installation of the apps, and an intuitive understanding of the holographic instructions could be observed. The user-friendly interface of the Fologram app permitted participants to just follow the instruction given by the bespoke guides. The Fologram app was streaming information directly from a Grasshopper file, rather than being a standalone app, so a prior knowledge of that platform was helpful, as this allowed users to adapt and customise certain functionalities.

Future studies could benefit from incorporation of other softwares, such as Unity Reflect, that allow sending data from third-party plugins such as Rhinoceros, Revit, or Sketchup to a Unity Reflect cloud server or to a Reflect server on your machine. This data is then pushed to the device of choice, such as IOS or Android phones or the Unity Editor itself where the data can be enhanced. This improves overall workflow, because a live data link can be set up between the base geometry and the applications. This data change can be viewed simultaneously by users across multiple applications.

5. Conclusion

Today, AR enhanced craftsmanship has the ability to be taught remotely and online around the world by the aid of XR integration. This study demonstrates that XR and photogrammetry technology have the ability to enhance clay modelling craftsmanship, allowing for a technology-driven democratisation of skill. The incremental slippage between sculpting iterations showcases how, as the hand becomes a key component in these computer-numerically-controlled workflows, inevitable innate and unpredictable human imprecision, inaccuracy, and error can become a constructive, qualitative part of the creative process. In doing so, this study proposes a counter-narrative to common research on robotic or CNC fabrication aiming for high accuracy and precision.

Acknowledgement

This workshop was taught by Dr. Kristof Crolla (LEAD/HKU), Garvin Goepel (CUHK), Keung Shing Fung, Adwin (CUHK), and Chan Tsz Sun, Ovan (CUHK) as part of the Digital FUTURES World Workshops from 27 June to 03 July 2020, with participants Akshata Ghuge, Duong Nguyen, Xu Jiaqi, Xu Ke, Li Yuan, Yao Jiaxian, Hong Yuhan, Luisa Gutierrez, Zhuang Xinwei. Visualisations were made by Julien Klisz (LEAD).

References

"Unity Reflect" : 2020. Available from <https://unity.com/> (accessed 4th February 2021).

"3D Scanner App" : 2020. Available from <https://www.3dscannerapp.com/> (accessed 4th February 2021).

"Theasys" : 2020. Available from <https://www.theasys.io/> (accessed 4th February 2021).

"ReCap" : 2020. Available from <https://www.autodesk.com/products/recap/overview> (accessed 4th February 2021).

"Meshroom" : 2020. Available from <https://alicevision.org/> (accessed 4th February 2021).

"Grasshopper3D" : 2020. Available from <https://www.grasshopper3d.com/> (accessed 4th February 2021).

"Fologram" : 2020. Available from <https://fologram.com/> (accessed 4th February 2021).

"Rhinoceros3D" : 2020. Available from <https://www.rhino3d.com/> (accessed 4th February 2021).

"Apple Website: I-Phone 12 Pro and pro max" : 2020. Available from <https://www.apple.com/hk/en/iphone-12-pro/?afid=p238%7CsYXQ6PWn9-dc_mtid_18707vxu38484_pcrid_474478576921_pgrid_114386872274_&cid=aos-hk-kwgo-iphone--slid---product--> (accessed 10th December 2020).

Chi, H.L., Kang, S.-C. and Wang, X.: 2013, Research Trends and Opportunities of Augmented Reality Applications in Architecture, Engineering, and Construction, *Automation in Construction*, **33**, 305-16.

Chu, M., Matthews, J. and Love, P.E.D.: 2018, Integrating Mobile Building Information Modelling and Augmented Reality Systems: An Experimental Study, *Automation in Construction*, **85**, 305-16.

Crolla, K.: 2018, *Building simplexity: the 'more or less' of post-digital architecture practice*, Ph.D. Thesis, RMIT University.

Crolla, K., Goepel, G., Keung, S.F.A. and Chan, T.A.O.: 2020, "Secret Whispers & Transmogrifications Workshop Website" . Available from <https://secretwhispers2020.wixsite.com/secretwhispers> (accessed 10th December 2020).

Franco, J.T.: 2019, "This is How a Complex Brick Wall is Built Using Augmented Reality" . Available from <https://www.archdaily.com/908618/this-is-how-a-complex-brick-wall-is-built-using-augmented-reality.ISSN0719-8884> (accessed June 9, 2020).

Goepel, G.: 2019, Augmented Construction - Impact and opportunity of Mixed Reality integration in Architectural Design Implementation, *In Ubiquity and Autonomy, Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Austin Texas, 430-437.

Goepel, G. and Crolla, K.: 2020, AUGMENTED REALITY-BASED COLLABORATION - ARgan, a bamboo art installation case study, *In RE: Anthropocene, Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference*, Bangkok, 313-322.

Jahn, G., Newnham, C., van den Berg, N. and Beanland, M.: 2018, Making in Mixed Reality: Holographic design, fabrication, assembly and analysis of woven steel struc-tures, *Recalibration: On Imprecision and Infidelity Structures, Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture 2018 (ACADIA)*, Mexico City, 88-97.

Jahn, G., Newnham, C., van den Berg, N., Iraheta, M.I. and Wells, J.: 2019, Holographic Construction". In Impact: Design With All Senses, *Design Modelling Symposium Berlin*, Berlin.

Jahn, G., Wit, A. and Pazzi, J.: 2019, "[BENT] Holographic handcraft in large-scale steam-bent timber structures, *Ubiquity and Autonomy, Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Austin Texas, 438-447.

Ren, J., Liu, Y. and Ruan, Z.: 2016, Architecture in an Age of Augmented Reality: Applications and Practices for Mobile Intelligence BIM-based AR in the Entire Lifecycle, *International Conference on Electronic Information Technology and Intellectualization*, Guangzhou, 664-665.

MASS PARTICIPATORY DESIGN ON THE WEB

A Voxel-Based 3D Modelling Approach

ANNA CLAUDIA YENARDI[1] and PATRICK JANSSEN[2]
[1,2]*National University of Singapore*
[1]*annaclaudiay@gmail.com* [2]*patrick@janssen.name*

Abstract. The traditional participatory design approach has its physical limitations regarding the number of workshop participants and visualisation tools used. In order to get the input from more people and to enable three-dimensional design visualisation, an online web-game is developed as a mass participatory design tool. For the purpose of this research, a specific social issue regarding the "Not In My BackYard" (NIMBY) attitude in Singapore was chosen as a vehicle. The results from a small pilot test group of a prototype shows that the participants find this approach engaging. The game also has a potential in terms of recording participants' design and attitude inputs.

Keywords. Mass Participatory Design; Citizen Participation; Web-game Design; three.js; WebGL.

1. Introduction

Participatory design is an effective approach for solving community-based design problems. The designer can facilitate the discussion and contribute their design expertise while people from the community can offer their knowledge about the site context. A traditional workshop-based approach typically uses drawings, plans and other two-dimensional visualisation tools.

One example that managed to use traditional participatory design workshops at a large scale was a city-wide project in Vancouver, Canada, in 2015. The CityPlan Vancouver project was carried out over a period of two and a half years, involving 100 000 citizens (Rosol 2015). The project has generally been regarded as being very successful.

However, such traditional approaches suffer from two main drawbacks: limited scalability and limited support for spatial exploration. The scalability issue stems from the fact that face-to-face workshops have inherent limits regarding the number of workshops that can be held, and the number of participants that are able to join those workshops. Scaling up the participatory process, as was done in Vancouver, is often prohibitively costly and time consuming. The spatial exploration issue stems from the fact that physical plans and models commonly used in participatory design workshops mainly support two-dimensional planning.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 31-40.

In high-density cities, the most innovative solutions often require 3D solutions that are spatially complex (Pietsch 2000).

This research proposes to overcome these drawbacks by leveraging online digital tools that allow participants to explore alternative design options. Al-Kodmany (1999) has highlighted that: "Used on their own, the traditional non-computerized tools lack the capabilities for sophisticated analysis, display, and visualization that enable the public to make more informed decisions". One issue with such tools is that they are often too overwhelming and intimidating for the general public to use. For participatory design, any such tools should be as simple and as unintimidating as possible (Al-Kodmany 2001). However, this often results in digital tools being used solely for the visualisation of design options. For example, a well-known case-study is the participatory design project led by the University of Glamorgan, on the proposed development of a wind farm in South Wales (Berry et al. 2009). The workshops included various GIS visualisations that show how the windfarms would be visible in the landscape. While these digital tools were successful in allowing citizens to understand the visual impact of the wind farms it did not allow the citizens to modify or change the design.

The aim of this research is to allow participants to create their own designs, thereby giving feedback on the types of spatial configurations that could be acceptable. We believe that innovative spatial configurations may be able to ameliorate various types of social tensions that may exist in high density urban environments. Configurations may involve stacking different types of programs. From a planning perspective, we suggest that it would be useful to be able to gather data on different types of configurations that citizens would find desirable. This data could then be used to inform the planning of future urban environments. Furthermore, if such tools can be developed as online games, they could potentially be accessible to a much larger number of citizens, in contrast to the limiting context of a traditional participatory design set-up. Games as a medium offers immersive problem-solving experiences where players can learn not just facts, but also multiple ways of seeing and understanding problems (Squire 2008).

A number of researchers have developed online participatory design tools specifically for allowing citizens to develop their own designs. The most well-known example is the "Qua-Kit" urban modelling tool developed by Anonymous (2016, qua-kit.ethz.ch/about). The tool allows participants to do a simple massing of 3D components on a base map. Qua-kit records the configurations submitted by the participants and other participants can then view and leave reviews on them. Qua-kit allows for a quick exploration of urban planning iterations, however, the unconstrained modelling approach used in this tool was still found to be rather complex for usage by the lay-people.

Another interesting tool is Block'Hood, an architectural simulation videogame developed by Jose Sanchez (2015). The game aims to educate players on the concept of trade-offs in city planning, with a focus on sustainability. The goal of the game is to design a sustainable city that is ecologically interdependent, testing the players' resource management skills. This game was studied for its simple voxel-based modelling approach which can be adapted for the context of this research.

In this research, we have developed an online web-game that addresses the aforementioned limitations of a traditional participatory design workshop. The game uses a voxel-based 3D modelling approach that is easy for citizens to use, but that nevertheless allows complex spatial configurations to be created. The focus of the game is to develop spatial configurations that resolve various potential social tensions and conflicts between different programs, including residential housing, worker dormitories, markets, restaurants, and parks. The game allows citizens to develop and explore their own design ideas within the constraints imposed by the game environment.

Section 2 describes the proposed design scenario and section 3 describes the implementation of the first version of the game. Section 4 presents the results from a pilot study while section 5 discusses the limitations and future work.

2. Design Scenario

A social issue in Singapore has been adapted as a vehicle for this research. NIMBY, which is short for "Not In My BackYard" is a term coined in the 1970s and it refers to "the protectionist attitudes of and oppositional tactics adopted by community groups facing an unwelcomed development in their neighborhood" (Dear 1992). NIMBYism in Singapore is not new. With its high population density, Singapore has no choice but to build unpopular facilities near residential areas. In the past decade, there have been numerous NIMBY cases in Singapore, usually regarding the construction of nursing homes and foreign worker dormitories. NIMBYism often arises from the lack of proper communication between the two parties involved in the development: the residents and the developer.

A study conducted by Sirianni (2007) highlighted that a well-designed participatory planning process could curb NIMBYism as it increases mutual understanding between the two parties involved. Therefore, the aim of this research is to create a game that will allow participants to develop an understanding of how 3D spatial planning can resolve many NIMBY issues. Urban proposals that incorporate programs such as nursing homes or worker dormitories can result in various mutually advantageous solutions that would benefit all the residents.

The web-game developed for this research is a simple town building game with complex rules. It has a simple interface where participants will be able to build a 3D configuration by selecting a module, placing it into, or deleting it from the neighbourhood. The interface is made to be as intuitive as possible to make sure that it can be understood by anyone. However, the computational rules behind the scoring system require a certain level of complexity in order to capture various relationships and trade-offs relating to NIMBYism and city planning.

An imaginary site that represents a typical Singaporean neighbourhood has been designed as the game environment, see figure 1. After accounting for a 10m building set-back from the road, the site consists of a 90 x 90m buildable plot for the game. This plot is further divided into 9 x 9 grid of 10 x 10m squares as this grid size was found to have a good scalability in the context of Singapore's built environment.

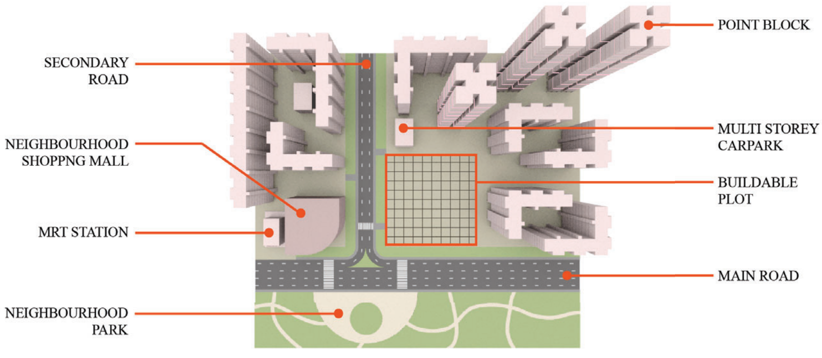


Figure 1. Game environment details.

In the proposed web-game, players are faced with the challenge to develop a plot of land with different programs. There will be some inherent conflicts between these programs and players can then explore different types of spatial configurations to minimise the conflicts and maximise the benefits. Some of these conflicts can be built into the UI/UX of the platform while some others can be a written description. Additionally, the building constraints and goals can be incorporated in the UI/UX of the platform, such as by not allowing participants to submit their iteration before they have fulfilled certain requirements.

The in-game conflicts will mainly be based on the concept of trade-offs:

1. Trade-offs based on resources: Participants will be given a fixed number of modules of different programs (housing, education, F&B etc) that they will be able to build on the buildable plot. For example, the housing program includes residential, worker dormitories and nursing home modules. Building more dormitory modules means less residential and nursing homes modules can be built.
2. Trade-off based on critical mass: The more people who live in the neighbourhood, the more facilities the residents get to share and enjoy together. NIMBY facilities such as worker dormitory modules are denser than residential units such that there will be an incentive to include more dormitories in the neighbourhood in order to unlock bigger facilities such as a food court.

Participants will not be given a single numerical score for their iteration. Instead, several different 'share-holders' are identified and each of them will have their own scores. For example, building many nursing home modules but no playgrounds will give a high satisfaction score for senior citizens but a very low score for children. These scores will only be shown to participants after submission so as to not affect their decision making while playing the game. For each participants, the scores serve as a personal check on the NIMBY attitude. These scores and their related numerical data indicate preferences and attitudes of the participants, and hence will be useful for planners, see table 1. Planners can customise the limitations implemented in the game to test for different participants' attitudes. For example, a group can be tasked to build a minimum number of worker dormitories while another is free to build what they want.

Table 1. Types of scores and their relevance.

Type of score	Description	Implication
Ratio based score	Scores based on the ratio between various variables e.g., the ratio between Singaporean Residents and Foreign Workers.	Indicate how comfortable participants are with a certain compromise in living arrangement.
Proximity based score	Scores based on how close some modules are to another e.g., the proximity of residential units to green spaces versus the proximity of dormitory units to green spaces.	Indicate the facilities participants are comfortable sharing with other parties.
Count based score	Scores based on the number of modules built in the neighbourhood.	Indicate the type of facilities participants want from new developments.

3. Prototype Implementation

In order to test the proposed method, a prototype version of the game, called "Sharing a Backyard" was developed. The game was implemented as a web application that could be accessed in any web browser. The main software library used behind the development of Sharing a Backyard is three.js. Three.js is a cross-browser JavaScript library and application programming interface (API) that allows users to create and display 3D models and animations in a web browser using WebGL renderer. The numerous 3D models used for the game are first built using Rhino and Blender. glTF file format is chosen for the final export as it allows for faster and more efficient use in 3D games.

Figure 2. From left to right; samples of residential, park and worker dormitory sub-modules.

In this prototype version, three types of modules are included, namely a residential module, a foreign worker dormitory module and a park module, see figure 2. The residential and dormitory modules are included to introduce a conflict of interest related to the social issue addressed in the context of the game. The park module is included as a neutral, public good facility. The design of the modules for Sharing a Backyard is made with minimal details to avoid imposing the idea of a model residential building and to avoid overloading the system. Using an abstracted design also allows participants to better relate the environment to their own neighbourhood.

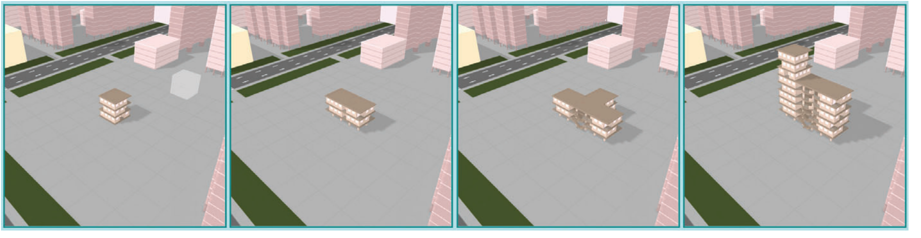


Figure 3. ‘Mutation’ process, cluster forming .

When a module of the same type is built next to each other, the modules mutate to form a cluster of connected modules, see figure 3. There are two types of module propagation, namely a planar propagation and a 3D propagation. The current dormitory and residential modules follow the 3D propagation logic, allowing vertical expansion, while the park modules follow the planar propagation logic. In order to create clusters of interconnected modules, the different method of propagation requires different numbers of sub-modules in a set. For planar propagation, six sub-modules are required in a set, while 24 sub-modules are required for 3D propagation. The logic of propagation is explained and tabulated below, see table 2.

Table 2. Planar and 3D propagation sub-modules.

Graphic	Number of Neighbours	Neighbour Type	Planar Code
	0		0
	1		1
	2	adjacent	2A
	2	opposite	2P
	3		3
	4		4

Graphic	Bottom	Top	Vertical Code
	ground	0	S
	ground	1	V
	1	0	R
	1	1	W
	0	0	R
	0	1	W

For planar propagation, six different types of sub-modules are identified based on the number of filled neighbours a voxel has and the location of the neighbours relative to the voxel. A numeral code is assigned to the sub-module for identification. These sub-modules are then programmed to rotate to face the correct position in relation to the location of neighbouring modules.

For 3D propagation, the same planar rules applies but with a vertical component added to the logic. A sub-module type is evaluated based on the voxels on the top and bottom of the said voxel. An alphabetical code is assigned to the sub-modules for identification.

The game interface contains a brief description of the design scenario, along with a few basic instructions on how to proceed to play the game. A task is given for the participants to build a certain number of each module type on the empty plot. There is a counter at the side of the screen to keep track of this. A brief explanation on the three different modules and the game controls are also given at the side of the screen.

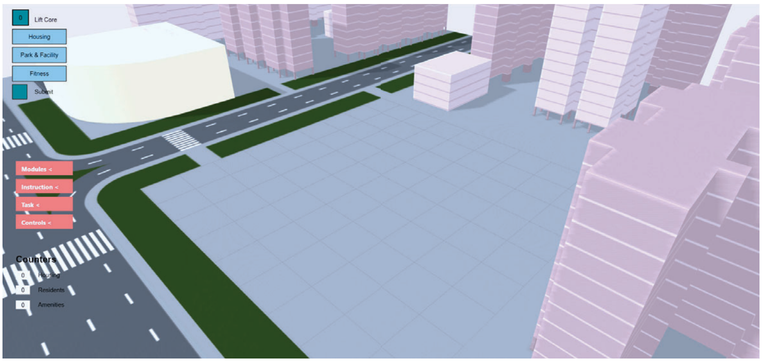


Figure 4. The latest user interface for ‘Sharing a Backyard’.

The image above is the latest interface of “Sharing a Backyard” and is slightly different from the one used for pilot testing, see figure 4. Some new updates have been implemented in the latest version:

1. A build limiter has been introduced to stop participants from building more than tasked.
2. New modules have been introduced including, “hawker center” (a typical neighbourhood food court in Singapore), elderly fitness corner, tennis, and basketball court. These are unlockable when the neighbourhood has reached a critical mass of a certain number of residents.
3. Resident count variables have been introduced, different sub-modules have different resident counts according to the size and number of housing units.
4. A saving mechanism has been developed for participants to submit their iteration in the form of an array of keys to the cloud. The developer side can then import the submitted files to the game to examine the participants’ iterations and scores.
5. A simple scoring mechanism has been introduced to evaluate participants’ iterations. These scores will be shown to participants after they have submitted their iterations.

The latest version of “Sharing a Backyard” can be accessed through:

https://annayenardi.github.io/SHARING_A_BACKYARD_CA/index.html

4. Pilot Study

A small pilot test involving even participants with various demographic backgrounds was conducted to confirm the feasibility and effectiveness of this approach. The group of respondents was relatively diverse with people coming from different age groups and occupations. It was interesting to see that different people come up with very different design strategies and iterations. Only the respondents with an architecture background massed the dormitory and residential modules in the same cluster. Others separated the two masses, often building the residential block higher to give the residential apartments better views. Some other iterations separated the dormitory and residential apartments while connecting the masses with roof gardens, saying that the garden was for the two parties to share. Some snapshots of the design iterations by the participants can be seen in the figures below, see figures 5-8.

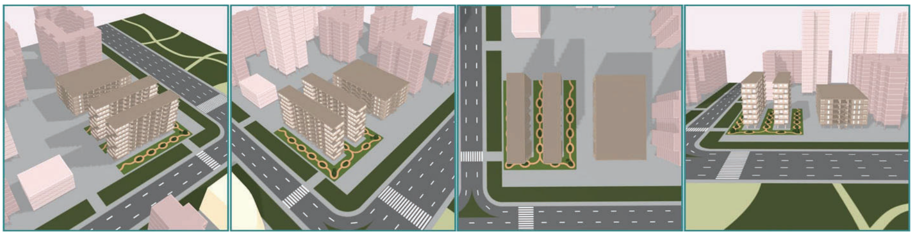


Figure 5. Respondent 1: 24 F, Singapore Permanent Resident, Product Designer.

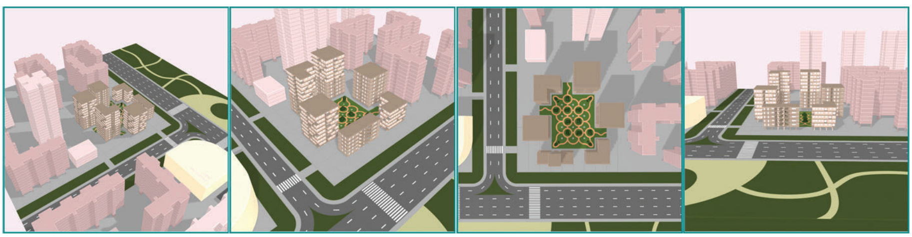


Figure 6. Respondent 3: 23 F, Singapore Citizen, Architecture Student.

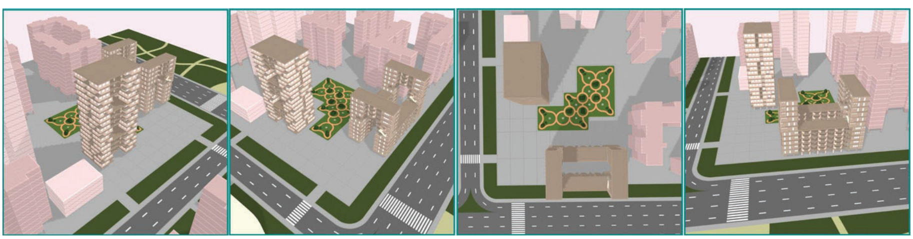


Figure 7. Respondent 4: 24 M, Singapore Citizen, Student / Naval Officer.

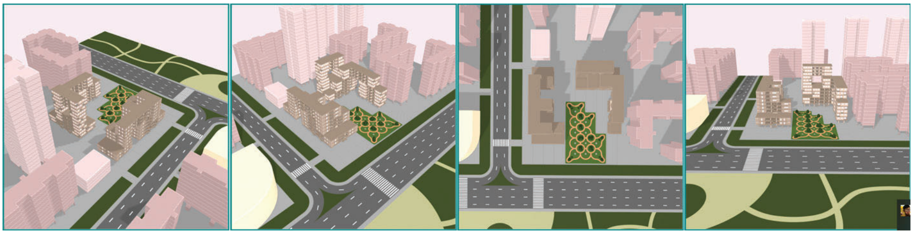


Figure 8. Respondent 7: 60 M, Singapore Citizen, Security Officer.

The mean rating for the game was 8.9/10, with 3 respondents rating it 10/10. This is a good indication that Sharing a Backyard has a potential to be an even more enjoyable game to play when it has more features. Making the game enjoyable to play is important, as it must be engaging for the participants if it were to collect meaningful attitude data and also raise awareness among the participants.

At the pilot-testing stage, the proposed method might not be so effective in changing participants' attitude towards NIMBYism. However, this can be attributed to the lack of avenues for the participants to get inspiration for their design. For example, several participants mentioned their strategy of building the residential volumes high for better views and property price which could have been executed better if they were to build the residential volumes on top of the dormitory volumes, yet they separated the two volumes. To address this limitation, the development of an online repository of previous designs can be considered. Participants can be shown a number of previous designs before they start building their own so that they can be more aware of the various creative spatial planning solutions that can be built in the game.

5. Future Work and Limitations

This research aims to develop a web-game as a participatory design tool which will allow a greater number of participants and better interface for 3D spatial planning. The web-game also has a potential to raise awareness among participants regarding the target issue, while at the same time, providing planners with meaningful data regarding spatial preferences. However, there is still a lot of room for improvement. First, the scoring system needs to be developed further. A more complex scoring system would be able to better estimate a participants' attitude towards the target issue. In the context of the vehicle of this research, it would be to estimate a participant's NIMBY attitude based on the submitted design iteration. More modules should also be included to create a more complex and realistic trade-off between the different programs.

The current version of the game only works on a desktop browser. Adapting this game for smartphone access is an important future goal. When coupled with a smartphone interface, the web offers the means to reach out to a lot more audiences than any physical workshops could. When a participatory design activity can be easily done from our personal smartphones, simply by scanning a QR code, anybody can submit their design entries anytime and anywhere.

Figure 9. What ‘Sharing a Backyard’ is envisioned to be able to generate in the future.

There are some inherent limitations that arises from the choice of medium and interface of this web-game. First, the simplicity of the 10 x 10m grid result in a limitation of the size of the modules and hence the complexity of the overall design. Secondly, with a building game, there is a tendency for the participants to prioritise the overall aesthetic of the neighbourhood they are building instead of reflecting their actual preferences regarding the target issue which will result in inaccuracies in the data generated. Lastly, intangible qualities such as ‘attitude’ are difficult to measure and quantify. Therefore, more research would still have to be done in order to further investigate these issues.

References

“Quick Urban Analysis Kit” : 2016. Available from <https://qua-kit.ethz.ch/about> (accessed 16th November 2020).

Abras, C.A., Maloney-Krichmar, D.M.K. and Preece, J.P.: 2004, User-centered design, *Bainbridge, W. Encyclopedia of Human-Computer Interaction. Thousand Oaks: Sage Publications*, **37**(4), 445-456.

Al-Kodmany, A.K.K.: 1999, Combining Digital and Traditional Visualisation Techniques in Community-Based Planning and Design, *Digital Creativity*, **10**(2), 91-103.

Al-Kodmany, A.K.K.: 2001, Visualization tools and methods for participatory planning and design, *Journal of Urban Technology*, **8**(2), 1-37.

Dear, M.D.: 1992, Understanding and overcoming the NIMBY syndrome, *Journal of the American planning association*, **58**(3), 288-300.

Berry, Higgs, Langford, Fry, R.G.M.R.: 2009, *AN EVALUATION OF ONLINE GIS-BASED LANDSCAPE AND VISUAL IMPACT ASSESSMENT TOOLS AND THEIR POTENTIAL FOR ENHANCING PUBLIC PARTICIPATION IN THE UK*, Ph.D. Thesis, University of Glamorgan.

Pietsch, S.M.P.: 2000, Computer visualisation in the design control of urban environments: a literature review, *Environment and Planning B: Planning and Design*, **27**(4), 521-536.

Rosol, M.R.: 2015, Governing cities through participation—a Foucauldian analysis of CityPlan Vancouver, *Urban Geography*, **36**(2), 256-276.

Sanchez, J.S.: 2015, Block’hood-Developing an Architectural Simulation Video Game, *eCAADe 33*, **1**, 89-97.

Sirianni, C.S.: 2007, Neighborhood Planning as Collaborative Democratic Design: The case of Seattle, *Journal of the American Planning Association*, **73**(4), 373-387.

Squire, K.D.S.: 2008, Video game-based learning: An emerging paradigm for instruction, *Performance Improvement Quarterly*, **21**, 7-36.

THE DIGITAL DESIGN BUILD

Modes of Experiential Learning in the Pandemic Era

TATIANA ESTRINA[1], VINCENT HUI[2] and LENA MA[3]
[1,2,3]*Ryerson University*
[1,2,3]*{testrina|vincent.hui|lena.ma}@ryerson.ca*

Abstract. In recent years, academia has deviated from the lecture-based model to a hybridized system of instruction and experiential learning. Experiential learning aids students in understanding collaborative processes in architectural praxis and exposes them to engaging learning opportunities, a critical component of architectural studio education (Nijholt et al. 2013). During the COVID-19 outbreak, students are barred from accessing on-campus facilities. This causes a redevelopment of curricular delivery and disrupts experiential learning which heavily relies on in-person interaction. It is imperative for instructors to retain experiential learning in the transition to virtual instruction. This paper explores experiential learning within virtual platforms for instruction. Through outlining the implementation of technologies, capitalizing on connectivity, and maximizing opportunity for digital problem solving, the authors posit a framework that other educators may adopt. The paper concludes with a case study of a virtual design-build project, and the various techniques implemented in retaining experiential learning during the pandemic.

Keywords. Pedagogy; Experiential learning; Social connectivity; Resilience; Disrupted education.

1. Introduction

Experiential learning has proven to expose students to engaging and rewarding hands-on learning opportunities while also providing them platforms for applications of design thinking that develop over the course of their studies (Nijholt et al. 2013). With social distancing dramatically altering curricular delivery in most architectural institutions worldwide, the lack of contact and hands-on learning has not only created a knowledge gap, but also has dramatically reduced students' engagement in curricular learning. By critically examining conventional pedagogical models and current pandemic experiments, architectural education during these unprecedented times may be enhanced for the sustainability of the practice and quality of learning environments. Along with presenting some key strategies for implementation such as capitalizing on international connectivity, advancing emerging technologies, transporting instruction outside the digital

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 41-50.

classroom, and maximizing opportunity for digital problem solving, the paper examines several examples from Canada's largest architecture program, focusing on modes and alternative methods of experiential learning via virtual platforms during the COVID-19 pandemic.

2. Experiential Learning in Architectural Education

Experiential learning derives from the act of doing or experiencing (Lewis and Williams 1994). The learning tactic is meant to immerse students within methods of education that focuses on the development of new skills and manners of thought in the reflection of 'doing' (Lewis and Williams 1994). Experiential learning focuses on techniques of performance, practice and experimentation that allows students to cognitively understand the implications of their learning subjects in a real-world and meaningful format (Lewis and Williams 1994). Within the context of architectural education, experiential learning is more interactive and engaging than reading, writing, or hearing about design and its concepts. These activities would include field projects, physical construction, and other methods that demand a high level of thinking, analysis, and knowledge in order to carry out activity and ensure success of the project (Kolb 2014). Kolb's Experiential Learning Theory (ELT) involves Reflective Observation, Active Experimentation, Abstract Conceptualization, and Concrete Experience (Hui et al. 2018). While Concrete Experience is essential to experiential education during the pandemic, students are limited in its traditional applications and experimentation. Rather than be mired in a lack of facilities and resources, by taking advantage of digital workflows at home, students are exposed to expanded methods of learning as technology provides opportunity to experiment with design through efficient sharing of ideas that help translate architectural thinking into a tangible reality (Hui et al. 2018). According to Kolb, lifelong learning is derived from experiential learning which exposes students to unique situations of problem-solving, activity, and collaborative environments (Kolb 2014). In the context of the multi-faceted topic of architecture, these areas of education retain the greatest fidelity to the core of the praxis as it addresses constructability, team design processes, cost mediation, model experimentation, and more.

3. Experiential Learning Techniques during Remote Instruction

Due to the COVID-19 pandemic, most post-secondary institutions closed their campuses and transitioned to online learning (Silverman et al. 2020). While access to workshops, and in-person collaborations are restricted during the work from home paradigm, the fundamentals of architectural education can be maintained through the adaptation of current curricula and a focus towards an experiential approach to pedagogy. No longer endowed with access to advanced digital fabrication and simulation facilities on-campus, students are challenged to reduce their idea into its most basic components to develop experimentation techniques that are possible to conduct at home while extremely effective in the learning process.

3.1. ACCESS TO VARYING EXPERIENCES AND CAPITALIZING ON INTERNATIONAL CONNECTIVITY

In order to retain a positive learning atmosphere for the students, it is crucial for a variety of experiences to be offered to the students, both within the virtual classroom and through extracurricular initiatives. Such experiences range from the incorporation of guest lectures within course environments, virtual site visits, and individualized learning opportunities for students. To diversify perspectives and draw upon a practical commentary into pedagogy, instructors can begin to incorporate more diversity inviting guests as both reviewers and lecturers. Capitalizing on the opportunity brought about by the lack of a physical learning environment invites a great variety of previously unavailable individuals, due to distance, timing and subject matter. For instance, for a studio with a focus on developing resilient architectural solutions in the COVID-19 pandemic, guest reviewers included medical specialists with the most up-to-date factual information and insight on the subject. Similarly, many industry professionals find themselves with a more flexible daily schedule, thereby increasing the opportunity for professional expertise to play a part in pedagogical discourse. On several occasions, industry experts were invited to give students guidance in their respective areas of skill. Such visits ranged from tutorials given by local visualization firms on the development of architectural renderings, to international firms shedding light on their approaches to modular construction.

3.2. IMPLEMENTATION OF EMERGING TECHNOLOGIES

As education turns to technology, new methods of representation and experience are revealed to enhance the learning experience. Although the conventional typical forms of course delivery during the pandemic have consisted of video conferencing with a slide-by-slide narrative, this format reduces the student from an active participant in their education, to a passive observer. More engaging ways of communication become crucial in retaining students' interest allowing them to contribute in more significant capacities. Such means involve turning to more technologically driven methods, which include the incorporation of varying media into education going beyond videos and imagery. Instead, the focus is on interactive media such as the use of video games and virtual reality (VR).

Video games share several commonalities with the architectural design process such as involving graphical representation, narration of architectural ideas, and collaborative teamwork (Di Mascio 2017). They also demand an interactive approach, where to understand how to 'play', users and designers must have active participation (Di Mascio 2017). The first objective of expressing ideas through video games is to immerse players in a world that is believable, evoking emotions, curiosity, and exploration, that may be indistinguishable from real experiences (Di Mascio 2017). Therefore, the use of video games as an expression of architectural education is an asset to experiential learning during the pandemic through its ability to narrate ideas, manipulate perspectives of design, and demand for details and research to be effective.

The reference of historical architecture in video games requires incredible detail for the representation of construction, systems, and materiality (Di Mascio 2017). The involvement of existing architecture in video games to develop a contextual understanding of projects requires thorough knowledge and research on the behalf of the students that may otherwise not have been explored given the restrictions to visiting sites during the pandemic. Not only is the player able to navigate through reconstructed architecture and urban environments (of varying fidelity), but they are also able to experience the social context of the buildings and how they were originally occupied, enhancing their understanding of the urban fabric as a whole. The understanding of historical architecture and the construction of buildings through the lens of video games allow for a simulation that will enhance experiential learning and thus the expression of architectural ideas. Video games can simulate the visual appeal of cities and atmospheric quality, approaches to the cityscape, and other details that express the designer's intentions (Di Mascio 2017). The development of a video game in architectural education allows students to thoroughly understand the implications of its existing counterpart from conceptual to technical stages of its design, and even further beyond the concrete experience of the city by the implementation of their own ideas and narration of the world (Di Mascio 2017). For example, in a second year architecture studio, students were directed to examine the fidelity between construction methods of various commercial buildings including the Washington State Convention Centre in Seattle and the design of structural systems in their own performance hall designs.

VR environments allow for students to experience their projects from a participatory means rather than as an exterior observer. Incorporation of VR into pedagogy presents itself on a variety of levels, from the inclusion of interactive virtual field trips (iVFTs) where historical and distant locations and architecture are examined using VR photographs and videos as an alternative to images which are less personally engaging for the students (Tawhai, 2017). For instance, during school trips, students are able to document their excursions through 360° photography and subsequently re-examine the spaces, as well share the experiences with others (Hui, Estrina, Lee, Zhou, & Kinuthia, 2020).

In VR, students are given the opportunity to occupy the spaces they design, thereby taking hypothetical environments represented through orthographic imagery and scale models into 'real' occupiable spaces. Although VR is most typically used in architectural pedagogy through the use of expensive VR headsets for the representation of student's unbuilt work, there are a variety of alterative means of engaging virtual environments. Due to the COVID-19 pandemic, students find themselves scattered throughout the world, and most frequently lack access to the hardware required for navigable VR operation, which are often prohibitively expensive (Snigh, et al., 2020). However, through the implementation of much more affordable solutions such as Google Cardboard, students are able to still interact virtually from their homes. The majority of popular rendering software such as Twinmotion, Enscape, Yulio, and V-Ray allow for not only navigable VR experiences, but also the creation of 360° imagery and videos for students to easily view on their mobile devices (Hui, Estrina, Lee, Zhou, & Kinuthia, 2020). In addition, the aforementioned software packages are able to generate desktop-based playable environments, placing the student's model into an environment similar to that of a video game. Through this interface, faculty and students alike are able to navigate through student's projects easily and freely without the need for expensive hardware.

3.3. TRANSPORTING INSTRUCTION OUTSIDE OF THE DIGITAL CLASSROOM

Due to restrictions of material resources and access to workshops, students can continue to develop and experiment with physical models by producing smaller scale elements with more common materials. This sustains the experiential learning aspect of sketch and final models in the architectural design process by demonstrating how large projects may operate on a miniaturized level. Through an assignment that involved students to propose designs of light fixtures, physical models were created using stationary materials and techniques such as the use of corrugated cardboard and paper in modular forms. This approach to design during the pandemic provides an alternative but effective approach to construction without the necessity of workshop machinery or complex materials. By simplifying architectural ideas in these sketch models, students are able to have a more direct representation of their design, develop a stronger grasp of the necessary components of their concept, and maintain the experiential learning component of the design process.

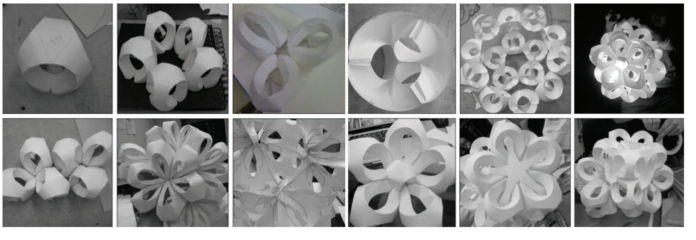


Figure 1. Paper models for light fixture project.

In another example, a student's independent study initiative with the involvement of memory shape alloys, led the student to design an installation proposal incorporating 3D motion using these wires. Although the student was unable to fabricate their entire proposal due to workshop access restrictions, they conducted a full-scale testing as both a means to experiment and as a proof of concept. Through this process the student was able to, with very little access to resources, problem solve and learn from the fabrication and testing process.

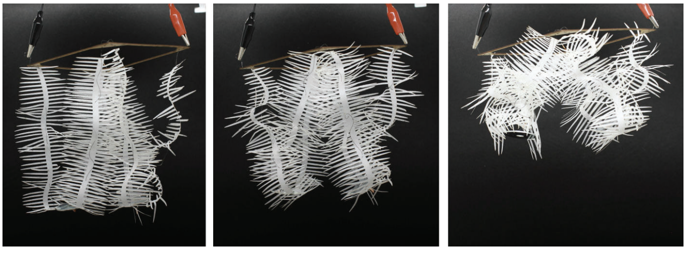


Figure 2. Students' experiments with memory shape alloys.

A common pedagogical paradigm in architectural education is to undertake design projects that simulate design-builds but do not conclude with physical construction of the project itself. Through this process, students experience the procedure of composing an architectural structure that will be brought into reality by addressing issues such as client, site, cost, transportation, and buildability in great detail. In an initiative where students were tasked to propose pavilions as a part of the annual Winter Stations Festival on Toronto's beaches, the project specified an in-depth analysis and presentation of how the structures were to be constructed if chosen as a winner. This demanded that students to develop applied knowledge of required components of structure necessary to withstand harsh Canadian winters, conjecture how it would be constructed, and explore the possibilities and efficiencies of the project's production. While the pandemic can limit students' ability to construct their designs due to limited workshop access and prevention of large gatherings, the outline of student projects may be adapted to incorporate more detailed exploration of the design process to enhance experiential learning in architectural education.

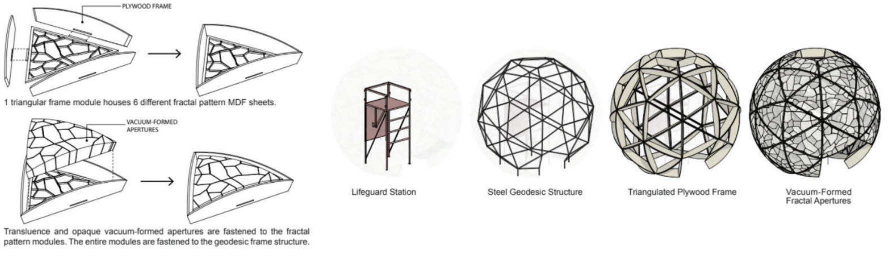


Figure 3. Assembly exploration for Winter Stations Festival proposal.

In another example, an Ontarian camp for children with disabilities collaborated with students to design an animal paddock which involved a thorough analysis of client-influenced parameters. This method empowered students to participate in an experience that simulates the demands of a client, their requirements towards program, budget, and more importantly, that addresses the implications of a real-world experience. This type of project can be easily applied to several architectural remote learning assignments through a flexibility of program and site that facilitates conversation between designer and client throughout the education of an architect.

3.4. MAXIMIZING OPPORTUNITY FOR DIGITAL PROBLEM SOLVING

The online learning environment provides many challenges, especially through the implementation of more digital workflows and tools. While this provides a steep learning curve for many older generations, younger students are very much accustomed to adapting to new technologies rapidly (Hui et al. 2020). In order to keep students engaged and to continually expand their digital problem-solving capacities, a range of individual and collective problem-solving opportunities need to be provided. These digital learning conditions can be represented on a chart, categorized by team size and difficulty on the axis, respectively.

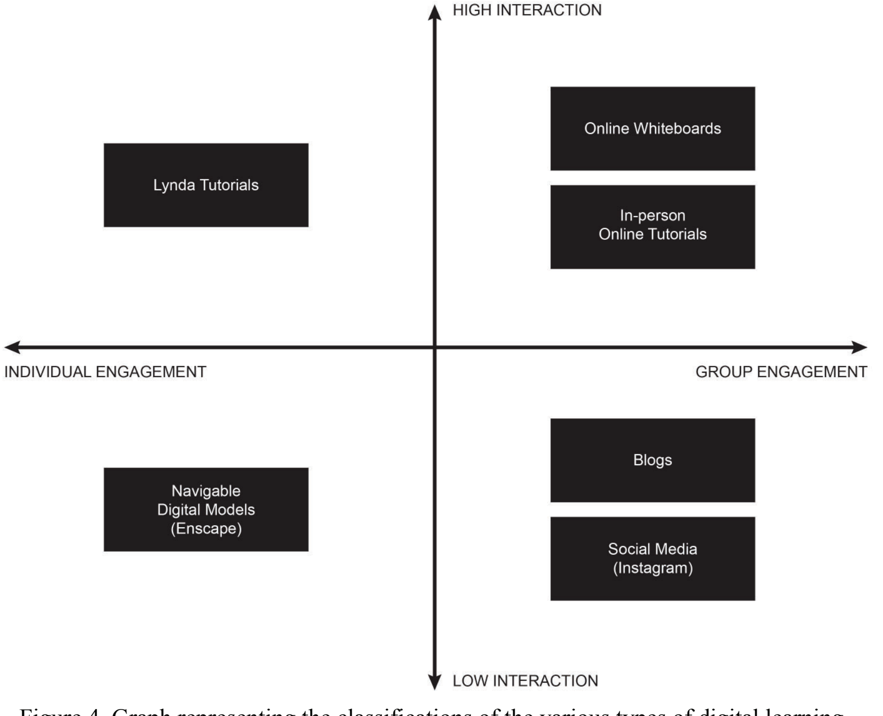


Figure 4. Graph representing the classifications of the various types of digital learning .

For instance, the adaptation of new communication platforms, such as the whiteboard software *Miro*, serve as a low intensity and collective learning effort. This allows studio groups to work together to incorporate the tool into their workflow. In contrast, learning the coding language *Python* and its implementation into *Unity*, would be an individual, high intensity learning goal. A mixture of various challenges scattered throughout the chart's four quadrants (Figure 4) provides the most engaging opportunities for students to not only collaborate and learn from one another, which serves as a large portion of architectural learning (McClean and Hourigan 2013), but also delivers a variety of difficulty within the learning journey. Although typical studio building projects may help engage students in various digital challenges, such as 3D modeling and manipulation of graphic imagery, it does not offer a platform for students to truly engage in experimentation with reality the way design build projects do. This is where the approach of 'digital design builds' comes into play. By pivoting the end goal for the project from a typical 'build' installation or physical experienced space to a digitally experienced environment instead. Such an approach alleviates many impediments that come about with remote learning, such as limited fabrication and manpower capabilities. Instead, these projects aim to challenge students with the design and development of digital environments, allowing for both individual and collaborative work to take place in tandem with low and high intensity learning. The students, operating in small groups, are able to not only experiment with their ideas of space, but also exceed the constraints the physical would place in order to fully embrace the virtual interactivity of the project. In addition, these projects allowed students to individually hone into digital skill sets of interest to them, while through the combination of such various strengths the projects emerged multi-faceted.

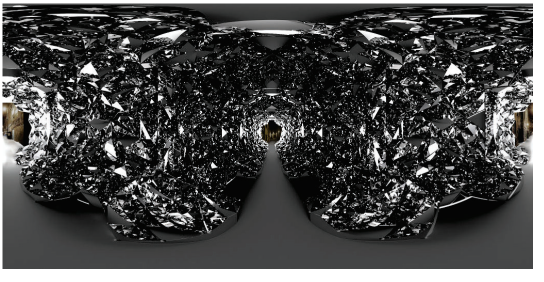


Figure 5. A digital VR environment designed by students when challenged for a digital design build.

4. Case Study - Blended digital design build

Emerging from the challenge of experiential learning during remote education, the new typology of a blended digital design build arose. Typically, extracurricular design-build projects are carried out by groups of students aiding with the fabrication and installation. However, this was no longer a valid typology as access to the building became limited with the rise of COVID-19 cases in the area. As an alternative, the students turned to the blended digital design build typology, where larger emphasis was placed on the digital component of the project as opposed to the physical as is typically done. Rather than fabricating architectural propositions for applications of robotics, this project focused on the possibilities of digital projection mapping, challenging students to explore the opportunities of the combination of interactive media and projected digital environments (Figure 6).

The project's development was composed of two portions. The first consisted of a digital and interactive component, which integrated the motion tracking of any passersby to create a responsive digital projection. The second constituent involved the physical structure itself, which served as the medium to be projected upon. In order to reduce the extents of fabrication demands, the physical components were computer numerically controlled (CNC) routed foam panels, optimizing cost, fabrication time, and reducing personal contact among the team members. This work division not only allowed much of the work to be digital and more ideal for remote completion, but also permitted for the fabrication to be outsourced without the requirement for students to fabricate on their own. This paradigm mandated that students design with an even greater sensitivity on logistics and feasibility. By adopting a procedural prototyping model, students incrementally developed modest full scale samples of a modular system before proceeding to a larger execution. The team focused on creating an array of 2’x2’ sample forms with which they are able to test materials and projections. In adopting this incremental strategy, the students were able to focus on digitally generating both the virtual and physical components at a controlled scale while simultaneously testing various interactions and possibilities of interplay between the two.

Although working remotely proved to be a challenge due to hardware limitations and difficulty in communication, students continued to successfully collaborate in the remote context. Once the students landed upon the software *Touchdesigner* as the most appropriate to accomplish their design goals, the group was able to adapt to the relatively straight forward software collectively. Within the group, several students became interested in more technical exploration, and began to explore the possibilities of raymarching within the projection in order to facilitate the possibility for complex 3D geometries to be manipulated and projected live. This required the students to learn the coding language *GLSL* and its incorporation within the *Touchdesigner* ecosystem as well as its integration within the *Azure Kinect* feedback loop. In contrast, other students were more inclined to further develop their parametric modeling skillsets and investigated the possibilities for the CNC’ed portion of the project through the use of the *Grasshopper* and *Rhinoceros* interfaces. Such a staggering of skillsets not only provided students with opportunities for more individualized explorations of their own interests, but also allowed for a variety of collaborative, individual, high and low-intensity digital learning to take place throughout the course of the project.

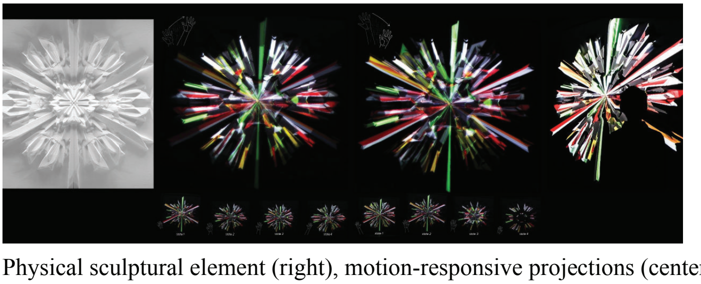


Figure 6. Physical sculptural element (right), motion-responsive projections (center) and an impression of the installation (left).

5. Conclusion

While the pandemic forces students and professors to feel restricted to the confines of their homes, it provides an opportunity to expand the techniques of architectural education through technology and domestic experimentation that would not have been possible in different conditions. Undoubtedly architectural education is dramatically different during the pandemic however the experiential learning capacities need not diminish; if anything, they will merely evolve and adjust via the technological resources available. Architecture has always adapted and adopted technological innovation in not only the design of the built environment, but the materials, methods, and models of production. This is yet another challenge and milestone for architectural pedagogy. Through remote learning and its capitalization of international connectivity, implementation of emerging technologies, transporting instruction outside of the digital classroom, and maximizing opportunity for digital problem solving, the value of experiential learning is enhanced through a multitude of facets that have yet to be explored during the COVID-19 pandemic.

References

Hui, V., Cairns-Spicer, M.K., Komyshenko, M.S. and Zhou, G.: 2018, From Being Digital to Experiential: Revisiting Negroponte in the Age of Kolb, *Proceedings of ICERI 2018*, Seville.

Hui, V., Estrina, T. and Huang, A.: 2020, Online Design Education: Uncovering the Pedagogical Digital Divide in the Pandemic Era, *Proceedings of ICERI 2020*, Seville.

Hui, V., Estrina, T., Lee, S., Zhou, G. and Kinuthia, V.: 2020, Architectural Accessibility and Pedagogy via Virtual Reality Integraation, *Proceedings of HUIC ASHE 2020*, Honolulu.

Kolb, D.A.: 2014, *Experiential Learning: Experience as the Source of Learning and Development, Second Edition*, FT Press.

Lewis, L.H. and Williams, C.J.: 1994, Experiential Learning: Past and Present, *New Directions for Adult and Continuing Education*, **1994**, 5-15.

Mascio, D.D.: 2017, 3D Representations of Cities in Video Games as Designed Outcomes: A Critical Overview and Systematization, *Proceedings of CAADRIA 2017*, 33-43.

McClean, D. and Hourigan, N.: 2013, Critical Dialogue in Architecture Studio: Peer Interaction and Feedback, *Journal for Education in the Built Environment*, **8**, 32-37.

Nijholt, A., der Veer, G.V. and Vyas, D.: 2013, Creative practices in the design studio culture: collaboration and communication, *Cogn Tech Work*, **15**, 415-443.

Ockman, J. and Williamson, R.: 2012, *Architecture School Three Centuries of Educating Architects in North America*, MIT Press.

Silverman, M., Sibbald, R. and Stranges, S.: 2020, Ethics of COVID-19-related school closures, *Canadian Journal of Public Health*, **111**, 462-465.

Snigh, R., Javaid, M., Kataria, F., Tyagi, M., Haleem, A. and Suman, R.: 2020, Significant applications of virtual reality for COVID-19 pandemic, *Diabetes & Metabolic Syndrome: Clinical Research & Reviews*, **14**, 661-664.

Tawhai, C.: 2017, *Immersive 360° video for forensic education*, Murdoch University.

TRAVERSING UNKNOWN TERRITORIES: NOTES ON RESEARCHING THE LEARNERS' EXPERIENCE OF REAL-TIME VIRTUAL ENGINES IN THE ARCHITECTURAL DESIGN STUDIO

Notes on Researching the Learners' Experience of Real-Time Virtual Engines in the Architectural Design Studio

TANE MOLETA
[1] *Victoria University of Wellington*
[1] *tane.moleta@vuw.ac.nz*

Abstract. This paper explores the role of real-time-virtual-engines (RTVE) in contemporary architectural education. The research is a response to the increasing footprint virtual reality (VR) has begun to forge in the studios of architecture programmes. This paper stipulates that the use of RTVE in architecture is unique to CAAD research given the student motivation to 'create with' and 'for' VR. Presenting the results of two literature reviews that question: how does use of the Real-Time Virtual Engine shape the students learning experiences in the architectural design studio? The initial results are undertaken as a narrative literature review. This work uncovers the role of RTVE and ties it to a number of established educational frames. The subsequent search was undertaken using the systematic literature review framework. The knowledge generated from this piece of research locates that there is a substantial lack of empirical data exploring the experiences of student use of RTVE in the architectural design studio.

Keywords. RTVE; Education; Design Studio.

1. Background

As an academic, writing a paper in December, I am afforded the unique chance to take stock of the activities of the year, and in doing so, I wonder, as one does, 'why we do what we do', and also, why we often ask our students to 'do what we do' , 'do what we did' and sometimes, 'do what we wish we did'. As humans, many of our activities are ingrained. We have all been students prior to teaching. We have all received tutelage at one institution or another, and had some characteristics ingrained - and then at some point, we are allowed to teach. Then, to no fault of our own, quite a bit of time passes between the state of being a student and being an educator, and one could reasonably expect that the experience of the learner, as a learner, can be construed from experiences based on the educator. We can then question, do we genuinely have a vivid map of the experiences of our students?

To begin to understand how the learning experience of our students is constructed, it is valuable to look at the institutional structures of tutelage the

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 51-60.

student architects experience. One of the seminal studies and most frequently referenced studies that inform the education of an architect is authored by Donald Schon His work, 'The Reflective Practitioner', has had a profound and sustained impact on how, 'architecture' as a course of study is delivered to students (Webster, 2008). Proposing that 'the learning environment is 'mapped to the activities of the profession' (Schon, 1983) the work of Schon is a guiding influence for many schools of architecture (Webster, 2008)(D. A. Schön, 1988). His notions that students are set with a 'brief' (Koper, 2005) undertake their daily study and receive tutelage in a 'design studio' (Davies, 1960) endure to this day (MacGilvray, 1992). Additionally, and central to this study, the stipulation that students are to be instructed and given 'tools typical to industry' (Attoe & Mugerauer, 1991) is equally a defining characteristic and experience for students who study in this field. Research on the role of the 'design brief' (Lutnæs, 2015) is well established, as is the purpose, configuration, inhabitants and changes to the design studio. Additionally, considerable effort has been invested in understanding the 'tools' (Gramazio, Kohler, & Oesterle, 2010) and 'processes' (Oosterhuis, Bouman, & Lénárd, 2002) undertaken by both 'professional architects' (Gero, Neill, & Science, 2006) and also 'student architects' (Moleta, 2016).

Current literature states, the contemporary architectural student inhabits an era where the range of digital tools is perpetually expanding (Iriti, Bickel, Schunn, & Stein, 2016). This shifting of poles has generated considerable academic discussion, especially in within CAAD research. The instruments that have been historically significant for architects such as sketching (Ekströmer & Wever, 2019), modelling (Shih, Sher, & Taylor, 2017) and scale drawing have seen less of an emphasis as students are encouraged to prepare for industry and gain increasing fluency in the use of digital tools (Beckmann, 1998; Carroll, 2010; Whyte & Nikolic, 2018). The pressures influencing this change come from a range of fields: professional (Architects Accreditation Council of Australia (AACA) and the Australian Institute of Architects (AIA), 2013; Wang, Wu, Wang, Chi, & Wang, 2018.), legislative (Ostwald & Williams, 2008) and constructional (Wang et al., 2018). The literature suggests that contemporary communication technologies will assist the design (Yuen, Yaoyuneyong, & Johnson, 2013), visualisation (Moleta, 2017), documentation and construction of buildings (Chen, Cui, & Hao, 2019). Educators (who are often largely Architects themselves) are accommodating of these influences, hoping that these skills will better prepare graduates for the contemporary (and increasingly competitive) workplace (Spaeth, Khali, Spaeth, & Khali, 2018). Consequently, as others have noted, the knowledge required of students to succeed is continually evolving (Burdick & Willis, 2011; Heller & Heller, 2014). Where each of these fields seems to delve into the broad term of 'digital tools', there is an essential joint component, and that is the necessity to use digital tools to communicate (Bates-Brkljac, 2012; Birt & Cowling, 2018; Lin, 2012; Whyte & Nikolic, 2018). Digital tools have been heralded as the means to understand both the complexity of the problem (Nováková, Achten, & Matějovská, 2010) and also the communicate the sophistication of the solution (Abdelhameed, 2013). The Real-Time Virtual Engine as a communication tool has seen an increasing focus in educational research. Studies cover the entire gamut of scholarly research from medicine, to geography; however, for the student architect, The Real-Time Virtual Engine is reported to offer several compelling characteristics. The Real-Time Virtual Engine is inherently 'spatial' and possesses the capacity to communicate complex geometry in a manner that is not easily repeatable in other means (Chen et al., 2019; Ford & Ford, 2017). The Real-Time Virtual Engine also offers the ability for its inhabitants to better perceive proportion (Innes, Moleta, & Schnabel, 2018) and scale (Payette, 2012). The visual fidelity also allows users to better communicate types of material (Abdelhameed, 2012) and lighting qualities (Chen et al., 2019). It also affords its users the chance to produce the 'feeling' of a space, using the term 'atmosphere' and also locates the user within a 'temporal environment'. These affordances have seen the use of the Real-Time Virtual Engine achieve widespread employment in every school of architecture.

While this search uncovers a rich plethora of material and positions, what I find strikingly interesting, is that much of the material presented is from non-empirical studies. What is equally interesting is that in many cases, the studies are not constructed from the student perspective or have not included the student's voice.

2. Research motivation

The motivation for me as a design studio lecturer is that a defining characteristic of my daily tasks is that I spend time with my student cohort, converse and discuss their architectural design proposals. I listen, I offer suggestions, and I interpret their propositions. It is potentially an unsettling characteristic of a creative discipline that there is often no singularly correct answer; thus, it is often the role of the architectural educator to interpret the words of the student to understand their work and offer feedback. Communication is important and arriving at a common understanding is of considerable advantage for both parties, student and lecturer.

In my experience, in academia, the profession and in the student body each sector is keenly interested in the use of digital tools. I often discuss such matters with my colleagues. We debate the affordances of how we present, explore and experience the representation of an architectural design. We discuss what this means for our profession and as educators what this means for our students. It is often speculated that one of the intrinsically interesting components of the contemporary toolset is that we no longer review static projects on printed paper, but rather are enabled to inhabit and architectural design in ways not historically possible.

When employing the use of Real-Time Virtual Engine we can now make decisions on 'how' and 'where' we will 'inhabit' a representation of a project which ultimately and perhaps problematically, allows the creation of individual and unique readings of a given project. Dwelling on these notes, I postulate, the tools we use to communicate now shift from being didactic to being speculative, instructional to experiential, specific to in-specific. We can consider then, in the contemporary design studio, today's students are invested in creation in a way that is different from the way in which their predecessors ever did, or ever could. We could also speculate, given the unique readings contemporary tools offer, that our students are now faced with communicative hurdles that are undeniably divergent and undeniably significant. We will not know however unless we engaging in understanding these matters from their perspective.

3. Review of literature

In an attempt to answer ‘how does use of the Real-Time Virtual Engine as a communication tool shape the students learning experiences in the architectural design studio?’ The following literature reviewed is presented in four sections that trace the development of communication issues in the context of architectural education. It begins with the central issue of how abstract architectural ideas can be communicated. Changes to the field include the tool of virtual reality and its importance to architectural studies

4. Abstraction to the real

As with many professionally accredited programmes of study, students of architecture are quick to align themselves to the activities, aspirations and concerns of professional architects. Within a year of their education, students are largely equipped to read the same professional journals, enter competitions and participate in the many events of the professional world (Askland, Williams, Ostwald, & Australia. Department of Industry, 2012) A contributing factor to this culture occurs due to the fact that most academics in schools of architecture are, by in large, either former or current architectural professional themselves (Schön, 1988). This close relation to the profession is a strongly held tradition and one that is unlikely to change. These sentiments are supported in a number of key texts citing a desire in architectural studies to achieve the ‘real activities of an architect’ (Webster, 2008). Webster argues that “design studio learning simulated real professional action” (p. 63). There is, however, one considerable and frequently overlooked difference between the modes of practice between the aspiring student architect and the professional. This is a matter of knowledge gained from the experience of reviewing one’s work; a difference that can be seen in the ‘output’ that centres on notions of ‘media’ (Roudavski, 2011). Where the architect gains an understanding of their work through 1 to 1 review of the built outcome, the student, however, gains architectural understanding through communication with their lecturer. Considerable effort has been imparted in understanding and defining architectural education, Table 1 provides an overview of approximately six decades of theoretical literature and accreditation reports, organised according to key principles and aspects (or focus) of these studies.

Table 1. Table 1: Overview of theoretical literature.

Key Principle	Key aspects of architectural education	Literature
What	Research centred on defining what are the key principles for architectural education	Davies (1960); McEwen (2003); Varnelis (1998); Carlhian (1979)
Where	Works that define the studio experience	Caruso (2008); Gül (2012); Deamer (2005); Lyndon (1978); Attoe & Mugerauer (1991)
Creativity	Creativity as an educational goal	Herbert (2010); Wang & Huang (2018); Kilicaslana & Ziyrek (2012)
Technology	Research centred on the role of technology in architectural education	Nováková, Achten & Matějovská (2010); Westfall (2008)
Pedagogy	Research centred on pedagogical systems	MacGilvray (1992); Dutton (1987); Askland, Williams, Ostwald… (2012)
Qualification	Research defining the registry characteristics of professional degrees	Architects Accreditation Council of Australia (AACA) and the Australian Institute of Architects (AIA). (2013); Orr (2015)

Table 1 defines this body of literature within the categories of What, Where Creativity and Technology. The compelling finding from this literature is that the professionally-oriented educators in architecture have a tendency to refer to research centred on reviewing the work of professionals (Schön, 1988) and not students. This important characteristic, and point of difference from this proposed study is that architectural educators or professionals (Gero et al., 2006) are likely to be able to articulate their views on their experiences in greater detail (Shih et al., 2017).

This observation of the literature advances a case for the value of a study that explores the experience of the design studio from a student perspective. In schools of architecture students read about design, they talk about design and inevitably engage in the act of design. However, these 'designs' they speak of can only ever be articulated through 'abstraction' (Koper, 2005). Also, students will never gain experience of their design as a real building. Therefore, they will only ever be able to imagine and subsequently communicate their designs through sketches, measured drawings or physical models. This 'problem of abstraction' has been cited as a limitation to the study of architecture (Iordanova, 2007, p. 687). Students, in contrast to professionals, are unlikely able to achieve the experience of inhabiting their designed buildings. The important act of reflecting on a structure is not possible to the student architect. The journey through the spaces or exploration of a structure is only ever imagined in the minds of the student and speculated in the minds of their teacher. Peter Downton (2016) argues this position in 'Design Research' noting that, "In the case of projects, the referents for images or mock-ups are yet to be possible to experience and the project may never come to fruition and never exist beyond this modelling of it" (2016, p. 118). For the student, the 'imagined building' through communicative tools is the only possible outcome from the established design studio learning experience.

5. What is the Real-Time Virtual Engine?

In the past decade, the Real-Time Virtual Engine has arrived to power interactive computer graphics. The current generation of learners have been exposed to gaming, and more recently, virtual reality gaming from a young age. The equipment is not only more affordable, it is easier to use. The increased volume of feedback from consumers has produced increasingly more accessible user interfaces, and presently, the use of the Real-Time Virtual Engine has found its way into professional architecture as a communication tool that offers exceptional visual fidelity, and a novel means to allow clients to experience buildings prior to construction. The compelling characteristic is that inhabitants are often able to 'walk' freely in the Real-Time Virtual Engine, simulating the experience of 'being there' and making decisions of what to 'do', whilst there (Segard, Moloney, & Moleta, 2013; Vaai, Moloney, & Moleta, 2014). The experience of 'being there' has been seen as an answer to some of the criticisms of physical architectural communication tools. A user is able to experience the volumetric, material, and spatial characteristics of a design, without the 'difficult to acquire' intellectual translation required of sketches, scale drawings and models. This is however the established view recorded from practice and not a recorded experience of students who use it.

Architecture, as a field of professional tertiary education, relies extensively on the use of architectural communications such as: representation, simulation, and visualisation. Abstractions are an understandable requirement. The complexity, legal obligation and monetary cost associated with the act of constructing a building render the process of learning architectural design by planning, manufacturing, and then the important aspect of reviewing the completed building prohibitive to the extreme. To bridge this gap, the educators in schools of architecture set exercises for students to hone their communication skills. Tasks are designed to allow students to develop their designs and develop the skills to communicate their designs to others. Physical representational tools such as sketches, scale drawings and models have historically been routinely employed. In most prospectus's drawing is listed as a high priority for students of architecture, and additionally, many schools will offer numerous courses focussing on these and related skills. Drawing is also considered as an important 'expressive' and as unique in the way that it allows the designer to think through problems as they develop on the page (Lowe & Lowe, 1972; Webster, 2008). It is, therefore, considered an important arrow to develop in a very large quiver. Conversely, physical tools, such as sketching, however, have been criticised as focussing on a skillset that is removed from the act of design, postulating, that students of architecture become expert in the art of communication, at the expense of an intrinsic understanding of the spatial and constructional requirements of designing architecture. These voices report it is possible through physical media to misrepresent knowledge of a building through the manipulation of materials and space.

6. Why is the Real-Time Virtual Engine important for architectural studies?

Architecture as a field of study engages its students in design-based problems to facilitate learning the skills required for the design of buildings and structures (Wang et al., 2018.; Whyte & Nikolic, 2018). This field of education has historically required the learner to develop the ability to interpret two-dimensional drawings into three-dimensional relationships (Ascher, 2015; Varnelis, 1998). Examples of these skills may be found in the placement of a building on a complex sloping site, ensuring that a building envelope does not intrude into a neighbouring properties access to sun or a junction of three or more structural members. The spatial and geometric complexity required of the discipline are known stumbling blocks for the developing architect (Caruso, 2008; McEwen, 2003).

A number of reports note that the skills of 'spatial understanding' are difficult to muster because traditional means for depicting design situations are located in the orthographic drawing tradition (Abdelhameed, 2013; Aflatoony, Wakkary, & Neustaedter, 2018). It is common practice that two-dimensional drawings are used to communicate a three-dimensional structure. A series of pages are far easier to transport than a physical model, and if a model were used, it would need to be so complex that the utility of its role as a 'communication tool' would be debatable. The orthographic drawings system contains a view from above, a view from the front, a view from the side and potentially a section view. While this system of communicating is historically significant (Lowe & Lowe, 1972), rising criticism of the system is evident (Bilda, Gero, & Purcell, 2006) in conjunction with the rise of computationally-aided design (Ekströmer & Wever, 2019; Jonson, 2005; Poelman & Keyson, 2008.; Shih et al., 2017).

The rise of computational design is reported as offering significant change (Ekströmer & Wever, 2019). Ekströmer and Wever note virtual reality enables a shift from working primarily in two dimensions to working on a 'virtual model' in three dimensions. The field of CAD is a highly contested and the volume of research (see Table 2) and commentary is generated by architects, technologists and software developers actively promoting virtual reality. Five international conference circuits and two highly regarded journals support the peer-reviewed dissemination of this research.

Table 2. Table 2: Sub-fields of architectural education.

Sub-fields of architectural education	Literature
Educational Studies in Architecture	Cocchiarella (2015); Poelman & Keyson (2008)
Computational architecture	Abdelfattah, H. K. and A. A. R. (2004);
Technology in Architectural Education	Chieh (2005); Vecchia, da Silva & Pereira (2009); Liang (2006); Radford (2000)
Virtualisation as an educational tool	Nitsche (2008); Bogost (2007)

There have been many studies exploring the use of the Real-Time Virtual

Engine. A review of the literature using the search terms Game Engine, Virtual Engine, Real-Time, Technology, Education yielded a high number of results (Bozalek, 2014; Foot, 2014; Koszalka & Wu, 2004; Nussbaumer, 2012). In many of these studies, a complex system of recording the activities of the learners and their engagement with technology is employed. A high number of studies employed informal interviews or open-ended questionnaires. A number of researchers have referred to an 'interview checklist'. However, this is an incidence frequently found in the field of Human-Computer-Interaction and Interface Design. Yael Kali (2011) discusses the role of technology in creative contexts in 'Learning, Media and Technology'. She states, 'We believe that future progress in learning R&D will require more and better research on users, their needs, contexts of use and the affordances of the various tools and resources that are meant to improve their design activity..." (p. 130). This is a valid claim, the field needs more reporting to better our understanding of the impacts of technology on future learners. Propositions such as this indicate the need to undertake study; however, how do we study the experiences of those who employ virtual reality in the architectural design studio? Table 3 traces seven key principles important in architectural education and maps each principle to studies undertaken using a Real-Time Virtual Engine.

Table 3. Table 3: Architectural studies in virtual reality.

Key Principle	What aspects of Architecutre have been explored in VR	Literature
Atmosphere	The abilty to describe space in high fidelity to evoke an emotional response	Moleta (2015); Moleta (2017); Debono & Moleta (2016); Vasylevska, K., Podkosova, I., & Kaufmann, H. (2015).;
Construction	Constructability, project management and construction pratices are central to Architecure	Moleta, Vaai & Moloney (2014); Joch (2005) Beckmann (1998). Mitchell & McCullough (1991); Morgan & Zampi (1995); Livingston (2008); Kuliga, Thrash, Dalton & Hölscher(2015)
Collaboration	Architecture as a profession requires its students to develop skills in collaboration and sharing	Lo, Schnabel & Moleta(2018); Moleta, Walker & Schnabel (2018); Lo, Schnabel & Moleta(2016); Moleta (2016); Segard, Moleta & Moloney (2013);
Creative expression	Creative expression and speculation on design activity	Rogers, Schnabel & Moleta (2019); Voss & Moleta (2016); Dean (2008)
Geometry, Scale, Proportion	How architects use geometry scale and proportion	Holth, Meekings, Moleta & Schnabel (2019); Innes, Schnabel & Moleta (2017)
Culture	How architecture contributes to a culture through design of social spaces	Qureshi, Schnabel & Moleta (2019); Silcock, Rushton, Moleta & Schnabel (2018); Qureshi, Schnabel & Moleta (2018); Aydin, Schnabel & Moleta(2017); Duddumpudi, Moleta & Moloney (2013)
Design systems	How architects go about the activity of design	Wang & Moleta(2019), Wang, Moleta & Schnabel (2018); Nguyen, Moleta & Schnabel (2019) Dorta, Aydin, Schnabel & Moleta (2017); Chen & Wang (2017); Weibel, Schmutz, Pahud & Wissmath (2015)

7. Conclusion

Despite this amassed pool of knowledge, there are aspects of the Real-Time Virtual Engine's deployment in the contemporary design studio that do not appear to have been observed and documented. The literature review uncovers some striking findings the most telling being Mavers (1995) claim about CAD research pre-1995 cited a need for empirical evidence. I am therefore reporting that few papers contradict his postulation and furthermore, even fewer of these are from the perspective of the student.

References

Abdelfattah, H.K. and Raouf, A.A.: 2004, No more fear or doubt: Electronica Architecture in Architectural Education, *Proceedings of ASCAAD 'e-Design in Architecture'*, 155-176.

Askland, H.H., Ostwald, M.J. and Williams, A.: 2012, *Assessing creativity : supporting learning in architecture and design. Office for Learning and Teaching*, Australian Govenment Office for Learning and Teaching (OLT), Sydney.

Attoe, W. and Mugerauer, R.: 1991, Excellent studio teaching in architecture, *Studies in Higher Education,*, **16(1)**, 41-50.

Beckman, J.: 1998, *Virtual Dimension: Architecture, Representation, and Crash Culture*, Princeton Architectural Press.

Bogost, I.: 2007, *Persuasive games: the expressive power of videogames*, MIT Press.

de Bono, J. and Moleta, T.: 2016, Sentimentality and the Digital Expanse An Exploration of Virtual Environments and their Emotive Impact on Virtual Inhabitants, *SIGraDi 2016, XX Congress of the Iberoamerican Society of Digital Graphics*, Buenos Aires, 668-676.

Carlhian, J.P.: 1979, The Ecole Des Beaux-Arts: Modes and Manners, *Journal of Architectural Education*, **33**, 7-17.

Caruso, A.: 2019, Studio Culture: learning from the American experience, *The Oxford Conference : A Re-Evaluation of Education in Architecture*, Oxford.

Chen, Y.H. and Wang, C.H.: 2017, Learner presence, perception, and learning achievements in augmented–reality–mediated learning environments, *Interactive Learning Environments*, **1**, 1-14.

Chieh, J.L.: 2005, Space layout game: An Interactive Game of Space Layout for Teaching and Representing Design Knowledge, *CAADRIA 2005 [Proceedings of the 10th International Conference on Computer Aided Architectural Design Research in Asia*, New Delhi.

Cocchiarella, L.: 2015, *Working with the Image: Description Processing Prediction*, Springer.

Davies, R.L.: 1960, The Education Of an Architect, *The Education Of an Architect*, **50**, 1-14.

Deamer, P.: 2005, First Year: The Fictions of Studio Design, *Perspecta*, **36**, 10-16.

Dutton, T.A.: 1987, Design and Studio Pedagogy, *Journal of Architectural Education*, **41**(1), 16-25.

Gül, L.F.: 2012, Educating new generation of architects, *Proceedings of eCAADe 2012, Digital Physcality*, Prague, 77-85.

Herbert, A.: 2010, *The pedagogy of creativity*, Routledge.

Joch, A.: 2005, Design embraces the machine age: Digital fabrication of architecture, *Architectural Record*, **193**(12), 1-20.

Khrystyna, K., Podkosova, I. and Kaufman, H.: 2015, Walking in Virtual Reality: Flexible Spaces and Other Techniques, *The Visual Language of Technique*, **7**(7), 81-97.

Kilicaslan, J. and Ziyrek, B.E.: 2012, A research about creativity in design education, *Procedia -Social and Behavioral Sciences*, **46**, 1461-1464.

Kuliga, S.F., Thrash, T., Dalton, R.C. and Hölscher, C.: 2015, Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model, *Computers, Environment and Urban Systems*, **54**, 363-375.

Liang, C.H. and Chang, T.W.: 2006, TOWARD A PLAYFUL DESIGN ENVIRONMENT - DIGAME, *Rhythm and Harmony in Digital Space in Proceedings of CAADRIA 2006*, Kumamoto, 187-196.

Lyndon, D.: 1978, Architectural Education Here, *Journal of Architectural Education*, **31**, 2.

MacGilvray, D.F.: 1992, The Proper Education of Musicians and Architects, *Journal of Architectural Education*, **46**(2), 87.

McEwen, I.K.: 2003, *Vitruvius: Writing the Body of Architecture*, MIT Press.

Mitchell, W.J. and McCollough, M.: 1991, *Digital design media□: a handbook for architects and design professionals*, Van Nostrand Reinhold.

Moleta, T.: 2016, Game on: Exploring constructive design behaviors through the use of real-time virtual engines in architectural education, *International Journal of Architectural Computing*, **14**(3), 212-218.

Moleta, T.: 2017, Digital Ephemera - Autonomous Real-Time Events in Virtual Environments, *CAADRIA 2017 - 22nd International Conference on Computer-Aided Architectural Design Research in Asia: Protocols, Flows and Glitches*, Suzhou, China, 14-22.

Nitsche, M.: 2008, *Video game spaces: image, play, and structure in 3D game worlds*, MIT Press.

Nováková, K., Achten, H. and Matějovská, D.: 2010, Design Studio Pedagogy for Experiments with Unusual Material, Collaboration and Web Communication, *International Journal of Architectural Computing*, **8**(4), 557-572.

Poleman, W. and Keyson, D.: 2008, What Architects & Industrial Designers can teach eachother about managing the design process, *Technology diffusions and design. The metabolism of knowledge*, **1**, 90-107.

Qureshi, C., Moleta, T. and Schnabel, M.A.: 2019, BEYOND THE PORTAL: A Study of the Tangible and Intangible Rituals within Sacred Spaces, *Intelligent & Informed, Proceedings of the 24thInternational Conference of the Association forComputer-Aided Architectural Design Research in Asia*, Wellington.

Radford, A.: 2000, Games and Learning about Form in Architecture, *Automation in Construction*, **9**(4), 379-385.

Vaai, J., Moleta, T. and Moloney, J.: 2014, Integrating project management and mobile augmented reality, *Rethinking Comprehensive Design: Speculative Counterculture - Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia*, Kyoto.

Varnelis, K.: 1998, The Education of the Innocent Eye, *Journal of Architectural Education*, **51**, 212-223.

Vecchia, L., Pereira, A. and ds Silva, A.: 2009, Teaching/learning Architectural Design based on a Virtual Learning Environment, *International Journal of Architectural Computing*, **7**(2), 255-266.

Wang, T.J. and Huang, K.H.: 2018, Pedagogy, philosophy, and the question of creativity, *Teaching in Higher Education*, **23**(2), 261-273.

Westfall, C.W.: 2008, Why the Orders Belong in Studio, *Journal of Architectural Education*, **61**(4), 95-107.

THE EXPERIMENT OF NEURAL NETWORK ON THE COGNITION OF STYLE

WEI HU
[1]College of Architecture and Urban Planning, Tongji University
[1]1990huwei@sina.com

Abstract. This paper introduces a method to obtain quantified style description vector which is for computer analysis input by using image style classification task. In the experiment, 3331 architectural photos of three styles obtained by crawling and filtering were used as training data. A deep convolutional neural network was trained to map architectural images to high-dimensional feature space, and then the high-dimensional style description vector was used to output the measurement results of style cognition with fully connected neural network. Tested by test data-set of 371 architectural pictures, the accuracy rate of style cognition reached more than 80%. The neural network using architectural data training was applied to the style cognition of non-architectural objects, high accuracy rate was also achieved, it proved that this quantified style description vector did include the information about style cognition to some extent instead of simply classification. Finally, the similarities and differences between the cognitive characteristics of style of neural network and human beings are investigated.

Keywords. Deep neural network; style cognition experiment; eye tracker.

1. Introduction

In fine arts and performing arts, any art object or performance has its creation process and follows some unique generation ways and methods. If such methods are repeated over time to reproduce similar forms or actions, a characteristic pattern emerges and a style is formed(Chan, 2000). Most studies of style have focused on describing important forms of a style or reviewing the background to their development, and further exploring the background and relevance of their interactions with other forms. However, our definition of a style is almost always descriptive and qualitative, rather than numerical and quantitative, which leads to a question: Can styles be numerical described to facilitate input into the computer for computation or generation?

It is easy to map a picture of an architecture into a quantitative vector, but how to get a style vector with the right dimensions and retain the original style information is the key challenge. Maybe we can learn from the word embedding method in NPL, that is, can use the training of word prediction model in text to get

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 61-70.

the word vector in the intermediate step (Bengio, 2000). In this study, we use the task of architectural style recognition to obtain the style vector in the intermediate step.

This kind of high-dimensional spatial mapping transformation problem of images is actually the field of artificial neural network algorithms. The processing of the data related to the image or block is the advantage of Convolutional Neural Networks (CNN). In the 1990s, LeCun (LeCun et al.1989) introduced Backpropagation (BP) algorithm and simplified the Fukushima's (1975) network structure, marking the birth of modern convolutional neural network structure. Subsequently, complex convolutional neural networks composed of standard CNN structures were proposed, such as Lenet-5 (LeCun and Bottou 1998) proposed in 1998. With the progress of hardware technology, especially the successful application of GPU to neural network computing in 2006, the computing capacity of neural network training has been greatly improved, which makes the training of large and deeper neural network possible. A variety of complex neural networks with convolutional structure layer have been successively proposed, such as AlexNet (Krizhevsky et al. 2012), GoogLeNet (Szegedy et al. 2015), ResNet (He et al.2016), VGG (Simonyan and Zisserman 2015), etc., and have been applied to the image classification challenge competition, which has greatly improved the accuracy of image classification and surpassed human performance in this task in 2015.

Many artists and researchers have practiced the application of convolutional neural networks in style-related problems. Many of them are researches on style transfer. Gatys et al. (2016) and Shahriari et al. (2014) used convolutional neural network to transfer famous painting styles to architectural photos. Özel et al. (2019) used the convolutional neural network to transfer the two-dimensional painting style to the three-dimensional building model. In the process of style transformation, the content and style of the target building and the input image were separated and combined at multiple levels using the neural network, and the specific features were extracted and deployed. Zhang et al. (2020) studied the style transfer of 3D model images by using two GAN networks containing the convolutional neural layer. Some researchers try to use convolutional neural network to classify architectural styles. Obeso et al. (2017) used convolutional neural network combined with sparse features and primary color pixel values to classify three Mexican building images. Zhao et al. (2019) studied building classification using the convolutional neural network based on GoogLeNet. Yi et al. (2020) used convolutional neural network to conduct classification research on 8 types of American houses, but the classification accuracy was only about 40%.

This paper introduces a method to obtain quantified style description vector by using image style classification task, with the following main contents:

First, through the experiment on the cognition of architectural style of convolutional neural network, the results obtained the accuracy rate of more than 80%, which preliminarily verified the feasibility of artificial intelligence on the cognition of design style. In the intermediate step of neural network cognition, architectural style is mapped to high-dimensional space to obtain high-dimensional quantified style description vector, that's the style vector we're looking for.

Secondly, the style cognition ability of the neural network is further verified. Applying the neural network trained with architectural picture data to the style cognition of other kinds of objects, such as jewelry, clothing and furniture, has also achieved a high accuracy rate, which indicates that the method presented in this paper has a certain ability to recognize styles across different kinds, rather than simply classifying architectural pictures. This also proves that the style vector includes the style information of the non-building object, not the building category information.

Thirdly, on the one hand, the internal feature images of the convolutional neural network are visualized to observe the focus of attention of the neural network; on the other hand, the eye tracker was used to test the attention focus of human beings when they recognized the image style of buildings. In this way, the similarities and differences between the cognitive characteristics of style of neural network and human beings are investigated.

2. Method

In this study, an artificial neural network was used to recognize the style of Baroque, Byzantine and Gothic architectural pictures. The use of deep neural network is divided into four steps: First, collect and preprocess the data used in training and testing neural network; Second, select the appropriate neural network structure; Thirdly, use applicable method to train neural network; Finally, the trained network will be tested and applied.

2.1. DATA ACQUISITION

The image data used in the training of this paper is crawled by search websites, which are sourced from Google, Baidu and Naver. About 200,000 images of Baroque architecture, Byzantine architecture and Gothic architecture were downloaded by the crawler. However, most of these crawled pictures are duplicate pictures and inappropriate pictures such as images of books and text, etc. After deduplication and screening, there are about 3,700 pictures for this research, and the number of pictures of buildings of the three styles is roughly equal. The picture samples used in this research are shown in Figure 1.

Figure 1. Sample data images used in this experiment.

2.2. CONVOLUTIONAL NEURAL NETWORK STRUCTURE

The neural network used in this study is expanded based on VGG network(Simonyan and Zisserman 2015). The structure is shown in Figure

2. The main structure of VGG is divided into 5 groups of convolutional layers structure, each group includes 2-3 convolutional layers and 1 pooling layer. The convolutional layer is responsible for extracting the image features, while the pooling layer is responsible for reducing the size of the feature image. After each pooling operation, the size of feature image decreases, and the extracted features become more and more "abstract" and "macro". In this paper, the feature images will be visualized after each group of convolution operations, and their positions are indicated by the numbers 1-5 in Figure 2. After five groups of convolution operations with VGG, the feature images are mapped into a 256-dimensional feature vector by full-connected neural network, which will contain the neural network's "cognition" of the input image. Finally, this cognitive feature vector is output three numbers between 0 and 1 by using full-connected neural network, respectively representing the probability of Baroque, Byzantine and Gothic styles of neural network cognitive of the input image.

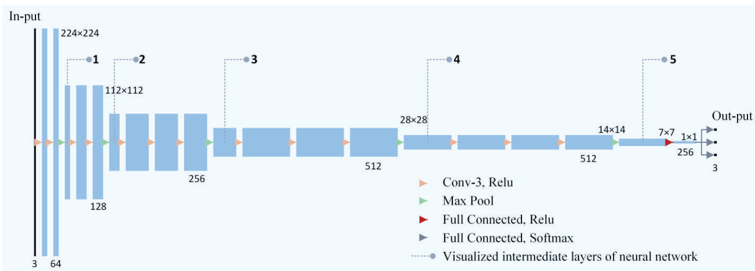


Figure 2. Network structure diagram for this study.

In fact, in order to achieve the research goal of this paper, that is, to find a quantitative vector to describe the style characteristics of the picture, so that it can be easily input into the computer, we carry out the training of style classification is only the means. In the method presented in this paper, the 256-dimensional vector before entering the classified fully connected neural network is the quantitative description vector we seek. We have made some attempts. On the one hand, there are enough vector dimensions of 256-dimension to preserve enough information, which has been proved by the high enough accuracy of classification in the following paper. On the other hand, the vector dimensions of 256-dimension are not too large, and good training can be obtained on relatively small data sets.

2.3. TRAINING

Human's ability to understand and generalize knowledge is far beyond the current neural network algorithm. All the textbooks that we use from elementary school to university can be digitized into a USB stick, and with such a small amount of data, humans can acquire quite a lot of knowledge. However, even teaching artificial intelligence algorithms to recognize buildings in satellite images, a very simple task in human eyes, requires more than 10GB training data (Sun and Hu 2020). Human can use very little information to learn a lot of knowledge, because humans have a special ability, analogy. We learn highly summarized the general theory of knowledge, deduce different details, would be generally useful in different application scenarios. With the expansion of the scale of neural network, the training needs more and more data and computing power, so it becomes more and more difficult to train a new network from scratch. At this time, it is necessary for artificial intelligence to imitate human's ability of analogy, and the method of transfer learning (Sinno and Qiang 2009) emerges at the right moment. To put it simply, transfer learning is to help train a new network or a new data-set by using some network parameters that have been trained with old data-set, which can greatly reduce the requirement of training data and training time for the new training. VGG is a large scale deep neural network, so this paper uses the method of transfer learning to speed up training. The parameters we transferred were part of the VGG convolutional neural network trained with the ImageNet data-set, which was applied to the classification task of 1000 categories of images. We have reason to believe that there is a great deal of commonality in the extraction of some underlying features, such as edges, textures and simple geometric shapes, whether it is in the cognition of picture design style, or in the classification of flowers, dogs, cats and vehicles. After experiments, the transfer learning method in this study can greatly improve the training efficiency, and the model is convergent in a short time.

3. Result

After the neural network model was trained to converge with the training data-set, the accuracy test was carried out with the test data-set containing 371 pictures which were not included in the training set. After calculation, the model's style cognition accuracy on the test data-set is 80.86%.

Figure 3 is examples of the test images, No. 1-4 are Gothic (Notre Dame cathedral), No. 5-7 are Baroque (Church of Saint Carlo), and No. 8-11 are Byzantine (Hagia Sophia). The cognitive results are shown in Table 1. The accuracy of cognition is relatively high. Several of them deserve special mention. For example, in picture No. 10, the data used in this experimental neural network training are architectural photos, while picture No. 10 is the engineering drawing of the section of Hagia Sophia cathedral. The probability that the neural network considered it Byzantine was as high as 96.57%. This indicates that the neural network has a certain ability of "analogy" in terms of the type of image input for the style cognition task. Picture No. 6, 7, 8 and 9 show the interior roofs of the Baroque and Byzantine buildings, respectively, with a greater similarity in appearance. The neural network correctly recognized three of the pictures, and the wrong No. 6, it can be seen that the neural network is not very sure about the wrong judgment. Picture No. 4, the top of the gate and sculpture of Notre Dame cathedral is another result of cognitive error. Similarly, the neural network is not very sure about the wrong cognitive result, but it also shows that the neural network is not very strong in "analogy" from the training of relatively overall buildings to the local features like relief or sculpture.

Figure 3. Architectural images for further testing.

Table 1. Probability results of neural network cognition.

	1	2	3	4	5	6	7	8	9	10	11
Baroque	5. 66%	4. 01%	30. 34%	66. 37%	97. 56%	27. 82%	87. 81%	1. 62%	1. 98%	2. 45%	0. 70%
Byzantine	26. 45%	4. 99%	4. 04%	5. 62%	1. 11%	70. 55%	5. 21%	98. 35%	97. 42%	96. 57%	99. 20%
Gothic	67. 89%	91. 00%	65. 62%	28. 01%	1. 33%	1. 64%	6. 98	0. 03%	0. 60%	0. 98%	0. 10%
Correct/Wrong	Correct	Correct	Correct	Wrong	Correct	Wrong	Correct	Correct	Correct	Correct	Correct

4. Further verification

In order to test whether the neural network actually recognized the perceived style of human beings or merely performed a simple image classification task, we designed an experiment for further verification.

When we talk about the Baroque, or the Gothic, we don't just mean the style of buildings, we can also mean furniture, jewelry, clothing or even music or literature. Although it is difficult to quantify, we can at least sum up some qualitative knowledge of architectural style. However, in terms of styles of objects across different categories, we can hardly even make qualitative generalization. If the neural network can recognize the styles of other kinds of objects across categories while only learning architectural styles, then it can be verified that the neural network has indeed learned the styles recognized by human beings.

We used architectural photos of three styles to train the neural network. In the above test, we have preliminarily verified that the correct rate of architectural style cognition is relatively high, and it even have a certain cross-category style cognitive ability, such as the cognitive ability of section drawing of picture No.10. In order to further test the style cognition ability of the neural network, we will test the style cognition of the neural network trained by architectural photos with non-architectural pictures. As shown in Figure 4, picture No. 1 is modern art in Baroque style; picture No. 9 and 11 are baroque style furniture; No. 5 is an oil painting whose interior furnishings and costumes are in the late Baroque style. Picture No. 2 is part of Chanel's "Paris-Byzantium" collection; Picture No. 4 is a Byzantine jewelry; Decorative paintings in picture No. 6 and 7 are in the Byzantine style. Picture No. 3 is gothic furniture; Picture No. 8 is a gothic fascinator for a modern doll; Picture No. 10 is a gothic style photo with modern Gothic makeup and clothing.

Figure 4. Non-architectural pictures for further testing.

As shown in Table 2, the test results show that the neural network trained by architectural photos also has a high accuracy rate in style recognition of non-architectural cross-category items. But there are some issues worth mentioning. Picture No. 2 Chanel "Paris-Byzantium" series of jewelry is recognized as Baroque style; Although the cognition of picture No. 5 oil painting is correct, the certainty is not very high. It seems that the neural network also thinks that it belongs to Byzantine style with certain possibility; According to the prediction results, the neural network seems to be lost in the style cognition of picture No.10, the probability of these three styles is relatively close and none of them is more than 50%.

Table 2. Probability results of further tests.

	1	2	3	4	5	6	7	8	9	10	11
Baroque	96. 15%	86. 36%	2. 01%	3. 43%	51. 49%	0. 72%	0. 36%	3. 71%	69. 87%	42. 38%	76. 47%
yzantine	2. 61%	11. 63%	1. 16%	94. 76%	44. 86%	97. 63%	99. 35%	0. 10%	27. 60%	32. 08%	14. 77%
Gothic	1. 24%	2. 00%	96. 83%	1. 80%	3. 66%	1. 65%	0. 28%	96. 19%	2. 53%	25. 55%	8. 76%
rect/Wrong	Correct	Wrong	Correct	Correct	Correct	Correct	Correct	Correct	Correct	Wrong	Correct

5. Experiment of attention focus in style cognition

Figure 5 shows the visualization process of the middle layer of the neural network from the shallow to the deep 5 positions, and finally superposing all the layers to obtain the thermal diagram of the neural network attention focus. The visualization method is to highlight the sensory field corresponding to highly activated neurons in the convolutional neural network, that is, the features "seen" by neurons in this layer.

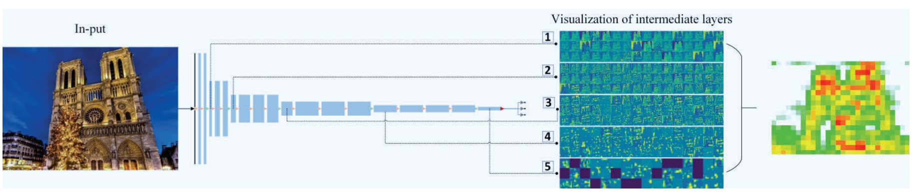


Figure 5. Neural network internal feature image visualization.

It can be seen that the features extracted from the feature images with serial numbers from 1 to 5 change from micro to macro and from details to the abstractions. The feature images extracted from position 1 are the most basic and detailed edge lines, angles and colors, etc. At position 3, they become larger parts, such as small windows, columns and eaves, etc., while at position 5, they become more integral large parts, such as large rose windows, the portal and even the whole front facade. This hierarchical perception of detail is to some extent similar to human perception of art or the process of creation- We may have similar experience when painting and looking at art exhibitions. one moment, we observe microscopic features such as details and brush strokes closely, and the other moment, we stand back to observe macroscopic features such as overall picture proportions, light and shade contrast and color collocation.

By further stacking all the feature images, the heat map of "attention focus" of all activated neurons in the neural network can be obtained. From the heat map of attention, we can analyze the areas that the neural network focuses on when cognizing the style of a picture, infer the possible judgment basis that the neural network thinks that a picture is a certain style, and try to peer into the corner of the black box of the neural network.

At the same time, we conducted an experiment with 15 architecture students, asking them to look at architectural pictures and judge their style. Eye tracker was used to record their focus of attention during the experiment, as shown in Figure 6.

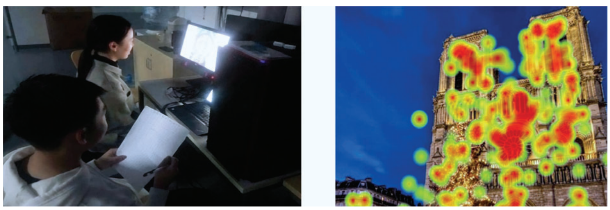


Figure 6. Eye tracker recording of architectural style identification by architecture students.

The results of neural network visual thermal diagram and eye tracker recording are shown in Figure 7. Above is the original picture of behavioral architecture, in the middle is the behavioral eye tracker recording the attention focus of architectural students, and below is the behavioral neural network attention-focus thermal diagram.

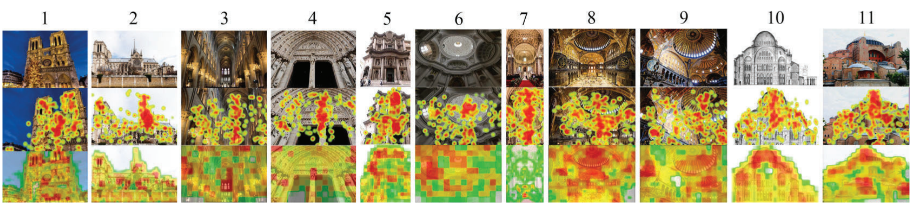


Figure 7. Comparison of the attention focus diagram of the neural network and the architecture students.

After comparison, the following conclusions can be drawn: First, the focus of attention of neural network is more dispersed and average than the visual focus of human beings, which may be because human beings have a better ability of generalization when observing, and they do not need to observe some regular patterns separately, but only need to focus on one of them. Second, there are many common points of attention between neural networks and human beings, such as rose windows, long lancet windows and spires in Gothic architecture; The junction of eaves and columns, decorative relief in Baroque architecture; the dome in Byzantine architecture. Thirdly, the attention focus of neural network is also different from that of human beings, such as attention to the junction of structures, attention to the vicinity of the edges of architectural components, and attention to sculptures or figures in architecture.

6. Conclusions

In this study, the cognitive ability of neural network to design style was investigated experimentally. In the intermidia step of the neural network, we extracted the quantified style description vector that we want. Based on this style vector, the probability that the input images are of Baroque, Byzantine and Gothic styles is recognized.

Architectural photos of three different styles were crawled through the network to train a neural network training. For this large neural network, the transfer learning method was used to speed up the training. After the training, the performance of the three styles cognition was tested in the test data-set, and the results showed that the accuracy rate of the three styles was 80.86%.

Furthermore, the neural network which was trained of architectural photo data-set is used to cognize the style of non-architectural objects, and the result still shows a high accuracy rate. To some extent, this indicates that the neural network has "discovered" some cross-category common style characteristics in the high-dimensional feature space, so that it can recognize the style of objects across categories without prior training of corresponding categories, that is to say, it has preliminarily acquired certain ability of "analogy" in terms of style cognition.

In order to further explore how the neural network cognizes architectural style, the feature images extracted from the middle layer of the neural network are visualized, showing that as the number of layers deepens, the architectural features extracted from the neural network also change from the subtle geometric features to the macroscopic architectural components. This cognitive pattern has some similarities with human beings. Then, all feature images are superimposed to explore the distribution of neural network's attention when "observing" specific images, so as to analyze the basis of its cognitive judgment. In addition, the eye tracker experiment of architecture students was carried out to record the focus of human attention when observing architectural style and compare it with the neural network. It is found that the focus of neural network is partly similar to that of human beings.

7. Discussion and Futures studies

It is difficult and controversial to describe a style qualitatively in a way that human beings can understand. However, the method presented in this paper can be regarded as a preliminary attempt to obtain a vector that can input a quantitative description of style into a computer without needing to be in a dimension that humans can understand. Although we cannot directly understand the specific meaning of this style vector, we can input the image style information into the computer in this way, which provides an input interface for us to deal with style-related tasks. Much further work is needed, such as trying to parse these style vectors on a human-understandable dimension; To further improve the accuracy of description; Study how to use style vector for generation and so on.

References

Bengio, Y., Ducharme, R. and Vincent, P.: 2000, A Neural Probabilistic Language Model, *Advances in Neural Information Processing Systems 13*.

Chan, C.: 2000, Can style be measured?, *DESIGN STUDIES*, **21(3)**, 277-291.

Fukushima, K.: 1975, Cognitron: A self-organizing multilayered neural network, *Biological Cybernetics*, **20(3-4)**, 121-136.

Gatys, L.A. and Ecker, A.S.: 2016, Image Style Transfer Using Convolutional Neural Networks, *Computer Vision & Pattern Recognition. IEEE*.

He, K., Zhang, X. and Ren, S.: 2016, Deep Residual Learning for Image Recognition, *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). IEEE*.

Krizhevsky, A., Sutskever, I. and Hinton, G.E.: 2012, ImageNet classification with deep convolutional neural networks, *NIPS'12: Proceedings of the 25th International Conference on Neural Information Processing Systems*, 1097–1105.

LeCun, Y., Boser, B. and Denker, J.S.: 1989, Backpropagation Applied to Handwritten Zip Code, *Neural Computation*, **V1N4**, 541-551.

LeCun, Y. and Bottou, L.: 1998, Gradient-based learning applied to document recognition, *Proceedings of the IEEE*, **86(11)**, 2278-2324.

Obeso, A.M., Benois-Pineau, J. and Acosta, A.A.R.: 2017, Architectural style classification of Mexican historical buildings using deep convolutional neural networks and sparse features, *Journal of Electronic Imaging*, **26(1)**, 011-016.

Shahriari, K. and Shahriari, M.: 2017, IEEE standard review — Ethically aligned design: A vision for prioritizing human wellbeing with artificial intelligence and autonomous systems, *Humanitarian Technology Conference. IEEE*, 197-201.

Simonyan, K. and Zisserman, A.: 2015, Very Deep Convolutional Networks for Large-Scale Image Recognition, *ICLR, 2015*.

Sinno, J.P. and Qiang, Y.A.: 2009, A Survey on Transfer Learning, *IEEE Transactions on Knowledge and Data Engineering*, **2009**, 1345-1359.

Sun, C. and Hu, W.: 2020, A Rapid Building Density Survey Method Based on Improved Unet, *the 25th CAADRIA Conference*, Bangkok, Thailand, 649-658.

Szegedy, C., Liu, W. and Jia, Y.: 2015, Going Deeper with Convolutions, *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, **07**, 1-9.

Yi, Y.K., Zhang, Y. and Myung, J.: 2020, House style recognition using deep convolutional neural network, *AUTOMATION IN CONSTRUCTION*, **118**, 103307.

Zhang, H. and Blasetti, E.: 2020, 3D Architectural Form Style Transfer through Machine Learning, *the 25th CAADRIA Conference*, Bangkok, Thailand, 659-668.

Zhao, P., Miao, Q. and Liu, R.: 2019, *Architectural Style Classification Based on DNN Model*, Springer, Cham.

Özel, G. and Ennemoser, B.: 2019, Interdisciplinary AI, *the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Austin, Texas, 380-391.

FACILITATING ARCHITECT-CLIENT COMMUNICATION IN THE PRE-DESIGN PHASE

CHENG-LIN CHUANG[1] and SHENG-FEN CHIEN[2]
[1,2]*National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan*
[1]*n76071021@gs.ncku.edu.tw* [2]*schien@mail.ncku.edu.tw*

Abstract. The process of architects exploring the program with clients often take place through face-to-face oral discussions and visual aids, such as photos and sketches. Our research focuses on two communication mediums: language and sketch. We employ machine learning techniques to assist architects and clients to improve their communication and reduce misunderstandings. We have trained a Naive Bayesian Classifier machine, the language assistant (LA), to classify architectural vocabularies with associations to design requirements. In addition, we have trained a Generative Adversarial Network, the sketch assistant (SA), to generate photo quality images based on architects' sketches. The language assistant and sketch assistant combined can facilitate architect-client communication during the pre-design stage.

Keywords. Architect-Client Communication; Pre-design; Architectural Programming; Machine Learning; Schematic Design.

1. Introduction

An architectural project begins from the pre-design phase, during which studies are done to analyze space requirements, opportunities and constraints of the proposed site, costs versus budgets. It is a critical phase for architects to explore the program with the clients to reach common agreement on an idea and direction. At this stage, the architect and the clients reached a consensus through a lot of communication to exchange the information (Taleb et al., 2017). Since architects and clients often do not share a common language about designs, their communication is slow and may result in misunderstandings. Past research has investigated architect-client communication issues and proposed models, strategies, and collaborative environments. While the efficiency of architect-client communication has improved for the design phase, in the pre-design phase, clients still encounter difficulties in articulating their needs or preferences. This seems to relate to a client's architectural knowledge, lacking of which makes it hard for the client to explain the needs and ideas well (Barrett, 1999).

To achieve mutual understanding, architects and clients employ various mediums to aid communications (Taleb et al., 2017). Clients often express their ideas with case pictures they like as a way to communicate with architects.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 71-80.

Compared with using language alone, having pictures or images help both parties communicate more smoothly. Therefore, toolsto visualize information and support visual communication are indispensable (Shen, 2011; Shen et al., 2013). Visual information could be abstract or realistic (eg. 3D renderings), static or dynamic, (eg. animation) where each style may af ford communications of certain types of information (Sirikasem and Degelman, 1990). BIM models, as a communication medium, allow clients to provide timely feedback of designs through virtual reality, thus enable architects to understand and record clients' preferences and to make design corrections in time design (Lertlakkhanakul et al., 2008; Shen, 2011).

Subjects of architect-clients often concerns appearances, functions and budget.Appearances relate to visual attributes of architectural spaces and exterior. The appearance of a building can affect customers satisfactions, which is essential for architects and clients to reach consensus. (Tessema, 2008). Function is the easiest subjection to communication between architects and clients (Kiviniemi, 2005). Budget is the issue that customers concern the most, because it affect many design, as well as construction decisions, including size, configuration, material selection and other details and determine whether the required building can be built within a given budget.

2. Research Objectives

In recent years, tools by using machine learning have been continuously developed to help people integrate and analyze complex information. It even uses the collected information to make combined predictions to help people see new relationships, new information, and inspire people to change their ideas. We plan to use machine learning technology to help architects and clients improve communication and reduce misunderstandings. We look forward to using computers to help us sort out some of the information (language or photo medium) provided by the client, analyze the client's preference for which building types, and let the architects based on the relevant conditions and precautions of this type of building discuss with the client, and then design according to the required materials of this type, and quickly form a visual medium by sketching to provide the client's reference to make the communication process smoother (Figure.1).

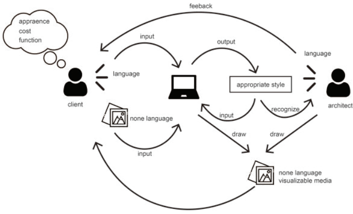


Figure 1. New communication flow.

3. Language Assistant (LA Model)

Clients often use their own experience to describe their requirement orally. They probably don't know what style of buildings are made of fair-faced concrete, but they tell the architect they want them house like some case was built by Tadao Ando. Or tell the architect, I want the Japanese style house. But the architect is not certain his thought the Japanese style is same or not with client thought. It's is easy to cause trouble for young architects with inexperience. Therefore, if we can help the architect to translate the blurred information in a clearer way, the architect can have a more accurate grasp of the needs of the client.

3.1. ABOUT THE TEXT

Because we lack the record of the dialogue between the architect and the client. Therefore, we use some record witch is the architectural magazine's editors interview to the client. Most of these interview records are narratives of the client's recollection of the process from selecting a site, interviewing with the architect, and completing the building. Although not actually participating in the discussion between the architect and the client, these interview records are based on the client's perspective and tone to discuss how they discussed with the architect and narrate their imagination and requirement for the space, which to some extent reflects the process of discussion.

3.2. MODEL

The NLP (Natural Language Processing, NLP) model is more accurate for semantic processing and is often used, but this model requires a large amount of sample data. Unfortunately, the dataset which related to architectural design is relatively scarce that we have to produce the dataset manually. In this experiment, all the data are classified through interviews and manual records, which cannot reach the amount required for deep learning. Therefore, we need to found an algorithm that can predict relatively accurately when the data is few. Finally, we use the Naive Bayesian Classifier which is commonly used in machine learning languages that still has a good learning effect when the data is not enough. The Naive Bayesian Classifier is based on the Bayesian theorem through the calculation of probability to allow the machine to determine which category a word should belong to. The important assumption of the Naive Bayesian classifier is conditional independence. Each feature is treated as an independent event, and the product of each feature's probability is used to obtain the maximum probability, and the maximum probability is the predicted value.

3.3. DATASET

In order to understand how the architect finds the conditions, limitations, and opportunities of the design in the massive dialogue messages with the client, and observe how the architect translates and classifies these clues into what kind of architectural professional words. And to observe whether different subjects face the same message, whether there are big differences in the labels of the key sentences and annotations. At this stage, we give different subjects the same text for them to read. And ask them to mark the words and sentences that are helpful to the design according to their own architectural professional judgments, and write their associated architectural professional words to the words and sentences. After the samples were collected, it was found that the selected key sentences were roughly the same (Table 1), and nearly 74% of the key sentences were the same. According to the test results, each subject is concerned about the client's occupation and living conditions. It can be seen that the issues that the architects are concerned about are roughly the same, but the depth and depth of their attention to the same words and sentences due to the different positions or experiences of the subjects (architects, office employees or students) The breadth is also different, and the vocabulary of the label is also different (Table 2).

Table 1. Keywords count and percentage.

	Keywords Selected	Same Selected	Individual Selected
Count	43	32	11
Persentage	100%	74%	26%

Table 2. The example of keywords sentence have different labels due to diffrerent subject.

Keywords sentence	Label			
The house will like a ship. Looks fashion and intersting.	Shape	Appearance	Imagery	
The building was built in fair-faced concrete rectangular box.	Shape	Appearance	Material	
The house is built for retire live.	Purpose	Long-term care	Universal Design	Barrier Free

3.4. DATASET PRODUCTION

After the collection is completed, we organize the data according to some rules. Each word or sentence will be labeled an architectural word. Sometimes only part of a sentence is marked, then the other parts of the sentence will be deleted and only the marked part will be kept. Sentences that are not marked are marked as "none" in order to increase the number of samples. Some headlines in the text are not marked.

Finally, we import the data set for training, and put the trained model into the data that the model has not seen before to distinguish. The result is not ideal, and the accuracy is about 21.4%. We summarized the following reasons:

1. The training set has the most labels with "None": Therefore, the chance of occurrence of nothing is the greatest. If there are more "None" labels in the test set, the prediction accuracy will improve. If the test set has fewer words and sentences with "None", it is possible The forecast rate drops.
2. The labels of the training set are too complex, and the same sentence has different labels, which causes the data set to be too scattered during training and affects the machine's judgment.
3. Data is not enough

In response to these problems, we modified the labeled rules of the data set on some of the factors that caused the problems:

1. The problem of label complexity and insufficient sample size: label complexity and sample size will affect each other. The higher the label complexity, the relative number of samples also need to increase to improve the training effect, so that the computer can strengthen the learning impression. However, data sets related to architecture are currently very scarce. If you want to conduct research on related topics, you need to create a training set yourself. Making training often consumes a lot of time and effort. Therefore, when the number of samples cannot be effectively increased, only The set can be modified to reduce the complexity of the label. In the first experiment, it was found that the words and sentences concerned by each subject were roughly the same, and the words marked on them also had a certain degree of relevance. As far as the results are concerned, we can classify these labeled words, sort out and formulate several architectural professional vocabularies for testers to choose, so as to reduce the complexity of labeling. Therefore, we classify and define several architectural professional vocabularies according to the tags of the previous test (Table 3), and let the architectural professionals select and label the important words and sentences they think. In order to be objective, we also asked the subjects to judge whether there are insufficient vocabulary to be added, and put them in the label after discussion.

Table 3. Definition of Label.

NO.	Label	Definition
0	Traffic	Car Movement; Parking Space
1	Site& Other Conditior	Site Location; Area; Terrain
2	MicroClimate	Temperature; Humidity
3	Building Performance	Ventilation; Lighting
4	Material	Archetectual Material
5	Client's Opinion	Client's Opinion
6	Client's Expect	Look forward something but not specified solution
7	Client's Requirement	Specific requirement
8	Historical Issue	In old street area; Historical building
9	Building Code	Building Code
10	Environment	Near by park or school which good for project
11	BulidingType	Residential; Commercial; Factory etc...
12	Function	Function
13	Landscape	Green Belt; River
14	View	Not block view; A good view poition
15	Cost	Cost; Money
16	Open Space	Outdoor Space; Public Space
17	Local Customs	About religon or culture

1. Will not label the unmarked information: In the entire dialogue process, there are very few words that are helpful to the design, so the words and sentences labeled as “no” are also the most. For designers, words and sentences are judged as “no” and have no meaning, and they cannot help designers to make classification judgments.
2. Annotate different texts: the purpose is to increase the number of samples. After reducing the complexity of the label, if the learning effect is to be better, the best way is to diversify the sample to achieve a better training effect. In the last experiment, it was found that the subjects concerned about the same words and sentences, it can be inferred that the words and sentences concerned by the architectural professionals are about the same, but according to their work experience and characteristics (architects, office employees, students, etc.) The depth and breadth of the same words and sentences are also different, and the vocabulary of their labels is also different. Therefore, in the second experiment, different texts of each subject were labeled to increase the number of samples to

improve the training effect of the model.

3.5. DISCUSSION

In addition to showing that the training was more successful(Figure 2), this comparison indirectly helped us sort out the themes that the owners and architects communicated most often. Among them, the top three labels with the largest number are: Client's Expectation (14), Function (11) and Site& Other Condition (10). It can be speculated that the communication between the owner and the architect is divided into two phases:

1. Functions and bases are the easiest building professional vocabulary to describe: The owner can clearly state what kind of space functions he needs, such as how many bedrooms are needed, where the toilet or kitchen is located. Since the owners need a lot of funds to purchase land and require rigorous evaluation, they have a good understanding of the information about the base.
2. The owners have many ideas but are not clear: The label is the most about the expectations of the owners, and it also proves that there are many less clear needs that the owners cannot clearly state. This result also indicates that it is necessary to classify these unclear requirements into several common processing methods in buildings, so that the architect can give the owner some clear suggestions. For example, if the owner wants a house that is different from the neighboring house, he can be advised to use different materials or shapes for design.

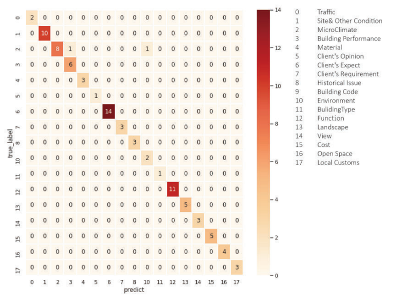


Figure 2. test data result.

Finally, the data that has not been read is put in for identification, and the accuracy is improved compared with the previous stage, about 57.1%. We observe the misjudged labels and find some associations(Figure3). Since the label is the owner's expectation during the training of the model, it is easy to distinguish this label when the model is looking at materials that have not been read. But we can observe that one of the correct labels is base and other conditions, but the machine judges it as microclimate. It seems that it can also correspond to the fact that although certain words are classified under one label, they are actually related to certain labels. The test example, such as building performance or function, may also be included in the scope of the label of the owner's expectation.

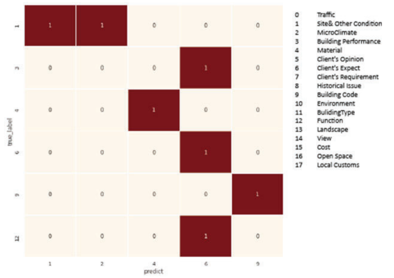


Figure 3. Table between true label and predict result.

4. Sketch Assistant (SA Model)

Why does the client like to take photos to communicate with the architect? Because the photos can directly show the owner's vision of the future of the project. The material and shape of the building itself can be presented in the photo. This is also an architectural professional vocabulary that the client can communicate with. Architects often use sketches for self-conversation, translating their thoughts into current drawings, and sometimes they must also use sketches to communicate with the owners, but they are often too abstract, requiring a lot of effort to explain and spend a lot of sketches. Let the clients understand.

4.1. MODEL

We use Generative Adversarial Network (GAN) to train the pixel-oriented PIX2PIX model. This model is composed of multiple layers of generators and discriminators(Figure4). The generator uses the color blocks we input to generate "fake" pictures and then uses the Discriminator to continuously discriminate the data until the discriminator knows that these pictures are "fake" pictures produced by the generator. The generator will also regenerate more realistic photos that are not judged by the discriminator as "fake" for the discriminator to recognize. The model is the result of the constant confrontation between the two. This model is based on this paper (Phillip Isola et al. 2017).

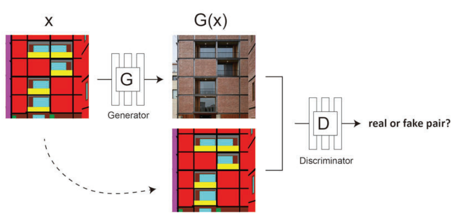


Figure 4. Principle of Pix2pix (Phillip Isola et al. 2017).

4.2. DATASET

We found 199 pictures on the Internet. Because the size of the input picture must be 64 times the length and width of the model, the picture was first cropped to 512*512 pixels. Then make the label color table corresponding to the material, the color is set according to the similar color of the real material. When choosing colors, try not to choose similar colors to avoid confusion. Objects other than buildings are classified as unrecognizable. Finally, we make a image set with a picture and a color block map according to the rules (Figure 5).

color/色票	R	G	B	label/標籤名
	255	0	255	NA
	236	97	0	painting
	0	153	68	stone
	255	241	0	grille
	0	0	0	metale_plate
	0	0	255	curtain_wall
	0	255	255	window
	255	0	0	brick
	147	45	0	wood
	115	115	115	concrete
	146	7	131	tile

Figure 5. Material Label Rule and Image set.

In order to understand how the architect disassembled the materials on the classified photos, we invited several experienced designers to assist in the labeling. After the label was recovered, we found some interesting classifications. Among them, the classification of certain materials is different due to the judgment of the labeler. For example, because many grids are made by wood, some people label the denser grids to the wood material or classify the sparsely arranged grids on the grid (Figure 6). These classifications are finally reflected in the results of the model.

Figure 6. Some label easy to confuse.

4.3. TRAINING

After organized the image set, we input it to train the model. In the training results of 1200˜7200 epoch, the generated image has roughly the color of the architectural frame and material, but the texture of the material is not satisfactory. Finally, we trained the model to 14,400 epochs, and the generated photos were almost consistent with the original images. Finally, we used the model to generate (Figure 7) and observed:

1. In the material part, according to the number of samples in the training set, it can be generated according to the texture and color with the largest number (for example, the most color of the metal plate is black).
2. The details of the material are still not ideal: from the generated image Look, types with more material details such as bricks or grilles are less effective, which may also be caused by insufficient training samples.
3. The unrecognized part works well: Judging from the generated results, it is surprising that the sky and plants can be drawn.

Figure 7. Result of test data by using epoch 14400 model.

4.4. DISCUSSION

We later discussed the results with the professionals who helped label. When classifying labels, it is found that even the same material will have different colors and textures. Because this model allows the computer to recognize the color of pixels for training, it may affect the training effect. After the discussion, if you want to use this model as a tool for communication, the training model can be adjusted as follows: Several models can be classified according to the type of building, and the choice can be judged according to the owner's needs, such as using style or geographical distinction: the same area or The styles of the buildings are basically similar to the materials used. If you divide them into several training sets (such as Scandinavian style, Chinese style; urban or country), you can choose in use, so you can more accurately judge the effect of the material, The discussion with the owner can be smoother.

5. Conclusion

Our research employed two machine-learning models to help architects communicate with clients more smoothly. In addition, we experimented how architects can transform messages into elements that are helpful to design. Through the process of making training sets and observing training results, we explored the interrelationship of visual and verbal communication data, as well as how to classify relevant data to establish a more accurate model to assist architects and clients to communicate. These two machines are designed for the pre-design stage.

Whether it is creating a perspective video or a BIM model, relatively accurate information is needed to create it. If there is a misunderstanding with the client at the beginning, drawing with incorrect data will not only cause waste in operations, but also difficulty in subsequent communication. Use the machine- learning model to judge the client's uncertain requirement or preferences, and draw photos as an aid communication tool to obtain relatively only inquiries and speculation. The information gathered is much more reliable, especially for new contacts and For junior architects who have less experience in communication with the clients, it can help them grasp the key points. It is also because these two machines have to judge blurred information. Compared with the renderings and BIM models, they cannot provide accurate architectural effects, nor can they allow the owner to experience the appearance of the house and the use of the interior. Simulation evaluation has been carried out.

The output media of the current LA and SA models are separate. The main purpose is to explore how the architect's operation of the verbal and nonverbal media can be transformed into information that he understands and communicate with the owner after translation. Since it is necessary to understand and confirm the relatively vague information of the owner, visualizing the information makes the communication between the two parties more smooth. In the follow-up research, we will focus on further transforming the information of the owner's language into a visual medium to reduce misunderstandings caused by speculation and make the information clearer for subsequent design.

References

Barrett, P.: 1999, *Better Construction Briefing*, Wiley.

Isola, P., Zhu, J.-Y., Zhou, T. and Efros, A.A.: 2017, Image-to-Image Translation with Conditional Adversarial Networks, *CVPR 2017*.

Kiviniemi, A.: 2005, *Requirements Management Interface to Building Product Models*, Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University.

Lertlakkhanakul, J., Choi, J.W. and Kim, M.Y.: 2008, Building data model and simulation platform for spatial interaction management in smart home, *Automation in Construction*, **17**, 948-957.

Shen, W.: 2011, *A BIM-based Pre-occupancy Evaluation Platform (PEP) for facilitating designer-client communication in the early design stage*, Ph.D. Thesis, Department of Building and Real Estate, Hong Kong Polytechnic University.

Shen, W., Zhang, X., Shen, G.Q. and Fernando, T.: 2013, The User Pre-Occupancy Evaluation Method in designer–client communication in early design stage: A case study, *Automation in Construction*, **32**, 112-124.

Sirikasem, P. and Degelman, L.O.: 1990, The use of video-computer presentation Techniques to aid in communication between architect and client, *ACADIA Conference Proceedings*, 205-216.

Taleb, H., Ismail, S., Wahab, M.H. and Rani, W.N.M.W.M.: 2017, Communication management between architects and clients, *AIP Conference Proceedings*.

Tessema, Y.A.: 2008, *BIM for Improved Building Design Communication Between Architects and Clients in the Schematic Design Phase*, Master's Thesis, Texas Tech University.

QUANTIFICATION AND TYPOLOGY METHODS FOR SPATIAL REGIONALISM

From Traditional Residence to Modern Chinese-style House Design

YIHAO WU[1], LIUQING WU[2] and DANRUI LI[3]
[1,2,3]*Tongji University*
[1]*hzwuyihao@163.com* [2]*liuqing.wu904@gmail.com*
[3]*1930063@tongji.edu.cn*

Abstract. The cognition of Regionalism in architecture has transferred from the surface to the essence, from the building appearance to space. Modern Chinese-style houses have sprung up all over the country these years but always fail to find back the main characteristic of space in traditional residences. Therefore, the paper focuses on the question of "what are the main features of the space in traditional Chinese residence", proposing 5 spatial quantification indexes for residential space and a score evaluation method to measure Chinese-style matching degree (Mch) with the help of a modified graph map generation method. 10 traditional Chinese houses and 16 built-up modern Chinese-style houses are taken as samples for empirical research. The paper also puts forward a hypothesis testing model for architects, which can quickly check the Chinese-style matching degree of the scheme and strongly support the design process.

Keywords. Spatial regionalism; spatial quantification; Chinese-style matching degree; typology; traditional Chinese residence.

1. Introduction

The regional uniqueness is the pursuit of all cultures and the field in them, including architecture. At the beginning of the 21st century, various modern Chinese-style houses sprang up all over the country and are vigorously pursued by the Chinese real estate market. However, few discussions were aroused in the academic field, leading to a lack of theory and methodology in Chinese-style house design. Also, most of the existing modern Chinese houses focus mainly on copying the details including the windows, the facade and the decoration to imitate the image of traditional residence but the most symbolic, changeable and fascinating part: the space pattern was ignored. The evaluation of the design mostly stays in the qualitative description, but the quantitative methods are very few.

Space is difficult to be understood and perceived. Fortunately, some studies have provided the potential to explain and quantify it. Many scholars have made

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 81-90.

attempts to associate graph theory with the architecture field. Levin (1964) first applied the graph theory to the architecture plan. Cousin (1970) and Friedman (1975) have tried to apply graph theory to design. March and Steadman(1971) gave a systematic description of applying the graph theory into architecture thinking, emphasizing the structural relationship of space rather than focus on the properties like area or volume. Space syntax (Hillier and Hanson,1984) is a milestone, which links the space morphology to the social and cultural aspects: space can reflect the process of social change and also affect the social change. Space syntax has been widely used in the interior space of the housing since it was proposed. Hanson (1998) transformed the floor plans into the 'justified map' and tested the relationship between the space form and the social changes based on a traditional housing of the Banbury region of Oxfordshire in the Renaissance. Brown (1986) analyzed the form of the dwelling in the seventeenth century in London through the justified map and Blanton (1994) illuminated the links of the lifestyles and the form of house plan.

There are two types of maps that are used to describe the structure of space. One is the access graph (called the Morphology map below) which erases the physical attributes but still retains the location information of the internal units. The other is the 'Justified form of access graph' (called Justified map below). All properties of the space are ignored and only the adjacency relations are preserved. However both of them have weaknesses: when the relative positions of space move, countless fractals will generate in the Morphology map. And the missing form and dimension in the Justified map will cause it to be out of touch with the architectural design.

The paper first proposes a modified Morphology map and a Justified map automatic generation method. Secondly, 5 spatial quantification indexes are constructed to unravel the main features of the space in Chinese-style residences based on the empirical research of 26 residential samples. Thirdly, a score evaluation system of a Chinese-style matching degree is put forward. Finally, 4 'genotypes' in Chinese residence and a hypothesis testing model is presented through a case study, which can strongly support the design process and lead to a scheme with spatial features of Chinese-style residences.

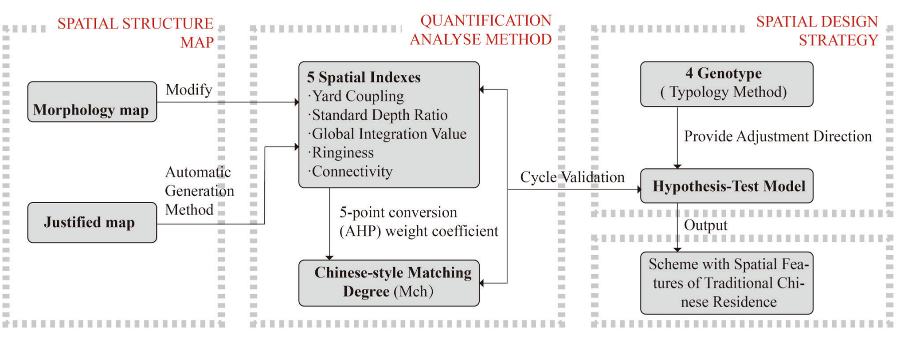


Figure 1. the study flow.

2. Principles and Adjustments of Space Topology Based on Space Syntax

2.1. MODIFIED MORPHOLOGY MAP

In the typical process of drawing a Morphology map, the circles representing rooms are usually placed at the geometric center of the space unit. But the defects are: the map is irregular and the relative positions between the units are unevenly distributed. Therefore, some adjustments have been made:

- Step1: Move the circles of the unit close to the outer contour to the outer contour, and move the circles of the unit at the corner directly to the corner point, and move the circles at the middle unit to their physical centers.
- Step2: Set a two-dimensional space grid, take the four corner points (Ba, Se, Yf, L) and the center point C as the reference points, and move the remaining points evenly on the Moore neighborhood of the reference point following the adjacent positions. When the Moore neighborhood can't meet the requirements, add the secondary level grid.

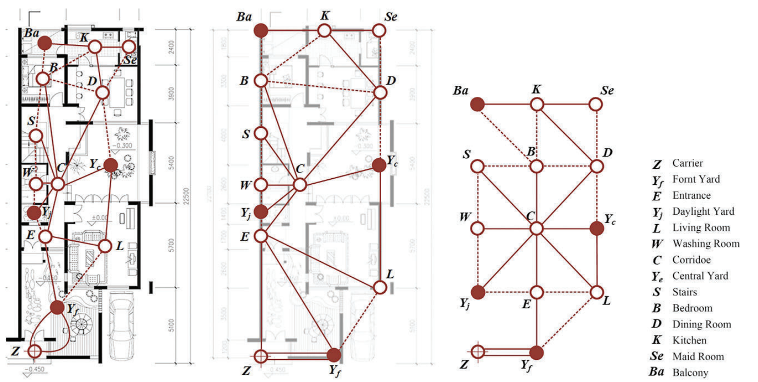


Figure 2. Example of modified morphology map(the Fifth Garden in Shenzhen).

2.2. JUSTIFIED MAP AUTOMATIC GENERATION METHOD

With the increase in the number of rooms and the complexity of the space structure, it will become more and more difficult to manually identify the correct number of steps for each unit. Take a traditional residential house in Jinyun, Zhejiang Province as an example. The house has 5 entrances. Starting from the outside, five different ways can lead to the same internal space with different steps and depth. It takes a long time and brings obstacles to researchers when measuring the number of steps of multipath paths. To overcome the shortcomings of traditional manual methods, the paper proposes a Justified map automatic generation method based on adjacency matrix and network analysis tool processing.

First, enter the connection relationship between each space in the adjacency matrix, if space is connected, the value is 1, and the rest is 0. Then, use *pajek* module in the social network analysis tool *ucinet* to quickly visualize the complex network.

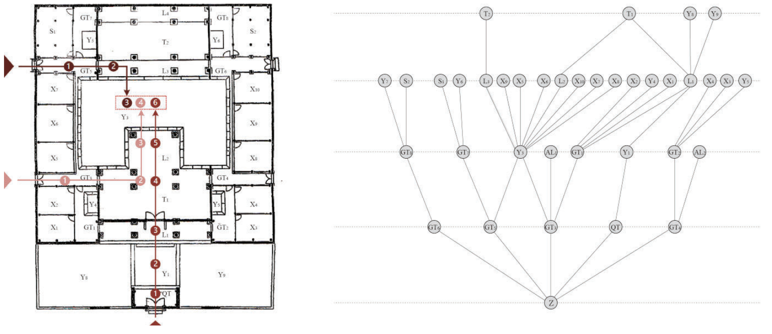


Figure 3. (left)the plan of house in Jinyun, Zhejiang (right) automatic generated justified map.

3. Spatial quantification indexes construction and calculation method

Chinese traditional houses present a modular paradigm with 'Jian' (a quantifier to measure the size of a building). The external interface of the Chinese house is extremely closed, but the interior next to the courtyard is often translucent and open.

In ancient times, cohabitation of three generations (over 15 people) was the most basic family structure. The area of the houses and the number of rooms were always very large. Nowadays, the family structure has changed a lot, and most of them are core families (3-4 people), so the number of rooms in Chinese-style houses is reduced. Therefore, we hope that in the study of quantification algorithms, differences brought by the number of rooms and the size of the building can be eliminated. Five indexes are chosen to measure the spatial features. Among them, standard depth ration, global integration value and connectivity are indexs that have been widly known and used. Yard coupling and ringiness are first proposed in this paper for describing the typical features in Chinese traditional dwelling.

3.1. SPATIAL QUANTIFICATION INDEXES

- **YARD COUPLING** (Y_c^1) The yard is the most significant spatial feature of traditional Chinese houses. The first index is used to measure the interaction between the courtyard and the indoor space.Where s is the number of solid lines in the modified Morphology map (connecting) between indoor units and courtyard, r is the number of dash line (adjacent but unreachable), k is the number of indoor units adjacent to the courtyard but without windows and v is an indoor unit that is not directly adjacent to the courtyard unit but can see the courtyard through the window. S is the total number of solid lines in the modified Morphology map. The larger the value of the result, the closer the communication between internal indoor and external courtyard spaces. Finally, a square arcsine transformation is performed on the result to improve the normality of the distribution.

$$Y_c^1 = \arcsin\left(\sqrt{Y_c}\right) = \arcsin\left(\sqrt{\frac{s + 0.25v - 0.5r + 0.5k}{S}}\right) \tag{1}$$

- **STANDARD DEPTH RATION** (S^1) Carrier depth is used to characterize the sequencing of a space. To compare systems of different scales, take twice the ratio of MD_Z to MD_{max} plus MD_{min} and record it as the standard depth ratio, and do the square arcsine transformation as well.Where MD_Z is the carrier mean depth, MD_{max} and MD_{min} are the maximum and the minimum of the carrier mean depth.

$$S^1 = acr\text{sin}\left(\sqrt{\frac{2MD_Z}{MD_{\text{max}} + MD_{\text{min}}}}\right) \tag{2}$$

- **GLOBAL INTEGRATION VALUE** (INT) Integration is the degree of aggregation or dispersion between a certain element and other elements in a space system, which measures the accessibility of the space system.
- **RINGINESS** (R^1)The Ringiness corresponds to the wandering feelings in traditional Chinese gardens and residential design. To simplify the calculation, only the fundamental circle will be calculated. Where *n* is the number of the space unit and I is the number of the fundamental circles. Similarly, make a square arcsine transformation. The greater the value, the stronger the wandering feeling of the space, the richer spatial levels, and the bigger the space feels.

$$R^1 = \arcsin\left(\sqrt{R}\right) = \arcsin\left(\sqrt{\frac{I}{2n - 5}}\right) \tag{3}$$

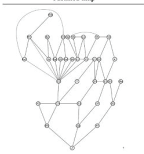
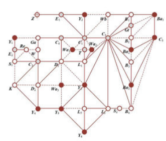
- **CONNECTIVITY** (C)Connectivity is used to quantify the organizational effectiveness of traffic space, including corridors, aisles, halls, stairwells. The value is the average integration of traffic space divided by the global integration of the whole system.

3.2. SELECTION OF TYPICAL SAMPLES AND CALCULATION OF INDEX

According to the five indexes constructed above, 10 well-known traditional houses, most of which are cultural heritages, and 16 built- up and widely reported and studied modern Chinese houses are selected as samples. The paper takes the traditional houses in Jiangsu and Zhejiang provinces as the research content of the traditional houses as they are the most typical ones and are less influenced by the foreign culture. The case selection strives to cover different scale types and periods. In this paper, two cases (one traditional, one modern) are presented in detail.

Jiujian House is designed by famous Chinese architect Zhang Yonghe, located in Pudong New District, Shanghai. The room design reproduces the Chinese architectural tradition and architectural intentions of “deep courtyard”. Each villa occupies an area of 3 acres, surrounded by 3.5-meter high walls, which effectively guarantees the privacy of the owner.

Table 1. The information of Jiujian House and Gezhai.

Sample number	M- 04	
Project name	Jiujiantang, Shanghai	
Year built	2006	
Location	Pudong, Shanghai	
		
Justified map		**Morphology map**
		

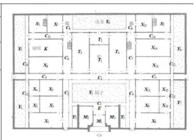
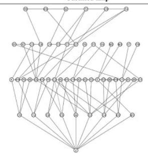
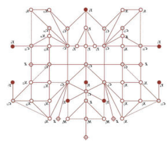
Sample number	T-01	
Project name	Ge Zhai, 6th village, Zhuangqiao Town, Ningbo	
Number of the space unit	n=33	
Wolfram Mathematica	I=Length[FindFundamental]Cycles []]=36	
Justified map		**Morphology map**
		

Table 2. Fundamental index and spatial features of 26 samples.

Number	Project name	Fundamental index							Spatial feature				
		s	r	k	S	v	n	l	Y_C^1	R^1	S^1	INT	C
M-01	Yunjian Water Village	3	3	0	18	2	15	3	0.7297	0.3537	0.5515	1.1612	1.512.8
M-02	The Lushi Hill	4	7	2	19	6	17	2	0.7061	0.2657	0.5967	1.0320	1.4307
M-03a	Shenzhen 5th Garden	5	4	0	13	2	14	1	0.8626	0.2102	0.7758	1.0320	2.3975
M-03b	Shenzhen 5th Garden	3	4	2	11	0	14	0	0.6473	0.0000	0.8529	0.7329	1.6867
M-04	Jiujiantang, Shanghai	18	19	3	52	2	35	20	0.7950	0.5880	0.5434	1.0535	1.2390
M-05	Shanghai 5th Garden	2	4	2	9	1	11	1	0.6447	0.4086	0.8440	1.0716	2.4772
M-06a	Jinyu Huafu	4	2	0	14	1	12	3	0.6591	0.2315	0.8440	1.0122	1.3607
M-06b	Jinyu Huafu	5	4	0	14	1	15	1	0.8033	0.2014	0.7717	1.0502	1.4689
M-07	Jiujiantang, Nanjing	8	5	2	33	2	24	8	0.5829	0.4460	0.5944	1.0723	1.4481
M-08	Peach Blossom House, Suzhou	4	3	0	24	6	18	6	0.5236	0.4555	0.6960	1.2137	1.4490
M-09a	Taoli Chunfeng Villa	9	6	2	23	0	18	7	0.7637	0.4952	0.7353	1.0032	1.0926
M-09b	Taoli Chunfeng Villa	8	5	1	16	2	14	2	0.9443	0.2993	0.8428	0.6787	1.8257
M-09c	Taoli Chunfeng Villa	6	9	1	17	0	17	1	0.8741	0.1868	0.8428	0.7312	1.4393
M-09d	Taoli Chunfeng Villa	9	1	1	18	0	15	4	0.7854	0.4115	0.7391	0.9072	1.0631
M-10	Peach Blossom House, Linqi	5	5	0	14	2	14	2	0.8571	0.2993	0.7276	1.0259	1.3314
M-11	Peach Blossom House, Yunxi	5	4	0	19	1	18	2	0.6658	0.2568	0.6050	1.2177	1.5446
M-12	Taoyuan Town	8	6	1	19	1	19	3	0.8514	0.3063	0.5779	0.7072	1.1848
M-13	Phoenix Mansion	3	3	1	14	1	15	2	0.5835	0.2868	0.7324	0.9782	1.4433
M-14a	Dongziguan Affordable Housing for Relocalized Farmers	4	2	0	17	4	16	3	0.6361	0.3398	0.6998	1.1796	1.4689
M-14b	Affordable Housing for Relocalized Farmers	4	4	0	17	2	14	5	0.6666	0.4850	0.6290	1.1378	1.6628
M-15a	Yunlin Chunfeng House	5	2	0	20	2	18	4	0.6066	0.3674	0.7677	0.8847	1.1351
M-15b	Yunlin Chunfeng House	3	2	0	11	2	11	2	0.6940	0.3501	0.7777	1.0675	0.8879
M-15c	Yunlin Chunfeng House	3	3	2	15	2	12	4	0.5426	0.4767	0.8331	1.0373	1.2522
M-16	Fengqiao Image House	3	3	1	14	2	13	2	0.6028	0.3137	0.6155	1.2401	1.4926
T-01	Ge Zhai, 6th village, Zhuangqiao Town, Ningbo	21	8	2	84	22	33	36	0.6343	0.8761	0.4433	1.2408	1.2192
T-02	Wuben House, Baitai Town, Dongyang	5	2	2	20	11	20	9	0.6719	0.5318	0.4152	1.5292	1.7479
T-03	Chen Zhai, 8th Village, Tiantai Town	5	1	1	23	7	18	11	0.5725	0.6381	0.4710	1.2198	1.2293
T-04	Mo's Manor	38	14	4	82	5	58	31	0.8251	0.5568	0.3342	1.1880	1.2270
T-05	A House in Feijia village, Yuyao Town	12	12	5	67	27	48	23	0.6142	0.5268	0.3391	1.1193	1.2277
T-06	Shuangmei House, Xinye Village	9	5	1	27	0	22	9	0.6923	0.5011	0.5551	1.1041	1.2102
T-07	Yetong House, Xinye Village	8	0	0	22	3	20	5	0.6824	0.3876	0.5207	0.9653	1.1953
T-08	Han Zhai, Dongbei Street	45	35	11	139	3	121	29	0.7005	0.3574	0.3119	0.8424	1.2608
T-09	Liu Zhai, Liaojia Lane	23	24	9	56	0	50	17	0.8301	0.4368	0.3563	0.9654	1.1350
T-10	Zhang Zhai, Songxianzhou Lane	26	17	8	58	4	56	8	0.8286	0.2770	0.4364	0.6750	1.0870

Gezhai is a typical Chinese traditional residence, located in Dongyang, Zhejiang Province. It is a typical "Thirteen Jian" style, consisting of three main rooms and five wing rooms on left and right with three courtyard inside the house.

Tabel 2 shows the fundamental indexes and spatial quantification indexes of all samples.

4. Score evaluation system of Chinese-style matching degree

To comprehensively evaluate the spatial matching degree between modern Chinese houses and traditional ones, a standardized evaluation system is established based on the five spatial indexes. For the convenience of measurement, the five-point evaluation method is adopted to map the original value. The rules are as follows: for each index, the valley value and the peak value respectively correspond to 0 points and 5 points. All the values in the middle are scored by the linear transformation, and those below the valley and above the peak are still scored 0 or 5 points.(Table 3)

The objective function: Chinese-style matching degree (Mch) is then defined to characterize the degree of matching between modern Chinese houses and traditional houses in spatial typology.

$$M_{ch} = w_1 \cdot G_Y + w_2 \cdot G_R + w_3 \cdot G_I + w_4 \cdot G_S + w_5 \cdot G_C \qquad (4)$$

Where G_Y, G_R, G_I, G_S, G_C respectively represent the value of Yard coupling, Ringiness, Global integration, Standard depth ration and Connectivity after 5-points conversion and w_1, w_2, w_3, w_4, $w_5$are the weight coefficient corresponding to each factor. This paper uses the analytic hierarchy process (AHP) to calculate the weight coefficient with the help of the evaluation assistant software *yaahp*. Since the Chinese-style matching degree only involves one middle layer, it is relatively simple to operate. w_1, w_2, w_3, w_4, w_5 are respectively 0.3955, 0.2398, 0.0679, 0.1152, 0.1816.

Based on the evaluation criteria above, the five spatial quantification indexes in the 26 samples are calculated into corresponding scores and Mch are calculated. The results show that the average (2.37) and median (2.36) of Mch in all test samples are very close to half of the full score (5.0) and about 71% are between 2.0 and 3.0. In the meantime, the data distribution is roughly symmetrical, and the skewness is not obvious, which proves that Mch is statistically significant.

It is worth noting that Mch is a score evaluation system for modern Chinese houses. Traditional houses are used mainly as a reference to find the functional characteristics of traditional houses.

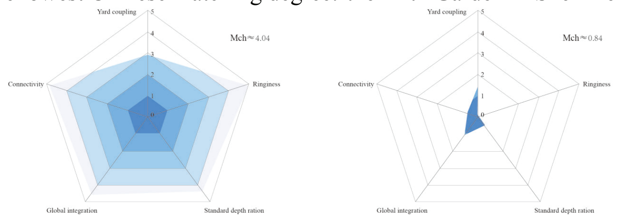
Table 3. 5-points conversion .

	yard coupling		**ringiness**		**global integration value**		**standard depth ration**		**connectivity**	
	valley value	peak value	valley value	peak value	valley value	peak value	valley value	peak value	valley value	peak value
Original value	0.5	1	0.1	0.6	0.6	1.1	0.5	0.9	0.8(left) 1.8(right)	1.25
Score	0	5	0	5	0	5	0	5	0	5

By comparing the scoring patterns of cases, we can explore some spatial strategies. The cases M-03b, M-05, and M-13 have low Mch (less than 2.0). In

M-03b, space is closed, and the entire space is organized in series without any interaction. Although M-05 has a central courtyard, no windows are opened on the walls beside the yard that faces the kitchen and the living room, which creates a barrier. M-13 is a typical three-part division of "yard-house-yard", and the middle part is long and deep with obvious internal and external separation.

Table 4. (left)the radar charts of the highest Chinese matching degree: Jiujian House and(right) the lowest Chinese matching degree: the Fifth Garden in Shenzhen.



5. The spatial strategy and optimization strategy of the Chinese residence

5.1. IDEAS AND TECHNIQUES OF CHINESE STYLE HOUSE DESIGN DRIVEN BY "GENOTYPE" SPACE

Using the method of spatial typology, by comparing the spatial features and the scores of Mch of each case, four key features of Chinese residence are identified and extracted which can be called "Genotype".

The first one is the **Central Courtyard**. The centrality of the courtyard of the Chinese-style house is the most important feature that distinguishes it from the townhouses in Europe and America. In the Chinese-style house, various courtyards are located in the center or in series on the central axis and the internal rooms are closely connected with it. The second is **Corridor Space**. In traditional Chinese houses, the corridor space is divided into corridors surrounding the courtyard and corridors connecting most of the rooms which are closely intertwined. The third is the **Migratory of space**. Traditional Chinese Houses provide people with good experience of wandering feelings of multiple open spaces, multiple functions and strong circulation which is not a single perspective, but a multi-dimensional connection and penetration. The last one is the **Entrance space**. The treatment of the entrance space in traditional Chinese houses is delicate. Usually, a certain sequence is realized by alternate conversion of the front yard, gate, corridor, and central courtyard. It appears to be closed first and then widened or vice versa, which is interesting and contrasting.

5.2. SPACE DESIGN PROCESS SUPPORTED BY BOTH SPACE TYPE AND MEASUREMENT

The process of design is relatively complicated, and it doesn't have a unique solution like logical reasoning. The design process is like a "**black box**" that is subjective but hard to explain. What we can know is only the input and output information, but it is difficult to analyze the design process. Architectural design is a cyclical and constantly revised process, which can be regarded as a ”hypothesis-test” cycle. Based on the Chinese-style matching evaluation system, the ”hypothesis-test” model can quickly verify whether the plan has the spatial features of Chinese-style traditional houses.

Architects first collect, analyze and sort out the external constraints in a certain project, predicting the effects of influencing factors and formulating corresponding strategies. Secondly, use the method of spatial typology, analyze the traditional residential houses in the local area, and summarize several representative spatial types. Then import external constraints and internal concepts to the black box and output the preliminary scheme. Through the Chinese-style matching degree evaluation system, architects can quickly test its spatial Chinese-style features and make adjustments according to each index. Through multiple rounds of the hypothesis-testing process, the best solution will finally be selected.

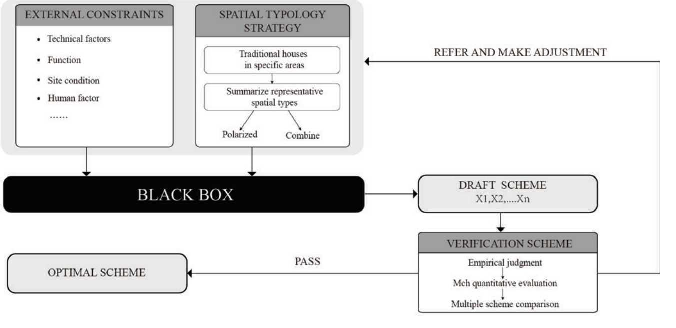


Figure 4. hypothesis testing design-process model.

5.3. EXAMPLE VERIFICATION

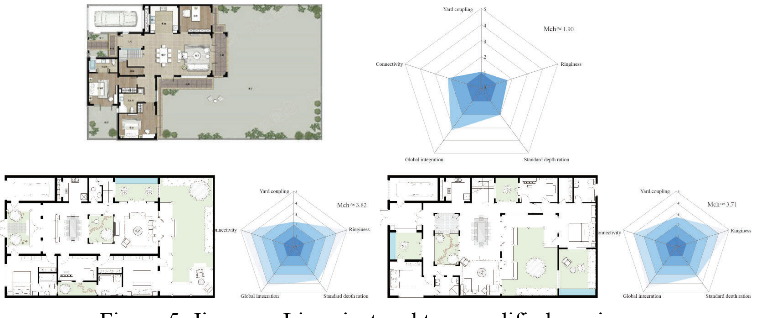


Figure 5. Jiangnan Li project and two modified versions.

Take the Jiangnan Li project, for example. First, test its Chinese-style matching degree, then adjust and optimize the space typology to increase the Chinese characteristics of the space. It’s a low-rise courtyard villa group, which is a typical modern Chinese house in recent years. The indoor space of it is intensive and compact with a large backyard. Mch is only 1.91. The courtyard coupling is the biggest shortcoming of the scheme, which is only 1.1, followed by ringiness and standard depth ratio of less than 2.0. Therefore, the direction of adjustments is to increase the interaction between the courtyard and the interior space, reduce the number of steps the indoor space takes to the entrance and increase the wandering feeling. Also, a mixture of different types of "Genotype" is adopted to adjust the plan. Each index and Chinese-style matching degree in the two adjusted schemes have been significantly improved and are at a high level in the overall samples.

6. Discussion

This paper starts from the graph theory and proposes a modified way of drawing the graph map. With the modified morphology map and the automatic generation method, it's easier to get an accurate map to represent the spatial relationship between each other. Also, the space features in Chinese residential houses are quantified by 5 spatial indexes and the Chinese-style matching(Mch) degree can be measured in a fast and direct way through the objective function, which will transform the design process into a more operable stage by the hypothesis-testing model. Also, the summary of the "Genotype" will provide clear adjustment directions.

However, there still have shortcomings. The "Hypothesis-test" model can only test whether the scheme has the spatial feature in traditional Chinese residences, but can't precisely control every step in the design process, which still relies a lot on the subjective initiative of architects.

References

Blanton, R.E.: 1994, *Houses and Households: A Comparative Study*, Plennum Press, New York.
Brown, F.: 1986, Continuity and Change in the Urban House: Developments in Domestic Space Organisation in Seventeenth-Century London, *Comparative Studies in Society and History*, **28:3**, 558-590.
Conroydalton, R.: 2005, Space syntax and spatial cognition, *Environment & Behavior*, **35(1)**, 30-65.
Cousin, J.: 1970, *Topological organization of architectural spaces*, Les presses de l, Canada.
Friedman, Y.: 1975, *Toward a Scientific Architecture*, MIT press, Cambridge.
Hanson, J.: 1998, *Decoding Homes and Houses*, Cambridge University Press, Cambridge.
Hillier, B.: 1996, *Space is the machine*, Cambrigen University Press, New York.
Hillier, B. and Hanson, J.: 1984, *The social logic of space*, Cambrigen University Press, New York.
Levin, P.H.: 1964, The Use of Graphs to Decide the Optimum Layout of Buildings, *Architects' Journal*, **140**, 809-815.
Li, Q.: 2010, *Chinese Vernacular House*, Tsinghua Press, Beijing.
March, L. and Steadman, P.: 1971, *The Geometry of Environment: An Introduction to Spatial Organization in Design*, MIT Press, Cambrige.
Rashid, M.: 2012, Shape-Sensitive Configurational Descriptions Of Building Plans, *International journal of architectural computing*, **10**, 33-52.
Seo, K.W.: 2005, *Spatial Interpretation of Housing*, Ph.D. Thesis, University College London.
Steadman, P.: 1970, *The Automatic Generation of Minimum-standard House Plans*, Cambrigen University Press, New York.

BEYOND EMBODIMENT

An Existential Project of Digital Tectonics in the Posthumanist Discourses

CHAO YAN[1] and PHILIP F. YUAN[2]
[1,2]*Tongji University*
[1,2]*{yanchao|philipyuan007}@tongji.edu.cn*

Abstract. The paper is a theoretical review on the nature of tectonic expressions in the context of digital design and construction. By investigating the origin of digital tectonics as a methodological exploration to dissolve the oppositional relationship between the digital and the tectonic, the paper identifies the lack of focus on the essential task of tectonic expression-constructing embodied experience on the building form. Therefore, the paper firstly reviews how tectonic expression is understood in its traditional sense, particularly within its indispensable relationship to human body in order to construct the empathic perception of structural dynamics. Then, the paper reveals the disassociation between human body and tectonic form in the posthumanist mode of design-to-construction of the digital age. Further, by articulating the dynamic nature of embodiment in the posthumanist scenario where the body is constantly reconstructed by the technocultural conext of the living environment, the paper proposes a theoretical model arguing for a reinterpretation of both the nature and the task of digital tectonics in order to reclaim the embodied experience in the digital age. Digital tectonics becomes an existential project that must be designed within its mutual determining relationship with the historical-cultural construction of the body-self.

Keywords. Digital tectonics; tectonic expression; embodiment; empathy; posthumanist body.

1. Introduction: The Tectonic and the Digital

Since the end of the 20th century, two oppositional subjects of architecture have been developing in parallel-the tectonic and the digital. On the one hand, the tectonic, as one of the key concepts in the architectural history of the 20th century, presents a demand for the authenticity of the building form. From a genealogical and historical perspective in architecture, the term tectonics originates from a tendency to resist to the superficiality of the image culture, consumerism and the society of the spectacle in general. By proposing a return to embodied experience, as well as its roots in phenomenology, the tendency focuses on material properties, structural logic, and construction process (Pallasmaa, 1996), and their expressive nature in association with human perception. On the other hand, in opposition to

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 91-100.

the return to material, the digital turn of architecture cultivated a tendency towards the virtual dimension of the living environment. Scholars and practitioners embraced the concept of posthumanism in the digital discourses, exploring new understandings on embodiment and materiality in architecture (Mitchell, 1996; Grosz, 2001; Picon, 2004; Bratton, 2009).

While the digital turn dissolves the ontological fundaments of the tectonic by challenging the material nature of human body and the living environment, its produced "exciting visual imagery" is simultaneously criticized as only confined to "the utopian world of the screen" (Leach, 2002). Even though digital technologies had also been utilized widely to explore advanced building construction method for realizing complex forms since the beginning, many of its contemporaries criticized the inconsistency between the form and the structure in those early experiments, such as Frank Gehry's Guggenheim Museum in Bilbao. In general, these criticisms indicate that the separation of digital design and construction causes the inconsistency of form and structure so as the elimination of human body in perceiving the building form.

Emerged from the efforts to mediate the oppositional relationship between the tectonic and the digital, the concept digital tectonics was adopted by many scholars and practitioners in the early 2000s to explore design methods that are based on the capabilities of then newly evolved digital tools to model the material properties of building components. One of the essential aim of these explorations is to transform the production process of architecture away from the mechanism of industrial reproduction to a new production mode sought to reconnect architects and construction and reinstate architects as the master-builder in the digital age. For example, in Philip Beesley's teaching and research based on early computer-aided design technology (CAD), digital tectonics is regarded as a generative design method of assembling building components in the software environment to drive form-finding process. It forms a methodological turn of design, aiming to translate traditional tectonics into shape grammars, and to iteratively manipulate the connectivity between the components to generate constructible form in a bottom-up way (Beesley and Seebohm, 2000). In doing so, it mediates computer-generated curvilinear form with the rules and limitations of building construction to some extent, challenging the traditional definition of tectonics and filling the gap between the tectonic and the digital.

However, as many criticisms have pointed out, the early experiments of digital tectonics only celebrated a new paradigm of design thinking which brings material back to the core of computational morphology, but failed to explicit the expressive nature of the digitally produced tectonics in responding to the embodied human experience (Chupin, 2004).

If, as Greg Lynn has stated, the practices during the digital turn of architecture share a similar perception of form as curvilinear and continuity (Lynn, 1993), the integrated model of design-to-construction of digital tectonics would have paved a methodological and technological path for exploring new construction logic and tectonic form, which could solve the problem of material connection and load transmission within the continuous variations of the curvature of the building form instead of traditional beam-column system (Turnbull et al., 2004). Even Kenneth

Frampton himself admitted in an interview in 2003 that curvilinear form, or the digital style, is not inherently contradictory to tectonics, by making a comparison between the works of Frank Gehry and Enric Miralles (Frampton, Allen and Foster, 2003). However, one question remains: is there a cultural implication in these newly evolved digital tectonics to form the embodied human experience so as the authenticity of tectonic expression? If yes, then what would it be? If not yet, what would be the task of design to cultivate one. To answer those questions, the paper will begin with a review on the theoretical discourses about the essence of embodiment in association with the expressive nature of tectonics.

2. Embodiment in Tectonic Expression

In pursuing the authenticity of the building form, tectonics have been always addressed in correlation with structure and construction. According to Eduard F. Sekler, the relationship between the three could be explained as such: structure, the intangible concept, is realized through construction and given visual expression through tectonics (Sekler, 1964). Later, scholars reveals that although tectonic form essentially roots on structural performance and construction process, it usually goes beyond the pure technique correctness (Nervi, 1965; Frampton, 1996). And, it is the expressive nature of tectonics, which is associated with the embodiment of human perception, that forms the tension among tectonic form, structural performance and construction process.

The expressive nature of tectonics is built upon an embodied relationship between the perceived object and the perceiving subject. From early philosophical enquiry and its later influenced German aesthetic study in the 19th and 20th century, and further to the contemporary neuroscientific findings of “mirror neuro”, empathy is always the key concept in addressing the constructive mechanism of the embodied perception of tectonic form.

In the preface to Gottfried Semper’s book Style, Harry Francis Mallgrave has unfolded the history of tectonic expression, in parallel to the historical formation of the concept of empathy. According to Mallgrave, the concept of empathy originates from the philosophical enquiry by Arthur Schopenhauer and is firstly introduced into architecture through the work of the German architect Carl Botticher. In that period, empathy was understood as a symbolic reading of the structural dynamics of building form. Influenced by Botticher’s work, Semper later constructed an animist view on tectonic expression-tectonics is not referring to any passive form, but an active organism expressing its resistance to the gravitational force of the structural load. And it is Semper’s vitalistic understanding on tectonic expression that influences Friedrich Theodor Vischer exploring his theory of tectonics in correlation with intrinsic nature of human perception. And, Friedrich’s son, Robert Vischer firstly articulated the mechanism of the animist reading of tectonic form by introducing the term empathy (Einfuhlung in German)-projecting “own bodily form into the form of the object”, in his doctoral thesis in 1873 (Mallgrave, 2004).

Robert Vischer’s doctoral thesis becomes the foundation for the further investigations of the concept of empathy in German aesthetic study through the

19th and 20th centuries, and influences subsequent scholars including Heinrich Wolfflin. But, it is only through the development of neuroscience in the late 20th century that would the internal mechanism of empathy have been fully revealed in a scientific manner. In the neuroscientific perspective, empathy is explained by the perceptual mechanism within the mirror-neuron system of the brain. Mirror-neuron system is firstly discovered by Vittorio Gallese and his colleagues at the University of Parma in Italy. It reveals the essential role of human body in forming empathic experience. In the empathic perception controlled by mirror-neuron system, the perceiving subject projects her/his body into a nonhuman object and simultaneously retrieves the pre-reflective experience back to the self (Clark, 2016). Mallgrave, in collaboration with Juhani Pallasmaa and others, introduces the mechanism of the mirror-neuron system into architecture, to articulate the perceptual relationship between human body and tectonic form. When standing in front of the twisting columns in the Portuguese church of the Monastery of Jesus in Setubal, the visually perceived structural dynamics within the column would activate a kind of twisting tension within the muscles of the perceiving subject (Mallgrave, 2013). In other words, when perceiving the structural dynamics within the building, the subject unconsciously projects her/his body into the tectonic form, and simulates its internal loads and supports with her/his own muscles.

The neuroscientific mechanism of empathic perception reveals necessity of the correlation between human body and tectonic form in constructing the embodied experience of the building form. In return, tectonics could be regarded as a potential media to intensify the embodied experience by designing the tectonic form in analogy to the form of human body. The argument could be traced back to Sekler's comparison between tectonic expression and artistic expression-tectonic form could be utilized to intensify the perception of structural dynamics just as art form is able to intensify the experience of the hidden reality. Although neither body nor empathy is directly addressed in Frampton's Studies in Tectonic Culture, his reference to Maurice Merleau-Ponty and the phenomenology of perception does confirm the importance of the embodied analogy in his understanding on the expressive nature of tectonics, not to mention Frampton's insightful discussion on the anthropomorphic conception of the joint in the works of Louis Kahn and Carlo Scarpa (Frampton, 1996).

3. The Posthumanist Nature of Digital Tectonics

The methodological shift cultivated by the invention of digital tectonics not only brings back the logic of construction to the early stage of digital design, but also reinstate material property as part of the source of design creativity. The AD issue Digital Tectonics edited by Neil Leach, David Turnbull and Chris Williams in 2004 particularly aims to dissolve the contradiction between the digital and the tectonic by forming an interdisciplinary design approach within the dialog between architecture and structural engineering. Taking figures like Antonio Gaudi as a historical reference, most of the essays in this issue have explored the possibilities of combining digital morphology with material property, integrating digital-generated form and structural principles in a bottom-up design process

(Leach, Turnbull and Williams, 2004). In this process, tectonics are not fully determined by designers as a way of assemble materials together for the purpose of a specific structural requirement or structural expression, but naturally formed and formulated in a self-generative way based on material property.

In this posthumanist mode of digital design, the self-generation process of structural form naturally prevents the involvement of human intuition, thus has no determinative relationship with the intuitive perception of structural stability in correlation to human body. Then, when human body is eliminated from the creation process, the created structural form would also prevent human subject to perceive the internal structural dynamics through the mechanism of the bodily empathy. Just as Patrik Schumacher argues in his theory of tectonicism, digital tools allow architects to operate on continuous variation to generate fluid and differentiated structural form, which usually resists human interpretation. Therefore, as he concludes, the task of tectonic articulation would be to represent the complicated dynamics of loads and supports for human subject (Schumacher, 2017). However, without the associative relationship between the tectonic form and the form of human body, it is still questionable that whether the semiotic representation of the structural dynamics of digital tectonics is adequate to activate the embodied experience of the building form.

Furthermore, in promoting the structural turn of digital design, the AD issue of Digital Tectonics have simultaneously revealed the posthumanist nature within the self-generative design process, but what is not fully explored by the issue is how the development of digital construction technologies intervenes the relationship between human body and the tectonic form.

When traditional craftsmanship is replaced by the contemporary digital technology for construction, CNC machines and rapid prototyping methods provide entirely new directions for creation as well. From ancient times to the Middle Ages, buildings were constructed by artisans and master builders working on the actual construction site. Through the process of making, the intuitive dialog between human body and material is regarded as part of the source of design creativity. Since Alberti's time, drawing as the notational tool has separated the architect from the actual process of construction (Carpo, 2011). Later, through further divisions of labor in the modernism movement, on-site building construction was replaced by industrial prefabrication and assembly lines. In these stages, although the construction of a building is completely dissociated from human body, the conception of the building form is still embodied with human subject. In contemporary, with industrial robots as the revolutionary construction platform in the digital era, the architectural profession is experiencing another paradigm shift from traditional crafts and industrial reproduction to a new production mode combining human with machine, fundamentally questioning the traditional understanding of creativity within the interactive feedback loop of human body and material.

In this human-machine collaboration, applications of digital tools and robotics are not limited to the realization of the pre-conceived form by human subjects, but can be involved directly in the creation process and become a source of creativity in itself. Specifically, and related to this research, tectonic form is not fully designed and determined by human and thereafter realized by machine, but possesses the characteristics of the automatic machine itself.

Fabio Gramazio and Matthias Kohler use the term digital materiality to describe the transformation of the nature of tectonic form under the informational intervention of automatic machines. Within the integrated mode of information exchange between digital design and construction, the logic of digital tools can be directly projected into the building form. Tectonics no longer only includes structural or material properties, but also has the characteristics of the digital morphology contained by the construction machines (Gramazio and Kohler, 2008). Meanwhile, the intervention of automatic machines also questions the origin of tectonic form. Greg Lynn once discussed the patterns produced by a CNC milling machine automatically and left on the curvilinear surface, arguing its origin not as an intended surface decoration, but as a tectonic expression that is formed naturally from the construction process of the machine (Lynn and Leach, 2004).

In a short summary, in this digitally framed process of making, the essence of creativity is no longer limited to the mere energy and contours of the human body, but now including an array of intelligent machines capable of extending human intentions outward, away from the body. No longer is the human the only author of the design of tectonic form. Machines are also part of the design subject, forming a new mixed subjective in the creation process. This evolution has resulted in another posthumanist tendency whereby human body have gradually lost its direct association with the construction and thus the creation of tectonic form.

4. Digital Tectonics and the Posthumanist Body

The posthumanist tendencies of digital design and construct evolves within a broader context of posthumanism, whose essential idea of human-machine symbiosis also calls for a fundamental reevaluation of the body itself. Then, by questioning the biological nature of human body, it could add another layer of dynamicity and uncertainty to the understanding of the correspondent relationship between the tectonic form and the form of human body.

In his article "Construction History: Between Technological and Cultural History", Antoine Picon argues that the mediating effect of human body in forming empathic experience is neither natural nor stable, but based on the historical construction of the perception of the body-self. And it is through the historical construction of the form of the body-self that tectonic expression is deeply connected to the cultural contexts of historical periods. In addition, Picon raised a question that whether the cyborg culture evoked by contemporary digital subjectivity and prosthetic technology has any relation to the dissociation between form and structure in the early projects of the digital turn in architecture (Picon, 2005). Although the question hasn't been fully unfolded in Picon's essay, it indeed reveals a necessity to rethink the expressive nature of tectonics in association with the transition of the understanding of human body from humanism to posthumanism.

Found in ancient Greek, Renaissance and early enlightenment period, humanism is an epistemological paradigm emphasizing the completeness of human. In contrast, the posthumanist thinking, which could be defined in a more dynamic view, is trying to challenge the fundamental assumptions about the stability of human nature. Regarding to the understanding of the body-self, what posthumanism proposes is that neither the self nor its material carrier-the body-is static and completed. Cultivated within the study of cybernetics around 1940s, and later influenced by the poststructuralist philosophy in the second half of the 20th century, the posthumanist thinking tends to recognize the form of human body as something being constantly reconstructed through existential synthesis with the living environment.

Furthermore, the posthumanist understanding of the body-self is also built upon the fact that tool, with its mediating effect, frames various interventions between human and environment. Tool can be regarded as the extension of the body-self to alter human nature and to enhance human capability. In early 1960s, NASA scientists Manfred E. Clynes and Nathan S. Kline used the term cyborg to articulate the way of equipping "tools" as the body extension to enhance human's capability of adapting to the external space (Clynes and Kline, 1960). Later, in the mid-1980s, the term cyborg was further circulated in association to the interrogations of the relationship between human and technology. Since then, the term has been appearing in various scenarios including the scientific, the artistic, the fictional, the intellectual, and so on. For example, in film, cyborg is a kind of expression about the situation that "man witnesses himself being progressively dehumanized" and "become an insensitive machine" (Picon, 2000). While, in philosophy, such as what Donna Haraway proposed in A Cyborg Manifesto-Science, Technology, and Socialist-feminism in the Late Twentieth Century, the term has been profoundly addressed in the exploration of gender issues (Haraway, 2016).

In general, different versions of the posthumanist thinking, as those mentioned above, are all indicating a understanding of the dynamic nature of the form of human body-body could be constantly transformed by its technocultural context. And essentially, the development of the understanding is also indebted to dissolution of the boundary between the virtual and the physical existence of human being and brings back the idea of body-environment incorporation based on information exchange (Gandy, 2005). Then, in this context, the posthumanist understanding of human body could also possess its relevance to the contemporary development of digital technology. According to Katherine Hayles, "for the human is the tradition of liberal humanism; the posthuman appears when computation is taken as the ground of being, a move that allows the posthuman to be seamlessly articulated with intelligent machines" (Hayles, 1999).

For example, the digital medias today have allowed human to be seamlessly connected with the environment through data exchange. Then, as William J. Mitchell argued in the 1990s, with digital aids in contemporary living scenario, the human subject shouldn't be only referring to the biological body and its sensory organs, but also the digital medias that have the capabilities of performing as the virtual extension of the body, with which human being could "sense and act at a distance but that also remain partially anchored in their immediate surroundings"

(Mitchell, 1996; Picon, 2015). In this way, digital technologies could completely reconstruct the perception of the body-self. They could establish “the fantasy of action, communication, and connectedness at-a-distance, the fantasy of an alternative or virtual existence that may bypass the gravity and weightiness of the body” (Grosz, 2001).

If, in the view of architectural phenomenology, “the unique form of the ever-present body” is the fundament for constructing all experiences (Merleau-Ponty, 1967; Bloomer and Moore, 1977), then the technocultural context of the digital age would have been constantly reconstructing the form of the body-self, would have destabilized the instantaneous experience of the tectonic form as a reflection of the form of body-self, and would have eventually altered the way, in which human subject experiences the building form.

In the context of posthumanism, the body-self could be interpreted as being constructed historically and culturally by the living environment. Then, we could conduct a reverse engineering on Picon’s argument about the latent relationship between cyborg culture and the disassociation of form-structure. To be sure, it remains uncertain and needs further historical investigation that whether the perception of the body-self in the cyborg culture of 1980s had any influence on the nature of the tectonic expression of the buildings in the early 1990s. However, digital tectonics, as the foundation of constructing the visual appearance of contemporary living environment, would certainly possess the capability to influence back on the perception of the body-self, then offering the possibility of reconnecting tectonic form and the form of human body in the posthumanist scenario, even though it still requires further experiments and explorations in the perspective of design.

5. Conclusion and Discussion: Digital Tectonics as An Existential Project

In the humanist understanding of tectonics, the task of tectonic expression is to enhance the formal correspondence between tectonic form and the form of human body, and to intensify the empathic perception of the structural dynamics in order to construct the embodied experience of the building form. Within the posthumanist mode of digital design and construction, the task of tectonic expression would have to be revealing the unperceivable form of the structure that involves the process logic of the automatic machines, trying to compensate the disconnection of human body and tectonics by visually providing a semiotic representation of the structural dynamics. Now, built upon the understanding of the dynamic nature of the posthumanist body, we can argue for a new task of tectonic expression that is to historically and culturally construct the perception of the body-self in order to directly rebuild the connection between the tectonic form and the form of human body in the digital age.

To achieve it, we need to establish a theoretical model interpreting digital tectonics as an existential project. In the first layer of the model, the nature of digital tectonics should not be understood as merely a methodological approach to reconnect digital morphology with structure property and constructability, but also a perceptual media to empathically reveal the structural dynamics in order to construct the embodied experience of the building form. Then, on the basis of the technocultural context of the digital age, the nature of digital tectonics requires a reevaluation of the humanist understanding of the embodied perception that is deeply indebted to the correspondence between the tectonic form and the form of the biological body. Built upon the posthumanist discourses, the nature of digital tectonics should be rooted in a mutual determining relationship between the tectonic form and the form of the body-self. As an existential project, digital tectonics "educates" the human subjects about how body is constructed and existed in the living environment through empathic perception. Meanwhile it is being perceived empathically through the mediation of the newly perceived form of the body-self. In this simultaneous reciprocity, we would eventually find a new connection between the tectonic and the digital in the posthumanist perspective.

Acknowledgement

This research is funded by National Key R&D Program of China (Grant No. 2018YFB1306903)National Natural Science Foundation of China (Grant No. U1913603), and Shanghai Science and Technology Committee (Grant No.18DZ1205604).

References

Beesley, P.B.: 2000, Digital Tectonic Design, *The 18th eCAADe Conference Proceedings*.

Bloomer, K.C.B. and Moore, C.W.M.: 1977, *Body, Memory, and Architecture*, Yale University Press.

Bratton, B.B.: 2009, iPhone City, *Architectural Design*, **79**, 90-97.

Carpo, M.C.: 2011, *The Alphabet and the Algorithm*, The MIT Press.

Chupin, J.P.C.: 2004, The "Tectonic Bug" (The Fall of the Body in Cyberspace)–Current and Recurrent Tensions between the Virtual and the Tectonic, *The proceedings of SIGradi 2004*.

Clark, A.C.: 2016, *Surfing Uncertainty: Prediction, Action, and the Embodied Mind*, Oxford University Press.

Clynes, M.E.C. and Kline, N.S.K.: 1960, Cyborg and Space, *Astronautics*, **September**, 26-76.

Frampton, K.F.: 1996, *Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture*, The MIT Press.

Frampton, K.F., Allen, S.A. and Foster, H.F.: 2003, A Conversation with Kenneth Frampton, *October*, **Autumn**, 35-58.

Gandy, M.G.: 2005, Cyborg Urbanization: Complexity and Monstrosity in the Contemporary City, *International Journal of Urban and Regional Research*, **29-1**, 28.

Gramazio, F.G. and Kohler, M.K.: 2008, *Digital Materiality in Architecture*, Lars Müller Publishers.

Grosz, E.G.: 2001, *Architecture from the Outside: Essays on Virtual and Real Space*, The MIT Press.

Haraway, D.J.H.: 2016, *Manifestly Haraway*, University of Minnesota Press.

Hayles, K.N.H.: 1999, *How We Became Posthuman: Virtual_Bodies in Cybernetics Literature and Informatics*, The University of Chicago Press.

Leach, N.L. 2002, Introduction, *in* N.L. Leach (ed.), *Design for A Digital World*, Wiley Academy Press.

Leach, N.L., Turnbull, D.T. and Williams, C.W. 2004, Introduction, *in* N.L. Leach, D.T. Turnbull and C.W. Williams (eds.), *Digital Tectonics*, Wiley Academy Press.

Lynn, G.L. and Leach, N.L. 2004, The Structure of Ornament, *in* N.L. Leach, D.T. Turnbull and C.W. Williams (eds.), *Digital Tectonics*, Wiley Academy Press.

Lynn, G.L. 2004, Architectural Curvilinearity: The Folded, the Pliant and the Supple, *in* G.L. Lynn (ed.), *Folding in Architecture*, Wiley Academy Press.
Mallgrave, H.F.M. 2004, Introduction, *in* G.S. Semper (ed.), *Style in the Technical and Tectonic Arts, Or, Practical Aesthetics*, Getty Research Institute.
Mallgrave, H.F.M. 2013, Should Architects Care about Neuroscience, *in* P.T. Tidwell (ed.), *Architecture and Neuroscience*, Tapio Wirkkala—Rut Bryk Foundation.
Merleau-Ponty, M.M.P.: 1967, *The Structure of Behavior*, Beacon Press.
Mitchell, W.J.M.: 1996, *City of Bits: Space, Place, and the Infobahn*, The MIT Press.
Nervi, P.L.N.: 1965, *Aesthetics and Technology in Building*, Harvard University Press.
Pallasmaa, J.P.: 1996, Review on Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture by Kenneth Frampton, *Architectural Research Quarterly*, **1**, 90-92.
Picon, A.P.: 2000, Anxious Landscapes: From the Ruin to Rust, *Grey Room*, **1**, 64-83.
Picon, A.P.: 2004, Architecture and the Virtual: Towards a New Materiality, *Praxis*, **6**, 114-121.
Picon, A.P.: 2005, Construction History: Between Technological and Cultural History, *Construction History*, **21**, 5-19.
Picon, A.P.: 2015, *Smart Cities: A Spatialised Intelligence*, Wiley Academy Press.
Schumacher, P.S.: 2017, Tectonism in Architecture, Design and Fashion: Innovations in Digital Fabrication as Stylistic Drivers, *Architectural Design*, **87**, 106-113.
Sekler, E.F.S.: 1964, Structure, Construction, Tectonics, *Aufbau*, **10**, 89-95.
Turnbull, D.T., Balmond, C.B., Delanda, M.D. and others, a.n.d. 2004, An Aesthetics of Calculus—Round Table Discussion, *in* N.L. Leach, D.T. Turnbull and C.W. Williams (eds.), *Digital Tectonics*, Wiley Academy Press.

DESIGN ANALYTICS AND DATA-DRIVEN COLLABORATION IN EVALUATING ALTERNATIVES

OSAMA ALSALMAN[1], HALIL ERHAN[2], ALYSSA HAAS[3], AHMED M. ABUZURAIQ[4] and MARYAM ZAREI[5]
[1,2,4,5]*Simon Fraser University*
[1,2,4,5]*{oalsalma|herhan|aabuzura|mzarei}@sfu.ca*
[3]*Stantec*
[3]*alyssa.haas@stantec.com*

Abstract. Evaluation of design ideas is an important task throughout the life cycle of design development in the AEC industry. It involves multiple stakeholders with diverse backgrounds and interests. However, there is limited computational support which through this collaboration is facilitated, in particular for projects that are complex. Current systems are either highly specialized for designers or configured for a particular purpose or design workflow overlooking other stakeholders' needs. We present our approach to motivating participatory and collaborative design decision-making on alternative solutions as early as possible in the design process. The main principle motivating our approach is giving the stakeholders the control over customizing the data presentation interfaces. We introduce our prototype system D-ART as a collection of customizable web interfaces supporting design data form and performance presentation, feedback input, design solutions comparisons, and feedback compiling and presentation. Finally, we started the evaluation of these interfaces through an expert evaluation process which generally reported positive results. Although the results are not conclusive, they hint towards the need for presenting and compiling feedback back to the designers which will be the main point of our future work.

Keywords. Design Analytics; Collaboration; Visualizations.

1. Introduction

In design, collaborating with the design stakeholders in evaluating design ideas has been an important challenge, especially when the design involves multiple stakeholders with diverse backgrounds and interests. Some of these stakeholders may directly participate in design while others provide valuable input as clients, local authorities, investors, public, etc. (Lu and Sexton, 2006; Serror et al., 2008; Daher et al., 2018). The complexity of design projects compounded with stakeholders' diversity can create serious bottlenecks in the design-evaluate-feedback cycle and design decision-making workflow (Klein et al., 2003; Sanders and Stappers, 2008; Bilal et al., 2016). These bottlenecks include the ambiguity of design information, lack of completeness of details or terms, unavailability or unfit of means for information sharing, sequential discourse, etc. This paper proposes a 'design analytics' approach relying on data-driven collaboration interfaces to enable effective design-information exchange and feedback sharing and gathering. We aim to alleviate some of these bottlenecks' effects to improve collaboration between the design stakeholders and design-decision makers.

Our research has three main objectives: (a) to enable participatory and collaborative design decision-making on alternative solutions as early as possible in the design process, (b) to identify the basic features of a platform of discourse on design alternatives by collaborating with industry partners, and (c) to explore and develop interactive online interfaces for sharing alternative design form and data and completing the feedback cycle as an integral part of design workflows. There are various examples of systems or interfaces for supporting the design stakeholders' involvement in design, in scenarios such as design review meetings (Fernando et al., 2013), online design modelling (Konieva et al., 2019), urban planning (Holzer and Downing, 2010), etc. Most of the existing systems are either highly specialized for designers or configured for a particular purpose or design workflow overlooking other stakeholders' needs. The main gap stays unaddressed: how to facilitate sharing design information and receiving feedback into the design decision-making considering the stakeholders' diversity and reducing the complexity of the design data.

We aim to improve collaboration between the designers, design stakeholders, and other parties by decreasing the overhead caused by discrete representations and labour intensive synchronous in-person meetings. We present our attempt to achieve this goal through an online platform we developed, called D-ART, as a simplified, data-driven, and flexible 'design idea and feedback' sharing platform. A formative evaluation of D-ART with various experts in the architectural design industry has shown that our proposed approach is promising. However, the evaluations revealed a few key interaction design challenges. Notably, the stakeholders are required to reduce the complexity of the design information interactively at a level important for different purposes. This adds an extra task layer for the stakeholders. In addition, the stakeholders' feedback on both form and performance data must invoke discussions around the ideas presented, yet fragmented interfaces or tools may hinder such discussions, including reporting the comments and suggestions back to the design teams.

2. Background

Participatory design aims for the empowerment of stakeholders and their continuous feedback to the design process (Klein et al., 2003; Robertson and Simonsen, 2012; Daher et al., 2018). In general, the stakeholders' involvement is facilitated through project review meetings synchronously or reporting asynchronously (Gautier et al., 2008). The prior can be resource-intensive as they require the availability of most stakeholders at a certain time and place (Healey, 1998; Kingston, 2007). Besides, the evaluation of multiple design alternatives can be seriously hindered by the resource limitations (Nuojua and

Kuutti, 2008). For asynchronous participation, the stakeholders are presented with reports and their feedback is compiled and incorporated in decision-making. While each has its benefits, asynchronous and online collaboration groups can result in broader discussions and produce more comprehensive reports (Benbunan-Fich et al., 2003).

Both synchronous and asynchronous modes demand a system-support for exploration and collaboration (Shneiderman, 2007). Recent developments in interactive computing and visualizations such as interactive 3D views and online collaboration platforms create new opportunities for stakeholders' involvement in design, even starting from the early phases (Hanzl, 2007; Brown et al., 2016; Erhan et al., 2020). We suggest that bringing the advancements in data analytics (Thomas and Cook. 2006), collaboration technologies (Farshchian, 2019), and early decision-making to design stakeholders through interactive visualizations can enhance stakeholders involvement to develop a "a stronger sense of commitment", higher rate satisfaction, and realistic expectations as discussed by Al-Kodmany (1999).

A study conducted by Yeomans et al. (2006) on how AEC experts reflect on collaboration identifies a set of principles necessary for a successful collaboration. These principles include the involvement of all stakeholders as early as possible in the design decision-making, development of common processes and tools, and the use of performance measurements for informed decision-making. Based on these principles, the systems aiming to support collaboration in the AEC projects must consider a data-driven approach, applicability in various design workflows and involvement of the design stakeholders with different interests in every phase of design. In particular, the last expectation poses the most difficult challenge. That is, the interfaces should be able to adapt to the stakeholder interests without demanding to operate on system-level settings and promote visualization of design form and data information at different abstraction levels.

3. Methodology

In this research, we adapted the design study approach as a problem-driven research method. It involves "analysis of a specific real-world problem faced by domain experts, designing a visualization system that supports solving this problem, validating the design, and reflecting about lessons learned in order to refine visualization design guidelines." (Sedlmair et al., 2012). In light of a comprehensive literature review, analysis of multiple collaboration systems, and directly collaborating with our industry partners, we identified five high-level system requirements for D-ART. These requirements are used as guiding principles in developing interface features and used in the formative evaluation of D-ART's first version.

- RQ1. Present each design alternative with customizable visualization of form and performance data along with the structured stakeholders' feedback.
- RQ2. Enable feedback as comments and questions on design form and performance data and responding to the other feedback.
- RQ3. Allow visual comparison of form, performance, and feedback on design

alternatives.

- RQ4. Accessible online, independent from the design environments, workflows, and systems.
- RQ5. Provide adaptable interfaces to accommodate a variety of stakeholders with different interests and backgrounds.

For building D-ART, we used an agile software development (Beck et al., 2001) process of continuous design-development-feedback cycles. D-ART is built as a Web application using the MEVN stack (MongoDB, Express, Vue, and Node.js) (Hautaviita, 2018). It is integrated with a design analysis setup (Figure 1) based on Rhino, Grasshopper (McNeel, 1998, 2020), and FlowUI (Erhan et al., 2020).

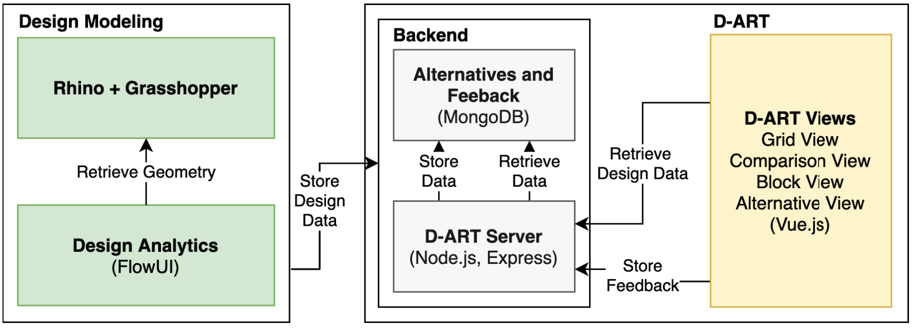


Figure 1. System Overview: System architecture for D-ART setup.

4. D-ART: System Design

D-ART's system has been developed using classical client-server web application architecture to accommodate communication between the design data repository and the D-ART's front-end interfaces presenting data on browsers and collecting feedback from the stakeholders.

4.1. HIGH-LEVEL TASKS AND WORKFLOW

D-ART supports three high-level tasks: design data visualization and discussion, maintaining persistent design data models, and receiving design data from CAD modelling tools (Figure 1). The D-ART interfaces facilitate the presentation of design form and performance information to design stakeholders and interactively reflect on the alternatives through commenting and discussions. D-ART's back-end component supports client-server communication and providing a dynamic and persistent repository of design data related to the curated design alternatives. The modelling environments connect with D-ART using a special plug-in responsible for enabling submission and update of design alternatives.

4.2. DESIGN DATA AND D-ART COMPONENTS

D-ART receives three different design data types: 1) design form, 2) performance metrics as categorical or numerical data, and 3) design targets. The form is the geometrical representation of design data and can take multiple formats such as images or 3D interactive models. Performance data relates to how an alternative performs on a metric interest to the stakeholders such as its cost, area, power consumption, etc. It can also be categorical such as program or function designation, e.g. residential, commercial, retail, etc. Targets are the anticipated values for the performance metrics to be achieved and set at the beginning of the design. The target values can change in the process as designers' and stakeholders' iterate on the solutions. Project targets and their units can be defined in the project creation interface. D-ART can receive an arbitrary number or type of performance metric data to accommodate the unique need of different projects (RQ4). This gives the flexibility of reusing the tool with multiple collaboration problems or scenarios. In the D-ART repository, the stakeholders' comments, questions and suggestions are associated with the design data and persistently stored for retrieval and report generation.

4.3. D-ART INTERFACE COMPOSITION

D-ART interface consists of four main views corresponding to the tasks associated with these views: Grid View, Alternative View, Building (Blocks) Components View, and Comparison View. A video demo of the interface can be found here: youtu.be/uuCCICYdP3E. The **Grid View** presents an overview of all curated alternatives in juxtaposed images augmented with controls to access the other views (RQ1) (Figure 2). Below each thumbnail image of an alternative, there is an expandable panel tabulating a summary of performance values. This view supports three tasks. First, the stakeholders can change the alternative thumbnail's size to show more or less of the form details. The second task focuses on a rapid comparison of alternatives through side-by-side tabulated performance data (RQ3). Finally, the Grid View is used as an entry point to access the Alternative Overview interface or Building Components Overview to examine each alternative in depth.

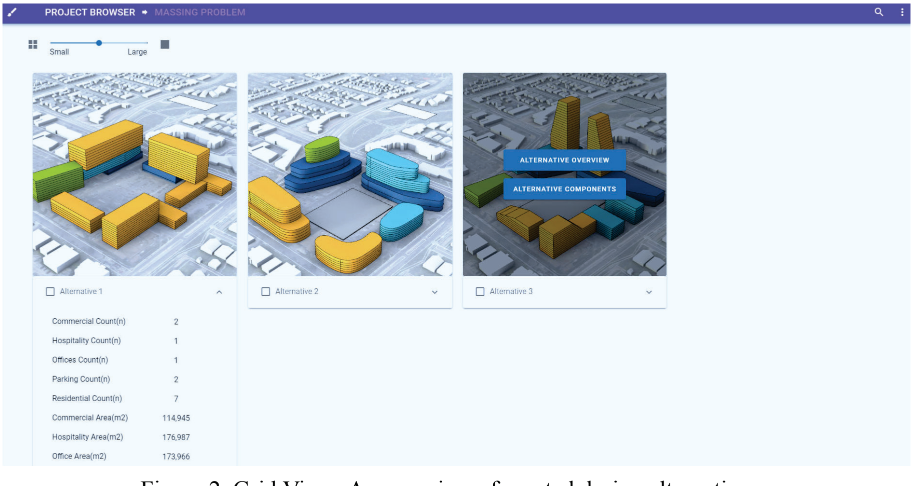


Figure 2. Grid View: An overview of curated design alternatives.

Alternative View supports inspection of a specific design alternative (RQ1) through four main interfaces focusing on design data, form, charts, and stakeholders' feedback (Figure 3). The data view is a tabular visualization of the select performance metrics, their target values, and their target satisfaction (percentage or real value) (RQ5). The form views include a 2x2 grid as a placeholder for displaying images of the design. The designers choose the images at the time of curating the alternatives. The stakeholders can zoom in on any of the images in a larger view. In the 3D model view, the stakeholders can interact with a 3D model of the design to inspect the 3D form in its context by zooming, panning, and rotating. In the charts view, the stakeholders create basic data visualizations like bar or line charts to understand better the relation between different performance metrics (RQ5). The interface for providing feedback is a dominant feature in D-ART to motivate discussion among the stakeholders (Willett et al., 2011). In the feedback interface, the design stakeholders can express their opinions, ask questions, or request changes to the present alternative (RQ2). This categorization aims to distinguish the stakeholders' concerns in the discourse and facilitate rich report generation. The stakeholders can review others' feedback and respond to them as in 'online discussion systems' in threads. A resolve feature is added to inform the stakeholders that the feedback is to be handled in the next iteration or an agreement is reached between the stakeholders.

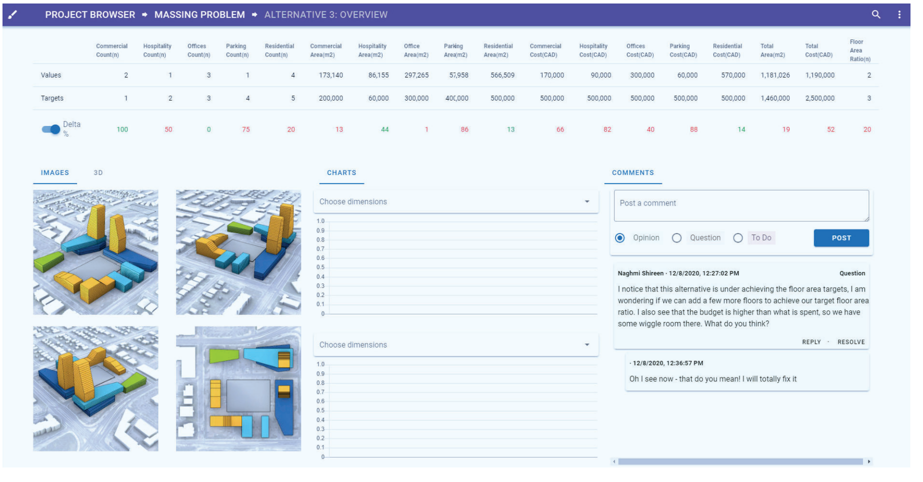


Figure 3. Alternative View: Inspection of alternative performance, form, and feedback.

Building Components View support inspecting the distinct components of an alternative in detail. A "component" in a design model can be any cluster of manifold geometry designated with a particular architectural function (e.g. residential, commercial, hotel rooms, etc.) as in a massing problem. This view is composed of a 3D Model View, Tabular data view, and Feedback interface (Figure 4). The tabular view lists each building component's performance. Selecting a row brushes and highlights the corresponding block on the model view or vice versa. The feedback interface works similarly in all D-ART interfaces. However, here it focuses on individual components (RQ2).

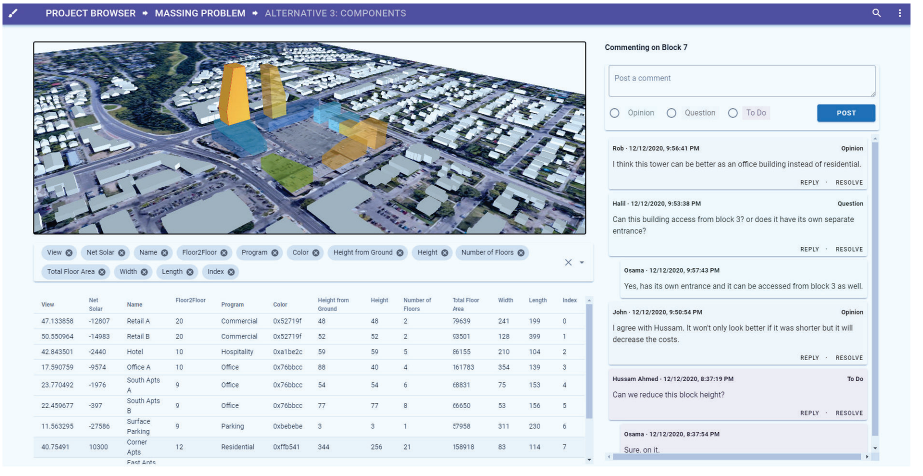


Figure 4. Building Components View: A block by block analysis of performance.

Compare View enables the stakeholders to compare multiple alternatives with each other (Figure 5). Presented in the Grid View, two or more alternatives can be selected, enabling a compare option in the menu. The stakeholders can visually compare form, performance data, and review feedback given to each alternative by other stakeholders (RQ3). The performance metrics can be compared using the tabular view on the upper section of the interface. The stakeholders can create custom charts by selecting the performance values they are interested in. Side-by-side visualization of 3D models enables rotating views using synchronized camera angles.

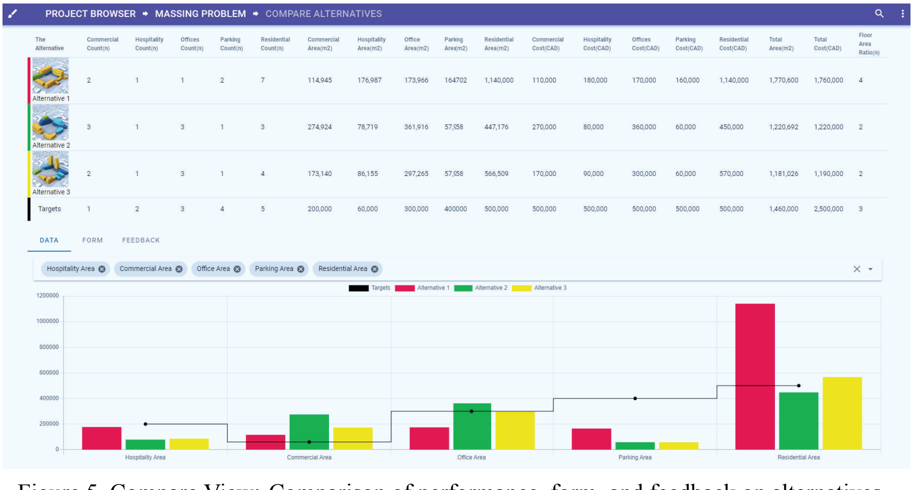


Figure 5. Compare View: Comparison of performance, form, and feedback on alternatives.

5. Evaluation

We developed an expert review analysis as a formative method to evaluate D-ART's current implementation to learn how it supports the proposed tasks. This method is generally used to discover the potentials and issues on the system in the early system development phases (Terry and Mynatt, 2002; Lam et al.,2012). The method involves inviting both domain and interface design experts to review D-ART under a predefined set of scenarios. The experts are asked to make comments on the system while performing the design review tasks from a design stakeholder's perspective, as described in the requirements section. A follow-up interview with the experts further probes the experts' opinion on the approaches we propose and the effectiveness of interfaces. We conducted a pilot study with one expert to assess our method design. In addition to the method's findings, the expert's comments hinted at what possible potentials or drawbacks D-ART may have when other experts complete the evaluation. Due to the time and COVID-19 restrictions, we could not complete the evaluation sessions at the time of writing this paper.

The pilot study showed that each expert would need about an hour to complete the given scenario. The feedback on tasks can be divided into four sections: design form and performance data presentation, exchanging comments and discourse on design alternatives, comparing a set of solutions, and feedback presentation. The initial findings on the interface were generally positive. The expert found the diversity of form-data visualizations helpful for accommodating multiple stakeholders' interests (RQ5). The consistent use of 'feedback features' was received positively for encouraging conversations on designs. However, the feedback functions should expand to include form and data visualizations, e.g. by marking or annotating design form or data in the context for a richer discussion. The comparison features could be enriched by adding a component-level comparison (within an alternative and across alternatives). However, this may increase the complexity of the interactions and traceability of the discussion. The expert suggested several system features for presenting feedback to the design team. For example, visualizing interaction logs can reveal how many times or by whom an alternative was explored, the most active stakeholder in giving feedback, sending notifications to indicate if any new activity occurred, etc. Finally, D-ART was found to be useful in other domains such as product design or engaging the public in projects involving both form and performance data.

6. Conclusion and Future Work

This paper questioned if and how design stakeholders' engagement with the design form and performance data can be supported through collaborative and data-centred design review tools. D-ART is a prototype web application developed in an incremental and iterative process with our AEC industry partners to seek answers to this question. In the pilot study of the formative evaluation of D-ART, we identified both limitations and strengths of our approach to online collaborative design review tasks and the interfaces supporting them. Although our findings are not conclusive, they are important to note here. D-ART needs to emphasize 'compiling and reporting results' back to designers. In the next steps, we will complete the evaluation with four additional domain experts. We will also conduct a formal user study of D-ART with potential users using real-life scenarios after its refinement using the feedback to be received from the completed expert study.

In this phase, we believe that we made several contributions by raising questions about developing data-focused collaboration between designers and design stakeholders and seeking answers to them. For example, we contend that the primary obstacle in supporting collaborative decision-making on a given set of design alternatives is determining the level of details in design data to be shared with the stakeholders. This can be partially addressed by giving the stakeholders the option to add or remove details from the default visualizations. The second is more pragmatic: the design of systems that support information sharing from modelling, design presentation, feedback, and feedback compilation and presentation requires devising a highly complex computational platform while reducing the cognitive overload caused by the new tasks. Generic approaches are not effective for design information sharing. The nature of design particularly is a factor for this: each artifact is unique. Therefore, the associated data is expected to be unique. We have yet to see how the design stakeholders in real life will respond to the online interfaces in D-ART that somewhat removes the in-person contact with the designers.

References

Al-Kodmany, K.: 1999, Using visualization techniques for enhancing public participation in planning and design: process, implementation, and evaluation, *Landscape and Urban Planning*, **45**(1), 37-45.

Beck, K., Beedle, M., Van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A. and Jeffries, R.: 2001, "Manifesto for Agile Software Development" . Available from <https://agilemanifesto.org/> (accessed 1st December 2020).

Benbunan-Fich, R., Hiltz, S.R. and Turoff, M.: 2003, A comparative content analysis of face-to-face vs. asynchronous group decision making, *Decision Support Systems*, **34**(4), 457-469.

Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., Ajayi, S.O., Akinade, O.O., Owolabi, H.A., Alaka, H.A. and Pasha, M.: 2016, Big Data in the construction industry: A review of present status, opportunities, and future trends, *Advanced engineering informatics*, **30**(3), 500-521.

Brown, N., Felipe, J. and Mueller, C.: 2016, Early-stage integration of architectural and structural performance in a parametric multi-objective design tool, *3rd International Conference on Structures and Architecture*.

Daher, E., Kubicki, S. and Pak, B.: 2018, Participation-based parametric design in early stages: A participative design process for spatial planning in office building, *Proceedings of the 36th eCAADe Conference - Volume 1*, 429-438.

Erhan, H., Abuzuraiq, A.M., Zarei, M., Haas, A., Alsalman, O. and Woodbury, R.: 2020, FlowUI: Combining Directly-Interactive Design Modeling with Design Analytics, *25th International Conference on Computer-Aided Architectural Design Research in Asia: Design in the Age of Humans, CAADRIA 2020*, **0**, 10.

Farshchian, B.A.: 2019, Collaboration as Commodity: What does CSCW have to offer?, *Proceedings of 17th European Conference on Computer-Supported Cooperative Work*.

Fernando, T., Wu, K.C. and Bassanino, M.: 2013, Designing a novel virtual collaborative

environment to support collaboration in design review meetings, *Journal of Information Technology in Construction*, **18**, 372-396.
Gautier, G., Piddington, C. and Fernando, T. 2008, Understanding the collaborative workspaces, *in* K. Mertins, R. Ruggaber, K. Popplewell and X. Xu (eds.), *Enterprise Interoperability III*, Springer, 99-111.
Hanzl, M.: 2007, Information technology as a tool for public participation in urban planning: a review of experiments and potentials, *Design Studies*, **28**(3), 289-307.
Hautaviita, A.: 2018, *Developing a web application on the MEVN stack: the architecture of a full-stack JavaScript application*, Master's Thesis, Turku University Of Applied Sciences.
Healey, P.: 1998, Building Institutional Capacity through Collaborative Approaches to Urban Planning, *Environ Plan A*, **30**(9), 1531-1546.
Holzer, D. and Downing, S.: 2010, Optioneering: A New Basis for Engagement Between Architects and Their Collaborators, *Architectural Design*, **80**(4), 60-63.
Kingston, R.: 2007, Public Participation in Local Policy Decision-Making: The Role of Web-Based Mapping, *Cartographic Journal - CARTOGR J*, **44**, 138-144.
Klein, M., Sayama, H., Faratin, P. and Bar-Yam, Y.: 2003, The Dynamics of Collaborative Design: Insights from Complex Systems and Negotiation Research, *Concurrent Engineering*, **11**(3), 201-209.
Konieva, K., Joos, M.R., Herthogs, P. and Tunçer, B.: 2019, Facilitating Communication in a Design Process using a Web Interface for Real-time Interaction with Grasshopper Scripts, *Blucher Design Proceedings*, Porto, Portugal, 731-738.
Lam, H., Bertini, E., Isenberg, P., Plaisant, C. and Carpendale, S.: 2012, Empirical Studies in Information Visualization: Seven Scenarios, *IEEE Transactions on Visualization and Computer Graphics*, **18**, 1520-1536.
Lu, S.L. and Sexton, M.: 2006, Innovation in small construction knowledge-intensive professional service firms: a case study of an architectural practice, *Construction Management and Economics*, **24**(12), 1269-1282.
Nuojua, J. and Kuutti, K.: 2008, Communication based web mapping: a new approach for acquisition of local knowledge for urban planning, *Proceedings of the 12th international conference on Entertainment and media in the ubiquitous era*, Tampere, Finland, 136-140.
Robertson, T. and Simonsen, J.: 2012, Challenges and Opportunities in Contemporary Participatory Design, *Design Issues*, **28**(3), 3-9.
Sanders, E.B.N. and Stappers, P.J.: 2008, Co-creation and the new landscapes of design, *CoDesign*, **4**(1), 5-18.
Sedlmair, M., Meyer, M. and Munzner, T.: 2012, Design study methodology: Reflections from the trenches and the stacks, *IEEE transactions on visualization and computer graphics*, **18**(12), 2431-2440.
Serror, M.H., Inoue, J., Adachi, Y. and Fujino, Y.: 2008, Shared computer-aided structural design model for construction industry (infrastructure), *Computer-Aided Design*, **40**(7), 778-788.
Shneiderman, B.: 2007, Creativity Support Tools: Accelerating Discovery and Innovation, *Commun. ACM*, **50**(12), 20-32.
Thomas, J.J. and Cook, K.A.: 2006, A Visual Analytics Agenda, *IEEE Comput. Graph. Appl.*, **26**(1), 10-13.
Tory, M. and Moller, T.: 2005, Evaluating visualizations: do expert reviews work?, *IEEE Computer Graphics and Applications*, **25**, 8-11.
Willett, W., Heer, J., Hellerstein, J. and Agrawala, M.: 2011, CommentSpace: structured support for collaborative visual analysis, *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, 3131-3140.
Yeomans, S.G., Bouchlaghem, N.M. and El-Hamalawi, A.: 2006, An evaluation of current collaborative prototyping practices within the AEC industry, *Automation in Construction*, **15**(2), 139-149.

21E8: COUPLING GENERATIVE ADVERSARIAL NEURAL NETWORKS (GANS) WITH BLOCKCHAIN APPLICATIONS IN BUILDING INFORMATION MODELLING (BIM) SYSTEMS

PROVIDES NG
[1] *UCL, Bartlett School of Architecture*
[1] *provides.ism@gmail.com*

Abstract. The ability of GANs to synthesize large sets of data is ideal for coupling with BIM to formulate a multi-access system that enables users to search and browse through a spectrum of articulated options, all personalised to design specificity - an 'Architecture Machine'. Nonetheless, due to challenges in proprietary incompatibility, BIM systems currently lack a secured yet transparent way of freely integrating with crowdsourced efforts. This research proposes to employ blockchain as a means to couple GANs and BIM, with e8 networking topology to facilitate communication and distribution. It consists of a literature review and a design research that proposes a tech stack design and UML (unified modeling language) use cases, and presents preliminary design results obtained using GANs and e8.

Keywords. 21e8; GANs; Blockchain; BIM; Architecture Machine.

1. INTRODUCTION

There has been an increasing amount of research in Generative Adverserial Networks (GANs) applications in architecture, mostly focused on generating floor plans to optimise building layouts or form-finding using techniques of StyleTransfer (Chaillou, 2019) (SCI-ARC, 2020). Besides creative production, GANs intelligence in handling 'large-scale problems, for they are too complex' and 'small-scale problems, for they are too particular and individual' has immense potential in relieving repetitive and bureaucratic processes for architects, including automating provision frameworks and the qualification of designs specific to local building regulations (Negroponte, 1970) (Coons, 1964).

Current research made significant contributions in generating new workflows, but they are generally scattered attempts that lack connectivity with one another, thus, may not necessarily be 'smart' - which requires dynamic networking - and may contribute to a trivial increase in productivity of the architectural industry (DOE, 2020) (McKinsey, 2017). Since much of GANs are open-source efforts, there needs to be ways in which such information can come together and freely integrate into app stacks - an 'Architecture Machine' that enables a multi-access system (Negroponte, 1970). Amalgamating readily available Information and Communication Technologies (ICTs) may assist inclusivity by directing micro-values back to individual actors who create/contribute contents.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 111-120. © 2021 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

BIM and blockchains may provide prospective ICT solutions - the former helps with interfacing between a scattered chain of actors; the latter helps with anchoring transaction and payment data in an immutable manner to facilitate transparency in information exchanges (Ng, 2020a) (Satoshi, 2008). Blockchain-BIM coupling enables streaming data channels and peer-to-peer (p2p) financial incentives for quality input in a Common Data Environment (CDE). This can sustain value/cash flow for actors and assist the formation of 'agencies models', 'in which one player could simply accept the "agency" of another player ... (although each player only works for their individual interests) ... The action of acceptance would have the form of being entirely cooperative, as if "altruistic" ' (Nash, 2008). Nonetheless, this would demand strategies in networking, to which the e8 topology presents a prospective optimal in information communication (Lisi, 2007).

This paper aims at proposing an agencies model that efficiently divide payoffs amongst open-source efforts in softwares and workflows - to diversify the limited proprietary softwares and smart workflow options - so as to be inclusive to a broader range of architectural inputs in our CDEs.

2. Methodology

This paper consists of a literature review and a design research. First, it reviews the most recent literature in GANs, e8, blockchain, and BIM research, and identifies prospects in integration. Then, it proposes possible solutions on means to integrate using a tech stack design, explains methods for implementation using UML use cases that illustrate how such systems may function for a scattered chain of designers, contractors, and clients. Finally, it presents sets of initial results on how GANs and e8 topologies may help to automate repetitive processes in urban design specific to Transit-oriented Development (TOD) and incentive zoning.

3. Literature Review

3.1. GANS

This research experimented with two types of GANs - StyleTransfer and pix2pixHD. The former 'render the content of one image with the style of another'; the latter synthesises 'photo-realistic images from semantic label maps' (Xu, et al., 2018) (Wang, et al., 2018). The author tries to integrate both GANs to diversify combinatorial production pipelines.

The potentials of StyleTransfer in generating and qualifying 'a large and highly diverse quantity of floor plan designs ... (and) offer a proper classification methodology' have been tested by Chaillou (2019). He focused on building-scale organisations that optimise functional parameters (e.g. building footprint, program, circulation, orientation, etc.). This research takes it one step further - from the transfer of function-style to network-style, which may offer prospective applications beyond building to urban scale.

Wang (2018) trained his Pix2pixHD on the Cityscapes Dataset (2020) to facilitate 'interactive image manipulation' in urban images, where users can 'change (semantic) labels in the original label map to create new scenes, like replacing trees with buildings' and 'edit the appearance of individual objects in the scene, e.g. changing the color of a car or the texture of a road'. This research expands this to the manipulation of videos extracted from 3D city models, which can act as a near real-time visualisation engine that directly translates between 2D and 3D representations to relieve the intensive rendering works for designers.

3.2. 21 & E8

A multi-access system would demand strategies that increase network speed, facilitate search functions in CDEs, and anchor all transaction data to secure royalty and liability in participatory workflows.

This research proposes to employ 21e8 strategies. E8 - a mathematical solution for the kissing number problem - presents a highly symmetrical and densely packed lattice in sphere packing (Lisi, 2007). It can be employed as a network topology that encodes and decodes messages during information transfer with high efficiency, thus, presents immense potential in the application of blockchain. 21 million is the total block capacity that can be mined; thus, '21' represents network strategies in blockchain (e.g. halving) (Satoshi, 2008). '21e8' has been rapidly studied by blockchain communities; one of which is a startup - 21e8.com (2020) - that decentralises real-time content creation for web3.0, which has potential application in building a BIM system upon a distributed network of databases.

21e8 may help to 'enable software studios to contribute to multiple projects concurrently ... combine the benefits of both open source code and enterprise grade engineering and support' (Agencies, 2020). Crowdsourcing efforts would need the design of agencies models to assist the division of payoffs and diversify coalitions (e.g. crowdfunding, where agencies can be modelled mathematically using game theory to design protocols for incentive provisions) (Nash, 2008).

3.3. BLOCKCHAIN & BIM

Nakamoto (2018) proposed a p2p transaction system secured with timestamp functions - bitcoin. 'It aimed at improving the autonomy of information transactions within a decentralised network to eliminate the time and resources needed for institutional authentication' (Ng, 2020a). The backend to which is blockchain - a distributed ledger perfect to be coupled with BIM systems to tackle fragmentation, both on a technical and a socio-economic level - softwares and supply chain. Blockchain-BIM coupling may enable not only BIM softwares, but BIM systems by assisting consensus mechanism in design negotiation between multiple, competing parties to accomplish larger, more complex tasks that each party otherwise could not have achieved on their own. This facilitates cooperative or non-cooperative games that give emergence to harmonic outputs (Nash, 2008).

There are various blockchain-BIM initiatives; nonetheless, most of them are not aiming for BIM systems that facilitate agencies models, but rather, proprietary BIM softwares, which is an obstacle towards inclusivity and accessibility, especially for small-scale actors, for two main reasons. First, scalability, which is the speed capacity for a network to handle a growing amount of transactions (Ng, 2020a). Scalability issues within a decentralised network contribute to high operational costs and significant transaction fees at each exchange. If crowdsourced or low-cut versions are not available, the proprietary cost itself may make most blockchain-BIM products potentially unaffordable to most businesses.

Second, incentives, which can take forms of monetary or social values. Currently, there are limited ways to realise values in architectural designs beside developing physical buildings. If architectural information is essentially intellectual content - same as any other content we see on social media, why can influencers realise value from their content almost instantly but architects cannot? There has to be ways in which incentive provisions are designed into the decentralized network structure. One way is to build consensus mechanism on valuation of information objects in CDEs to enable network effects (e.g. collaborative filtering/rating). This is what search engines, like Google Page's (1999) Rank, are doing to index information and rank web pages according to their relative importance, where content values can be realised in terms of network effects. A blockchain system would take this one step further: instead of a proprietary ranking, users can have control over such ranking and directly vote on works they appreciate in CDEs.

Along these lines, building connectivity within architectural production demands the design of BIM systems that are inclusive to open-source efforts, efficient in directing micro-values to content creators/contributors, and incentivise value/cash/data flow by rewarding quality work. This also helps incorporating open-source AI to relieve repetitive/bureaucratic works and increase productivity.

4. Design Research

4.1. INTEGRATABLE APP STACK

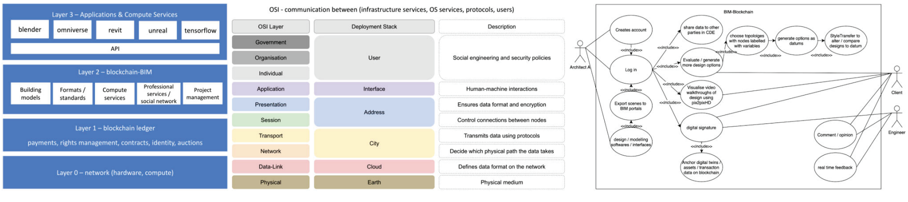


Figure 1. (a) The proposed tech stack. (b) The Proposed Open System Interconnection (OSI) model. (c) The proposed workflow. Source: author.

Blockchain's universal communication and control protocol can help the stacking of multiple applications and API (application programming interface) units into BIM software packages on demand; whereas its Shared Data Layer can help to anchor information assets to facilitate an immutable CDE and a means for BIM systems to incorporate crowdsourced efforts (Ng, 2020a). This has further applications in architecture, where decision-making and negotiation processes in design and contractual matters can be facilitated by an integratable app stack - we may begin to design a range of compatible interfaces as access portals for the specific needs of various users to enable real-time communication among a scattered chain of designers, contractors, clients, and, even, average citizens to diversify agencies models (e.g. crowdfund for collective housing) (Ng, 2020b).

GANs image-processing techniques can be incorporated as compute services that automate the generation of synthesized data. StyleTransfer can diversify available options based on users' different levels of design demands (e.g. clients can qualify design proposals by architects; amateur users can be empowered to deal with basic design works, etc.). Pix2pixHD can automate repetitive visualization works to provide designers with the autonomy of curation, and collapse the linearity between 2D to 3D translation. Together, the system and its users continuously create data that feed into itself via diverse value routes and streaming data channels, which can, in turn, be used for the training of AI (NChain, 2020). This forms a computer architecture that facilitates participatory production pipelines via crowdsourced services, which are built upon universal protocols.

4.2. UML USE CASE STUDY

Figure 1c demonstrates one possibility of workflow for urban design. First, architect A creates an account on the digital registry via BIM interface. A can choose to design with softwares that provide better creative control (e.g. Maya) and be visualized in BIM portals in real-time via APIs (e.g. Universal Scene Description) (Pixar, 2020). For design evaluation, A can use e8 topologies with nodes labelled with zoning parameters to generate a range of datum, which can be compared with A's designs to evaluate the deviation from the hypothesized optimal. A can then use StyleTransfer to automate alterations and generate more options; all articulated options can be shared to multiple parties simultaneously via CDE. Clients can download a low-poly version of the design/datum to save runtime and relieve network load, where surface subdivision and pix2pixHD visualization can be carried out at local desktop via simple interfaces at client-end BIM portals. Clients can directly label designs with comments, provide real-time feedback, and be distributed to involved parties. All information assets and transaction data are anchored on blockchain with each party's digital signature.

Within the stack, social media interfaces can be designed for architects to contribute micro-IPs (e.g. Minimal Viable Products, Proof-of-concepts, etc.) to build common asset models and collaborative designs. Micro-IPs can be traded at multiple stages of a project to crowdfund and collect users' opinions for future developments. The interface can be designed such that everytime a user posts, likes, comments, or forwards content, micro-values at the scale of a tenth of a cent/bitcoin/digital currency will be charged (Ng, 2020a). Users can also choose to pay with data or computational power. Subscription or other service models can be introduced for users who readily produce content. Percentage of the revenue can be shared among contributing/invested parties. Although the charge is minute, it may help to sustain high velocity value flows and prevent CDEs from populating with spam or low quality search results, because users are made aware that there is a realistic amount of cost to data input/processing/votes on information object, be it monetary or computational values.

This act as a means to decentralize information ranking within CDEs. Instead of a proprietary rank, users can vote on information objects via 'likes' to contribute their CPU/GPU power for mining or other computation-heavy tasks (e.g. AI training, rendering, etc.). This helps micro design challenges and information objects to progress into a physical architecture by competing, evolving, and surviving in a natural property market of architectural information (Ng, 2020a). When an IP is mature, it can be reverse auctioned to clients, who can easily analyse market options / cost benefits of the design and evaluate design quality / user-centric level via user rating/opinion, and benefit from the network effects already harnessed. Independent architects can take on a more proactive role within the supply chain, as opposed to waiting for design opportunities/client briefs, and sustain cash flows at early stages of design developments.

4.3. RESULTS - GANS

To further illustrate what the system can output in terms of architectural design, two on-going experiments on StyleTransfer and pix2pixHD are shown below.

4.3.1. StyleTransfer

This set of tests aims at reconfiguring urban topologies using GANs. One can infer the knowledge of 'types' using topology, which helps us to search for patterns in complex urban systems. Whereupon, we may begin to translate theoretical optimals in communication networks into urban topologies, and redistribute physical spaces accordingly.

This research experimented with e8 - a uniquely compact, simply connected lattice (Choe & Park, 2018). In spatial terms, this potentially implies a standard model to generate network optimals using different plane projections, and be used as a datum to analyse chaotic structures and qualify urban zoning. The e8 image below is a 2D representation of a 3D representation of a 4D projection of a 248D object (Madore, 2019). The high dimensional structure makes it technically difficult to operate on, but the ability of GANs to self-learn may help to open e8 opportunities for networking system and spatial configurations. Take TOD as an example, which aims at optimizing walking distance between public transport, residential, leisure, and business hubs. Each type of hub can be labeled as different types of nodes and be superimposed on e8 topologies to estimate the differences to the hypothesised optimal (Dittmar & Ohland, 2012).

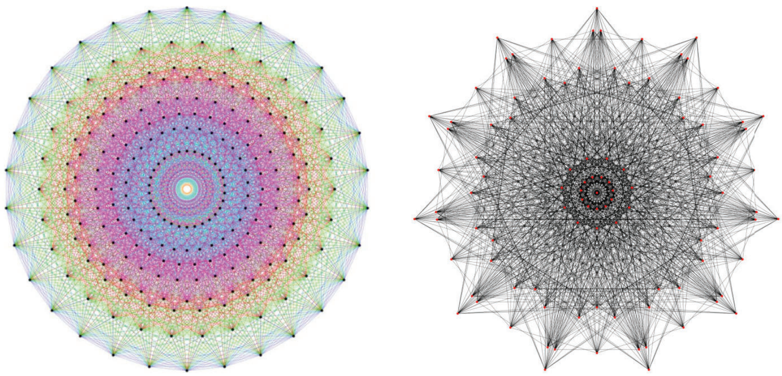


Figure 2. Representations of an e8 and a Leech Lattice (Lisi, 2007) (Madore, 2019).

Take incentive zoning as another example, which ‘allows new development in certain areas to voluntarily achieve extra floor area by providing certain public benefits [...] contributes to infrastructure investments in growing neighborhoods’ (Seattle.gov, 2018). This form of agencies model within urban developments can be assessed iteratively and adjusted periodically. For shorter time intervals, urban demands at different hours of the day can be sampled and evaluated using stochastic Markov models to predict changes in circulation, and formulate zoning provisions as a scheduler to incentivise private developments in facilitating different public benefits at different times of the day. For instance, incentivise malls to facilitate collective Taichi sessions or city forums during post-office hours. This would be especially helpful to highly compact cities like Hong Kong, where large-scale public areas are limited.

The following figures are two tests generated using StyleTransfer, e8, and Leech Lattice. The first test reconfigured the spatial planning of UCL using various projections of the Leech Lattice to distribute more communication channels between departments. The second test compared existing Hong Kong brownfield site topologies with e8 to deliver various recommendations on incentive zoning for revitalization. These sets of drawings remain as an artistic expression for now due to technical constraints, the next step to the project aims at developing high resolution outputs with enhanced precision.

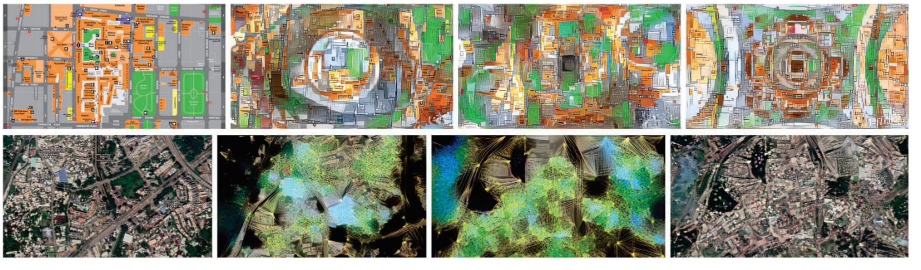


Figure 3. (a) UCL (2020) Bloomsbury Campus zoning plan and reconfigurations with Leech Lattice. (b) Current condition of Hung Shui Kiu Brownfields (scattered and fragmented sites with a highway segregating the urban fabric into two halves), reconfigurations with e8, and earth view visualization using StyleTransfer local urban texture maps. Source: author.

4.3.2. pix2pixHD

Project ‘CAN-D’ (City Adversarial Network Design) formulates a near real-time visualisation toolbox for architecture and urban design. CAN-D considers the participatory authorship problem, and aims at collapsing the linearity of pre- and post-production, also, human-machine design flow. Currently, the process of decision-making in design involves repetitive negotiation and contractual matters - a small change in a design triggers alterations in the entire digital model. Even if parametric tools are used to automate alterations, all visualisations would still have to be re-executed, causing repetitive work and low productivity.

There is an increasing amount of attempts on virtual desktops, which is especially challenging for real-time visualisation in a distributed system. For instance, blockchain-BIM decentralised computation is not very affordable outside central hubs due to scalability issues for the time being. It may work on a digital model with just a few megabytes, but BIM models easily reach over gigabytes. CAN-D tries to find alternative solutions by considering 2D-3D translation problem, which is fundamental not only to computational runtime, but also to architecture since the time of Brunelleschi. CAN-D takes a Gestalt approach - a perceptual grouping problem - which is perfect to be coupled with machine vision.

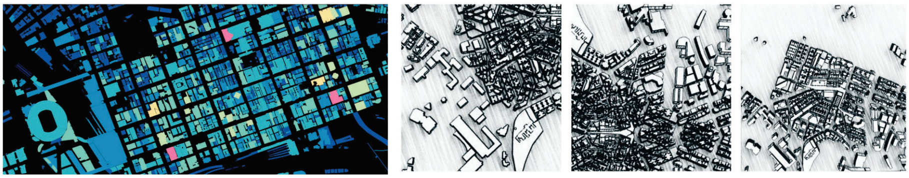


Figure 4. (a) A figure-ground drawing acquired from open-source mapbox. (b) Generated urban grids using procedural processing. Source: author.

Starting with a figure-ground drawing, which defines the boundary between spaces that can be acquired from any open-source mapbox, with color labels indicating the differences in building heights, embedding 3D information in a 2D drawing. CAN-D took a small portion of the city and utilised a rule-based procedural processing on mesh tension analysis to generate a range of new city grids, each has small articulated differences based on parameters. It helps to identify areas that are too segregated or densely packed with high rises, and provide options with better ventilation and circulation strategies. This step can also be done using StyleTransfer to estimate between the original functional zoning and a more organic arrangement, but for the aim of this project, CAN-D chose the cheapest compute combination possible.

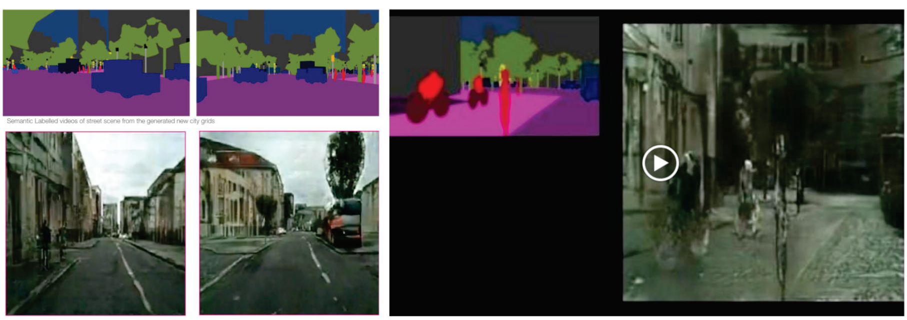


Figure 5. Screenshots taken from video demo, access: https://dai.ly/x7r2qm3. Source: author.

After design generation comes visualisation, CAN-D asked, how to visualise all options in near real-time so to efficiently communicate the designs? The drawings already have building height data embedded, which can be easily extruded using modeling softwares, to which zbrush was used. The digital model is then semantic-labelled for machine vision (requires some manual power). CAN-D flew a virtual camera around this city model and feed the video walkthrough into a pix2pixHD, which was trained on german city dataset, and outputs a texture mapping visualization.

This demo is computationally affordable - compressing what would take days of work into just hours with a fully trained neural net. The output resolution is low, but this can be leveraged between costs, availability, and quality for the needs and capacity of different design works and phases. For the next step, CAN-D is expanding to a city-scale semantic labeling with personalized datasets, which may classify objects like wind corridors, infrastructural provisions, and zoning types to perform visualisation for a broader range of design needs. CAN-D is also testing out integrating other open-source AI into the pipeline, like GANbreeder for static visuals to achieve greater speed and flexibility.

Figure 6. (a) The next step of CAN-D is city-scale semantic labelling. (b) Ongoing experiments using GANbreeder - an open-source algorithm using evolutionary dynamics. Source: author.

Imagine the compute/communication time that can be saved just from efficient collaborative methods enabled by an integratable app stack that encompasses StyleTransfer, pix2pixHD, GANbreeder, and many more; such an ‘Architecture Machine’ can be made available by a blockchain-BIM system that standardize protocols to include a growing amount of open-source efforts.

5. Conclusion

This research considered how readily available ICTs - blockchain and BIM - can be amalgamated as a coherent system that are inclusive to crowdsourced efforts, especially AI Image processing GANs, and act as a socio-economic drive to changes in architectural production and the democratisation of AI. This research argued that the formulation of such forms of multi-access systems should put emphasis on topologies to relieve network load in synchronising and distributing information and logistics, and gave examples of how e8 can be employed on both a software and a design level. This research proposed tech stacks, OSI models, and UML use cases to describe how various actors - architects, clients, general users - can interact with the proposed system, and showed sets of initial design results generated using StyleTransfer and pix2pixHD. This research also illustrated how these algorithms can be coupled with local building provisions, such as TOD and incentive zoning, to automate and relieve repetitive and bureaucratic processes for designers - an ‘Architecture Machine’ (Negroponte, 1970).

The experiments were merely starting points that narrowed down to specific problems in architectural design. The production pipelines proposed will have to be actively tested to see how units of system components and compute services can give rise to a broader range of combinatorial strategies. It is hoped that more system designs would be inspired to assist architects in comprehending across physical and disciplinary domains and promote information transfer. Two important components to be further considered is the design of interfaces that provide navigational strategies within CDEs, and means to direct information to those who will potentially need it (e.g. interdisciplinary personalisation).

References

21e8.com, 2.: 2020, “21e8™” . Available from <https://21e8.com/>.

Agencies, A.: 2020, “Agencies.” . Available from <https://agencies.network/>.

Bratton, B.H.: 2016, *The Stack - On Software and Sovereignty*, MIT Press, Massachusetts.

Chaillou, S.: 2019, AI + Architecture | Towards a New Approach, *Harvard University*, **188**.

Choe, D.H. and Park, K.: 2018, On intersection forms of definite 4-manifolds bounded by a rational homology 3-sphere, *Topology and its Applications*, **238**, 59-75.

Coons, S.A.: 1964, An Outline of the Requirements for a Computer-Aided Design System, *Proceedings of the May 21-23, 1963, spring joint computer conference (pp. 299-304)*..

Cityscapes Dataset, C.D.: 2020, The Cityscapes Dataset, *Retrieved November*, **24**, 2020.

Dittmar, H. and Ohland, G.: 2012, *Transit-oriented development*, Island Press.

DOE, D.O.E.: 2020, “US Department of Energy: SMART Mobility Modeling Workflow” . Available from <https://www.energy.gov>.

Imperva, I.: 2020, What is OSI Model: 7 Layers Explained: Imperva, *Retrieved November 25, 2020,*, **from https://www.imperva.com/learn/application-security/osi-model/**.

Kumar, N.(: 2020, January 01), *Truths about OSI layers (Simple Method)*..

Li, Y. and et, a.l.: 2018, A closed-form solution to photorealistic image stylization, *Proceedings of the European Conference on Computer Vision (ECCV*, 453-468.

Lisi, A.G.: 2007, An exceptionally simple theory of everything. arXiv, *no title given*.

Madore, D.: 2019, The Higman-Sims graph, *http://www.madore.org*.

McKinsey, M.: 2017, *A ROUTE TO HIGHER PRODUCTIVITY*, McKinsey Global Institute.

Nash, J.: 2008, The agencies method for modeling coalitions, *International Game Theory Review*.

nChain, B.S.V.: 2020, The Meta-Verse. Retrieved August 24, 2020, from, *no source given*.

N. Negroponte (ed.): 1970, *The architecture machine*, Cambridge (Mass.): M.I.T. Press.

Ng, P.: 2020a, Disrupting The Information Economy of Architecture With Satoshi’s Vision - How can blockchain applications in BIM help to support a circular economy inclusive to local independent and small-scale actors?, *DC I/O*, **10**, 47330.

Ng, P.: 2020b, *Applying Satoshi’s Vision to Brownfield Sites Revitalisation in Hong Kong*, International Forum on Urbanism [IFoU].

Page, L., Brin, S., Motwani, R. and Winograd, T.: 1999, *The PageRank citation ranking: Bringing order to the web*, Stanford InfoLab.

Pixar, P.: 2020, “Introduction to USD. Retrieved November 24, 2020, from” . Available from < https://graphics.pixar.com/usd/docs/index.html>.

Satoshi, N.: 2008, *Bitcoin: A Peer-to-Peer Electronic Cash System*.

SCI-ARC, S.-A.: 2020, “Cyborg Misprision 3 : AI Methodologies, SCI-Arc 2020” . Available from <https://www.subinjameel.com/ai-methodologies-studio-2020>.

Seattlegov, S.: 2018, “Incentive Zoning” . Available from <https://www.seattle.gov>.

UCL, U.C.L.: 2020, “UCL” . Available from <https://www.ucl.ac.uk/maps/downloads/>.

Wang, T.C. and et, a.l.: 2018, High-resolution image synthesis and semantic manipulation with conditional gans, *Proceedings of the IEEE conference on computer vision*, 8798-8807.

Xu, Z.: 2018, Learning from multi-domain artistic images for arbitrary style transfer., *arxiv*.

DESIGN AND DEVELOPMENT OF INTERACTIVE SYSTEMS FOR INTEGRATION OF COMPARATIVE VISUAL ANALYTICS IN DESIGN WORKFLOW

MARYAM ZAREI[1], HALIL ERHAN[2], AHMED M. ABUZURAIQ[3], OSAMA ALSALMAN[4] and ALYSSA HAAS[5]
[1,2,3,4]*Simon Fraser University*
[1,2,3,4]*{mzarei|herhan|aabuzura|oalsalma}@sfu.ca*
[5]*Stantec*
[5]*alyssa.haas@stantec.com*

Abstract. In architectural design, data-driven processes are increasingly utilized in creating and selecting design alternatives. Multiple design-aid systems that support such processes exist. Still, these systems dominantly support parametric modelling only or lack sufficient support for organizing, scanning and comparing multiple alternatives in the process of their creation while considering both their forms and performance data. In this paper, we argue that (a) evaluating and selecting potential alternatives must take place in the same context they are created and explored, (b) interactive data visualizations can provide real-time feedback about various aspects of design alternatives, and they should be incorporated as early in the design process as possible, and (c) design environment must enable comparing design alternatives as an integral part of the design workflow. We call our approach "comparative design analytics," which aims to identify, develop, and validate practical key features of visualization tools for assisting designers in analyzing and comparing multiple solutions with their data. We present D-CAT as a visualization prototype tool integrated with an existing CAD application. D-CAT acts as a platform for generating knowledge about using interactive data visualization for comparing design alternatives. Our goal is to transfer the findings from evaluating this interface to developing practical applications for real-world use.

Keywords. Comparative Design Analytics; Interactive System Development; Design Data Visualization; Design Workflow Augmentation; Creativity Support Tool.

1. Introduction

In architectural design, data-driven decision-making is gaining momentum(Kasik et al., 2005; Bilal et al., 2016). Considering design performance has become instrumental in generating and selecting design alternatives. We observe a general shift towards balancing the concerns of building form and performance as early as possible and throughout the design life cycle (Shi, 2010; Deutsch,2015; Erhan et al., 2020). Designers can use data to assess the degree to which they are fulfilling their project's objectives. (Inyim et al., 2015).

Although multiple systems have been proposed for working with design data (Doraiswamy et al., 2015; Wang and Steenblik, 2019; Parametric Monkey,2020; Ramboll Computational Design, 2020), we have yet to see a robust and seamless interaction between design form exploration and performance analysis. The specialized tools for this purpose either have a 'high threshold' for use in the early phases (Shneiderman et al., 2006a) or are computationally expensive to be used in a process parallel to design. Besides, most such systems rely on parametrically defined models, which are less efficient for early idea exploration. These interfaces also lack features necessary for organizing, scanning, and comparing alternatives considering their projected performances (Woodbury,2017; Garg and Erhan, 2019). Furthermore, data visualizations are generally overlooked or miss form-data dependence (Hamilton and Watkins, 2008; Bilal et al., 2016; Thelin et al., 2019). For design data analysis tasks, designers usually resort to general-purpose or improvised data analytics tools (Vergara,2018; Bilal et al., 2016), which force the evaluation and comparison of design alternatives to be relatively separated from (rather than integrated with) the design process.

Working with alternative solutions is a recurring and established pattern in design; we argue that (a) evaluating and selecting potential alternatives must take place in the same tool-ecosystem in which they are created;(b) decision-making must be supported by customizable interactive data visualizations that can reveal performance and form aspects of each alternative;(c) comparing design alternatives must be an integral part of the design process.

We put these arguments‘ plausibility to test on a prototype system composed of design data visualizations and interfaces that we have been developing with our industry partners as part of our 'design analytics‘ research program. We call the prototype Design Comparative-Analytics Tool, in short D-CAT. Its primary use case focuses on analyzing and comparing multiple directly-modelled design models seamlessly in the same design environment. Unlike single-state models and aligned with the discussions by Terry and Mynatt (2002); Woodbury(2017), D-CAT supports working with and comparing multiple alternatives with their form and performance data in the process and context of creating them. To achieve this, D-CAT extends FlowUI developed by Erhan et al.(2020).FlowUI can analyze non-parametric design models represented as manifold solid geometries with custom attributes and compute their select performance data in early design phases. FlowUI also presents computed data in real-time on a form-data visualization dashboard for design analytics. D-CAT extends these interfaces to include visualizations for comparing alternatives in real-time or on-demand, and without leaving the modelling environment. This approach aims to expand the designers' search space without the constraints of labour-intensive parametric modelling (Davis, 2020).

2. Background

The literature on design data analysis reveals opportunities and concerns on how the design data is accessed and used for decision making. We emphasize two of these concerns: the mismatch between the tool and the tasks in using design data and the limitation of the modelling techniques such as parametric or directly-interactive modelling for rapid feedback in design-decision making.

Design decisions rely on the analysis of design data (Danhaive and Mueller,2015; Touloupaki and Theodosiou, 2017). However, in general, taking advantage of these tools requires setting up parametric design models or using tools parallel to modelling systems (Fu, 2018). Frequently used simulation programs such as EnergyPlus (Crawley et al., 2001) and Ecotect (Roberts and Marsh, 2001)require design models to be restructured to their required computational format. In these tools, the process of modelling, analyzing, and decision making is discrete, and several steps of modifications and data transfer between tools are needed to achieve the desired outcome (Shi, 2010; Erhan et al., 2020). On the other hand, directly-modelled design models are preferred for their agility and the low-effort required for their setup (Hanna, 2012; Megahed, 2015; Erhan et al., 2020).

Direct modelling tools offer limited support for evaluating the performance of the modelled alternatives (Weytjens et al., 2012; Soebarto et al., 2015). The evaluation is implicit and only left to the designers' interpretation(Zapata-Lancaster and Tweed, 2016; Erhan et al., 2020). To address this issue, multiple parallel tools are proposed (Doraiswamy et al., 2015; Wangand Steenblik, 2019; Parametric Monkey, 2020; Ramboll Computational Design,2020; Erhan et al., 2020). A major bottleneck of these tools is that they continue to support single-state documents, i.e. they only allow working with one design option at a time. This limitation hinders designers from comparing the alternatives they are exploring, for example, to identify their respective potentials or drawbacks.

3. Developing D-CAT: Methods

In this research, we adapted the design study approach as a problem-driven research method. It involves "analysis of a specific real-world problem faced by domain experts, designing a visualization system that supports solving this problem, validating the design, and reflecting about lessons learned in order to refine visualization design guidelines." (Sedlmair et al., 2012, p.2). We developed and used D-CAT prototypes to generate knowledge about how design alternatives can be compared with each other using their associated form and performance data as an integral part of design exploration using interactive design analytics visualizations. The D-CAT visualizations are developed in collaboration with our industry partner, and we have evaluated them incrementally and continuously with domain experts. Below, we summarize the initial high-level requirements for D-CAT, which are derived from a literature review, design research, and our discussion with experts from the industry:

- **RQ1.** Support the comparison of design options by visualizing both form and

performance data in real-time or on-demand and in the same context they are created.
- **RQ2.** Enable customization of visualization of concerns, e.g. including or excluding data, selecting visualizations, toggling performance parameters on or off to compare, ordering design options, etc.
- **RQ3.** Allow exploration in the modelling tool while keeping visualizations on the locus of attention.
- **RQ4.** Provide support for storing, retrieving and sharing multi-state design form and data in the modelling systems.

For system development, along with the design study method, we combined the use-case driven and agile software development process (Beck et al., 2001)with design-develop-evaluate cycles. This process is initiated by identifying a set of priority use cases related to selecting and visualizing design data with domain experts, inspecting alternatives on data visualizations, and developing a workflow for comparing form and data. The project includes a demonstration of FlowUI and D-CAT as a design analytics platform for decision-making and assessing its role in the design. We will perform a formative qualitative system-evaluation through expert review in the next phase (Creswell and Poth,2016; Tory and Moller, 2005), which has been delayed due to COVID-19 restrictions.

D-CAT is a form of Creativity Support Tools (CST) (Shneiderman et al., 2006a) that provides rich interactions for exploration and comparison tasks. D-CAT's features are designed to augment creative decision making by presenting design form and data in a flexible structure. In current practice, general-purpose data visualization tools are used for studying design-data. However, they are cumbersome to integrate into the design decision-making, which is a fast, delicate, and cognitively intense process. The interrupted information flow between the parallel tools hinders real-time updates retrieved from the modelling environment (RQ4). To address this external and parallel tools' problem, D-CAT is coupled with the modelling environment, and it separates the design tasks from the management of design data.

We use HumanUI (Heumann, 2020) in experimenting with the interface designs (Figure 1). The advantage of HumanUI is that it is available as an extension to a widely used modelling environment, Rhino (McNeel, 1998), and takes advantage of CAD's internal model representations. It is a cost-effective alternative for rapid prototyping with its low-threshold for rapid development of prototype interfaces (Shneiderman et al., 2006b). Although it is limited for low-level interface programming, it provides an ecologically valid setting as designers and software developers use it in design practice for early prototype development.

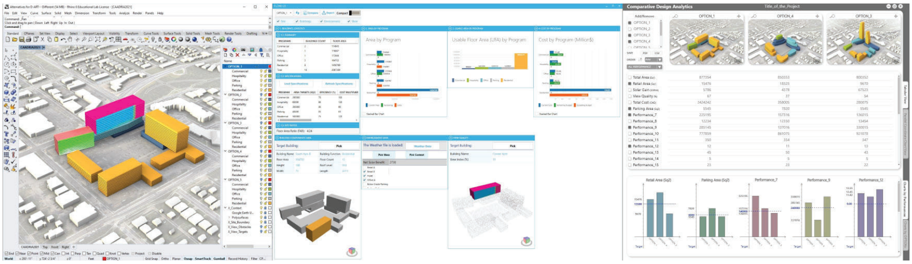


Figure 1. Left: Rhino modelling environment (McNeel, 1998). Middle: FlowUI interface (Erhan et al., 2020). Right: D-CAT interface. The three windows are integrated as our requirements (RQ4) suggest.

4. D-CAT System Design

To address the high-level requirements we listed above and building on previous research by Erhan et al. (2020), we developed a system architecture for D-CAT (Figure 2). This architecture allows interactive form exploration in the CADtools while presenting form and performance data on interactive visualizations (Gleicher et al., 2011) (RQ4) (Figure 1).

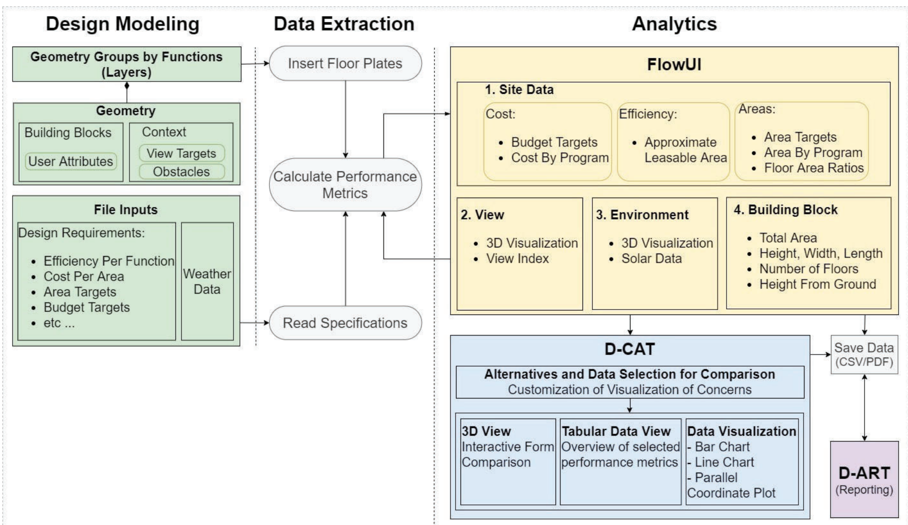


Figure 2. FlowUI—D-CAT System Architecture.

The D-CAT is part of a modular system architecture. Its primary function is to receive design data from an analytics module (e.g. FlowUI) for each alternative. D-CAT retrieves and visualizes design data as synchronized 3D form views, interactive queries on tables or charts, and customizable panels (Figure3). However, it cannot change design models in its current implementation: the information flow is unidirectional due to the technical difficulty we have faced in the system's API, which we will address in the next phases.

5. D-CAT Interfaces and Visualizations

D-CAT's interface facilitates diverse comparison tasks such as juxtaposed visualization of forms, selective comparison of performance metrics, grouped-by-alternatives or grouped-by-metrics comparisons, etc. All of which can be performed in real-time or on-demand (Figure 4). The interface consists of four main interaction panels (Figure 3): 1. Alternatives and PerformanceData Selection (RQ1 and RQ3); 2. Interactive 3D Geometry Visualization(RQ2); 3. Performance Metrics Tabular View (RQ2); and 4. Performance Data Visualizations (RQ2).

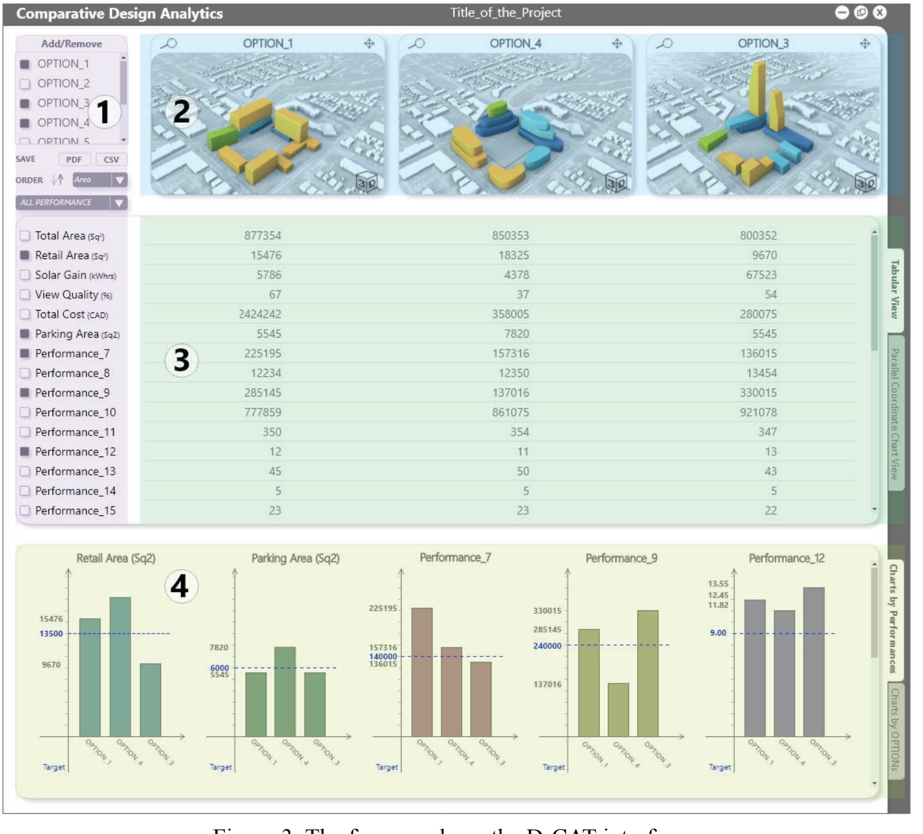


Figure 3. The four panels on the D-CAT interface.

The Alternatives and Performance Data panel provides customizable visualization of design data (Figure 4[1]) following the selection of design options. The system can export the comparison data to be shared with others or be further analyzed in design navigation tools such as DesignExplorer (Thornton Tomasetti CORE Studio, 2020) or DesignSense (Abu Zuraiq, 2020) in a parallel process.

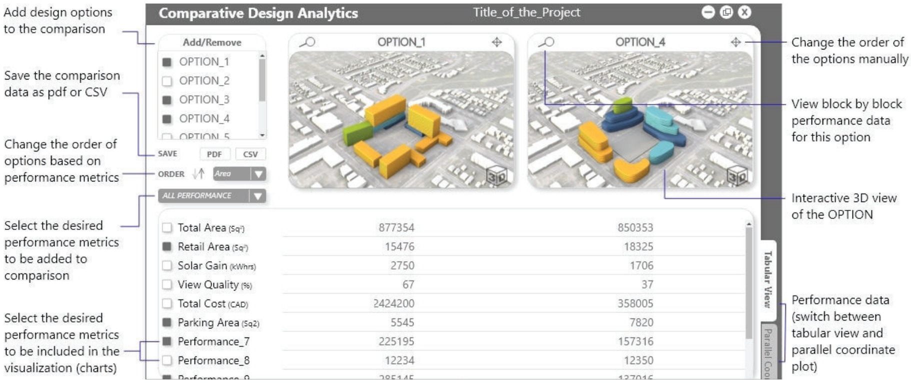


Figure 4. Possible interactions in the D-CAT interface based on the high-level requirements identified for a comparative design analysis system.

Juxtaposed design models are presented in the 3D Visualization panel. We use a colour-coded 3D form view, e.g., to indicate the associated functions of the building blocks (Figure 4 [2]). The Tabular Data View provides an overview of the selected performance metrics in a list with selectable data items [3]. The bottom panel (Figure 4, [4]) is composed of customizable visualizations such as bar charts, parallel coordinates plot, line chart, etc. (Figure 5).

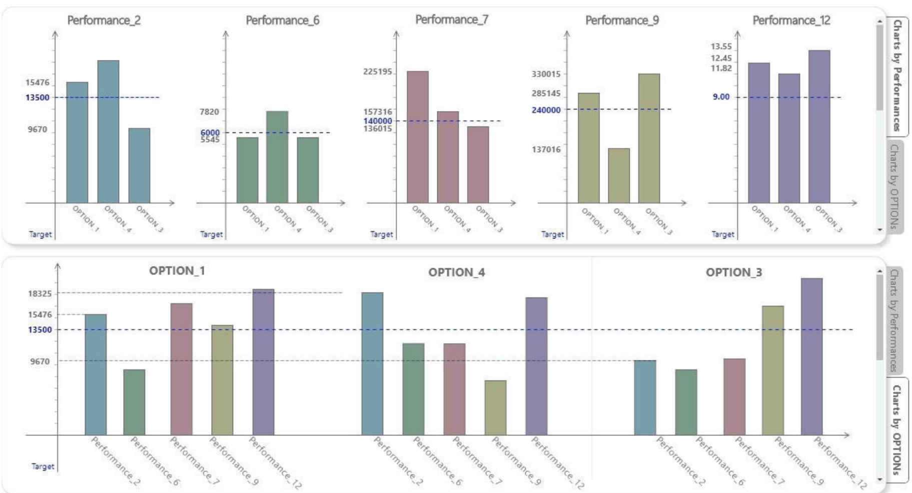


Figure 5. Top: Bar charts combining design options; Bottom: Bar charts showing the select performance metrics for each option.

6. Discussion and Conclusions: Thoughts on Comparative Design Analytics

This paper mainly argues a mismatch between the tasks and tools for working with multiple design alternatives, especially for comparison tasks considering alternatives forms and performance data. This mismatch creates a significant bottleneck in the design workflow. Hence, we should focus on searching for a new set of tools specifically designed to augment designers' capabilities for exploring multiple alternatives informed by data as early as possible in the design workflow. These tools should be developed and tested to replace the improvised and often scattered generic tools. D-CAT is an attempt towards achieving this goal. Although in its early stage, we plan to use it as a platform for learning more about the tasks and tool features required to streamline the exploration, comparison, and improvements of design alternatives.

We have identified the high-level requirements for such systems. The validation of these requirements will need further testing of D-CATvisualizations with designers working on real-world cases. We emphasize that the identified shortcomings of D-CAT interfaces are not necessarily reflections of the ideas behind them but most likely the design-choices we made in their implementation (Sedlmair et al., 2012). Therefore, we will continue developing different D-CAT versions to gradually generate knowledge around how such systems improve design-decision making. The iterative cycles of develop-test-reflect, which we adopted as part of the design study methodology, is proven to be effective in other domains relying on new interactive visualization solutions. Evaluation of design data visualization systems has two aspects to consider: the interface design decisions and the novel tasks proposed through these interfaces (Lam et al., 2012). In the next phase, we will conduct an expert review (Tory and Moller, 2005) as a formative evaluation of D-CAT with respect to predefined criteria on both the tasks and the visualizations supporting these tasks. This review is expected to reveal the concerns to be addressed in the following iterations as future work. We also plan to test the functional features of D-CAT in practice in collaboration with our industry partners.

References

Beck, K., Beedle, M., Van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A., Jeffries, R., Kern, J., Marick, B., Martin, R.C., Mellor, S., Schwaber, K., Sutherland, J. and Thomas, D.: 2001, Manifesto for Agile Software Development, *http://agilemanifesto.org/*, **0**, NA.

Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., Ajayi, S.O., Akinade, O.O., Owolabi, H.A., Alaka, H.A. and Pasha, M.: 2016, Big Data in the construction industry: A review of present status, opportunities, and future trends, *Advanced engineering informatics*, **30**(3), 500-521.

Crawley, D., Lawrie, L., Winkelmann, F., Buhl, W., Huang, Y., Pedersen, C., Strand, R., Liesen, R., Fisher, D., Witte, M. and Glazer, J.: 2001, EnergyPlus: Creating a New-Generation Building Energy Simulation Program, *Energy and Buildings*, **33**, 319-331.

Creswell, J.W. and Poth, C.N.: 2016, *Qualitative inquiry and research design: Choosing among five approaches*, Sage publications.

Danhaive, R. and Mueller, C.: 2015, Combining parametric modeling and interactive optimization for high-performance and creative structural design, *International Association for Shell and Spatial Structures (IASS) Symposium*, **0**, 11.

Deutsch, R.: 01, *Data-Driven Design and Construction: 25 Strategies for Capturing, Analyzing and Applying Building Data*, Wiley Publishing, New Jersey, USA.

Doraiswamy, H., Ferreira, N., Lage, M., Vo, H., Wilson, L., Werner, H., Park, M. and Silva, C.: 2015, Topology-based catalogue exploration framework for identifying view-enhanced tower designs, *ACM Transactions on Graphics (TOG)*, **34**(6), 1-13.

Erhan, H., Abuzuraiq, A.M., Zarei, M., Haas, A., Alsalman, O. and Woodbury, R.: 2020, FlowUI: Combining Directly-Interactive Design Modeling with Design Analytics, *25th International Conference on Computer-Aided Architectural Design Research in Asia: Design in the Age of Humans, CAADRIA 2020*, **0**, 10.

Fu, F.: 2018, *Design and Analysis of Tall and Complex Structures*, 978-0-08-101018-1. DOI Copyright © 2018 Elsevier Ltd, ISBN.

Garg, A. and Erhan, H.: 2019, Use of Data in Design Exploration: Design Analyzer, *"Hello, Culture!" [18th International Conference, CAAD Futures 2019, Proceedings*, Korea.

Gleicher, M., Albers, D., Walker, R., Jusufi, I., Hansen, C.D. and Roberts, J.C.: 2011, Visual comparison for information visualization, *Information Visualization*, **10**(4), 289-309.

Hamilton, D.K. and Watkins, D.H.: 2008, *Evidence-based design for multiple building types*, John Wiley \& Sons.

Hanna, R.: 2012, Parametric tools in architecture: a comparative study, *Swedish Design Research Journal*, **1**, 2000-964.

Inyim, P., Rivera, J. and Zhu, Y.: 2015, Integration of Building Information Modeling and Economic and Environmental Impact Analysis to Support Sustainable Building Design, *Journal of Management in Engineering*, **31**, A4014002.

Kasik, D.J., Buxton, W. and Ferguson, D.R.: 2005, Ten CAD challenges, *IEEE Computer Graphics and Applications*, **25**(2), 81-92.

Lam, H., Bertini, E., Isenberg, P., Plaisant, C. and Carpendale, S.: 2012, Empirical studies in information visualization: Seven scenarios, *Transactions on Visualization and Computer Graphics*, **18**(9), 1520–1536.

Megahed, N.A.: 2015, Digital Realm: Parametric-enabled Paradigm in Architectural Design Process, *International Journal of Architecture, Engineering and Construction*, **4**(3), 175-184.

Roberts, A. and Marsh, A.: 2001, ECOTECT: Environmental Prediction in Architectural Education, *Architectural Information Management*, **0**, 342-347.

Sedlmair, M., Meyer, M. and Munzner, T.: 2012, Design study methodology: Reflections from the trenches and the stacks, *IEEE Transactions on Visualization and Computer Graphics*, **18**(12), 2431-2440.

Shi, X.: 2010, Performance-based and performance-driven architectural design and optimization, *Frontiers of Architecture and Civil Engineering in China*, **4**(4), 512-518.

Shneiderman, B., Fischer, G., Czerwinski, M., Resnick, M., Myers, B., Candy, L., Edmonds, E., Eisenberg, M., Giaccardi, E., Hewett, T., Jennings, P., Kules, B., Nakakoji, K., Nunamaker, J., Pausch, R., Selker, T., Sylvan, E. and Terry, M.: 2006, Creativity Support Tools: Report From a U.S. National Science Foundation Sponsored Workshop, *International Journal of Human–Computer Interaction*, **20**(2), 61-77.

Soebarto, V., Hopfe, C.J., Crawley, D. and Rawal, R.: 2015, Capturing the views of architects about building performance simulation to be used during design processes, *14th International Conference of the International Building Performance Simulation Association*, **0**, 7-9.

Terry, M. and Mynatt, E.D.: 2002, Recognizing creative needs in user interface design, *Proceedings of the 4th conference on Creativity \& cognition*, 38-44.

Thelin, C., Bunnell, S., Salmon, J. and Gorrell, S.: 2019, Difference modeling for design space exploration and comparison of three-dimensional structural simulation results, *Information Visualization*, **18**(4), 455-470.

Tory, M. and T Moller, j.C.G.: 2005, Evaluating visualizations: do expert reviews work?, *IEEE Computer Graphics and Applications*, **25**(5), 8-11.

Touloupaki, E. and Theodosiou, T.: 2017, Performance Simulation Integrated in Parametric 3D Modeling as a Method for Early Stage Design Optimization—A Review, *Energies*, **2017**(10), 637.

Vergara, M.: 2018, Big data in building design: A review, *Electronic Journal of Information*

Technology in Construction, **23**, 259-284.
Wang, W. and Steenblik, R.S.: 2019, Bespoke Tools Providing Solutions for Contemporary Problems-Novel BIM practice for architects, *Proceedings of the 24th CAADRIA Conference*, **2**, 111-120.
Weytjens, L., Attia, S., Verbeeck, G. and Herde, A.: 2012, The 'Architect-friendliness' Of Six Building Performance Simulation Tools: A Comparative Study, *International Journal of Sustainable Building Technology and Urban Development*, **10**(5390), 237-244.
Woodbury, R. 2017, The Grammar Lens: How Spatial Grammar Channels Interface Design, *in* J.H. Lee (ed.), *Morphological Analysis of Cultural DNA: Tools for Decoding Culture-Embedded Forms*, Springer Singapore, Singapore, 199-226.
Zapata-Lancaster, G. and Tweed, C.: 2016, Tools for low-energy building design: an exploratory study of the design process in action, *Architectural Engineering and Design Management*, **12**(4), 279-295.
Abu Zuraiq, A.: 2020, *DesignSense: A Visual Analytics Interface for Navigating Generated Design Spaces*, Master's Thesis, Communication, Art \& Technology: School of Interactive Arts and Technology.

CAPTURING AND EVALUATING PARAMETRIC DESIGN EXPLORATION IN A COLLABORATIVE ENVIRONMENT

A study case of versioning for parametric design

VERINA CRISTIE[1], NAZIM IBRAHIM[2] and
SAM CONRAD JOYCE[3]
[1,2,3]*Singapore University of Technology and Design*
[1]*verina_cristie@mymail.sutd.edu.sg* [2,3]*{nazim_ibrahim|
sam_joyce}@sutd.edu.sg*

Abstract. Although parametric modelling and digital design tools have become ubiquitous in digital design, there is a limited understanding of how designers apply them in their design processes (Yu et al., 2014). This paper looks at the use of GHShot versioning tool developed by the authors (Cristie & Joyce, 2018; 2019) used to capture and track changes and progression of parametric models to understand early-stage design exploration and collaboration empirically. We introduce both development history graph-based metrics (macro-process) and parametric model and geometry change metric (micro-process) as frameworks to explore and understand the captured progression data. These metrics, applied to data collected from three cohorts of classroom collaborative design exercises, exhibited students' distinct modification patterns such as major and complex creation processes or minor parameter explorations. Finally, with the metrics' applicability as an objective language to describe the (collaborative) design process, we recommend using versioning for more data-driven insight into parametric design exploration processes.

Keywords. Design exploration; parametric design; history recording; version control; collaborative design.

1. Introduction

With the rise of the web in the 90s, the concept of the Virtual Design Studio (Wojtowicz, 1994) was born into the architectural pedagogy, where design projects were done over the network. During subsequent implementations of this concept, learning and collaboration was the focus, such as ETH Zurich's phase(x) (Hirschberg & Wenz, 1997), Harvard GSD's OpenD (Meagher, et al., 2005) or AA Design Research Lab's Collaborative Distributed Learning (Steele, 2006). Students were to exchange design works periodically, modify them creatively in a collective authorship scenario on a common web platform. However, such platforms often remained one-off technological proofs-of-concept, and lacked further investigation into the design process (Achten, 2009).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 131-140.

Independently, various design process studies have been manually performed to help better understand how designers from different fields (Lawson, 2006) or of different expertise (Eastman et al. 2001) think, including looking at the breadth and depth of the design exploration (Cross, 2004). The observants often had to perform think-aloud protocols while designing. With on-site observation, video and audio recording manually segmented and coded by experts in the field, scalability and generalisability issues were raised. Thus, in this paper, it is our aim to utilise data collected from such collaborative web platforms to understand the design process better, rather than relying on traditionally manual data collection and processing.

2. Data Collection

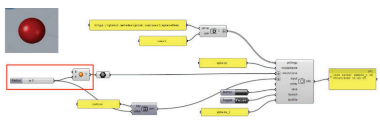


Figure 1. GHShot Design Versioning Grasshopper plugin.

In order to capture parametric design process data, GHShot (Cristie & Joyce, 2018; 2019), a design versioning plugin for Grasshopper previously developed by the authors, was utilised. GHShot works similar to the widely used code versioning tools (like Git) but on parametric model visual-coding rather than the usual software text-based coding. Critically for this work using GHShot, designers can send their design versions at any development point to the cloud. Consider the above sphere scenario in Fig. 1. The following data is captured upon sending:

Table 1. Data captured in each design version (based on simple sphere scenario).

Design Version Data	Meta-Data
• Parametric model definition *Sphere and Slider Components and Link*	• Design version ID *Auto-updated ID* • Time-stamp
• Parameter value *Sphere radius – slider value*	• Notes *If any, about the design*
• Geometry *Sphere mesh*	• Parental information *Previous version's ID*

2.1. EXPERIMENT SETTINGS

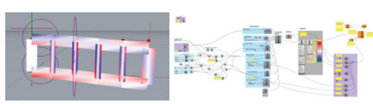


Figure 2. Base Truss Parametric Model given to the cohorts.

Three cohorts of second-year undergraduate architectural students (G1, G2, G3) in a structural design course were given a base truss parametric model (see Fig. 2) to collaborate on, to introduce them to different parametric structural typologies.

The two groups in each cohort were told to capture their design exploration process with GHShot and different instructions were given to see how it could affect the design process. While we tried to keep a similar timeframe over the cohorts, each year's ad-hoc scheduling often affected the experiment settings.

Table 2. The different experiment settings for each cohort.

	Basic Settings	Group A (user count)	Group B (user count)
G1	Given as a homework, continued in the class	No minimum design to submit (27)	Minimum 5 designs to submit (26)
G2	2 hour design exercise in the class, 3x30 minutes design block with design rating in between	Each design block, the students were free to continue their designs or their peers' (13)	Each design block, the students were to modify only the top 3 rated designs (12)
G3	1 week homework	Same instructions for both groups. Students were given extra points if they can make a cantilever model (14 and 13).	

3. Data Processing: Metrics Development

While in the past evaluating design processes required subject experts, recent developments has shown the ability to perform automated quantitative evaluation of parametric model's geometric diversity (Brown & Mueller, 2018), and flexibility (Davis 2013). In our context, we are interested in being able to meaningfully understand parametric design beyond its individual model level and probe further into its development process and collaboration, especially with the cohorts' design versions data. Both a macro (overall development) and micro (detailed, versions-based) approach are used for evaluation.

3.1. MACRO VIEW: EVALUATING DESIGN PROCESS THROUGH DESIGN TREE DEVELOPMENT

From helmet evolution in the centuries (Dean, 1915) to Latham's computer evolutionary art (Todd & Latham, 1992), to Tsunoda & Sakai's (2015) human-bot collaborative 3D house plan, traditionally design history has been represented as a tree. The diverging of design ideas and its development iteration is comparable to a tree's breadth and depth. To further characterise the design history tree captured, we use the following metrics:

1. Number of nodes/design versions (*nNode*). This number is an indication of the total amount of design options explored.
2. Branching complexities (*branchComplexity*). Being able to change the direction of one's thinking and generate more ideas is considered a characteristic of a creative thinker (Lawson, 2012). In a design version history tree, a node (design version) is considered branching if it has at least two child nodes. *branchComplexity* is calculated by aggregating all branching nodes in the tree. If there is no branching at all and the process is linear, *branchComplexity* is 0. Whereas, more branching will produce higher *branchComplexity* value.
3. Maximum/Average tree depth (*max_treeDepth*, *avg_treeDepth*). Although merging (convergence) operations is not currently captured; a linear continuation - the tree depth, could be a measure of how developed an idea is.
4. Collaboration Score (*collabScore*). This is measured by the ratio of the number

of nodes derived from someone else's version / overall nodes (*nNode*).

5. Number of distinct design ideas explored (*nIdeas*). A design version is considered as having a distinct design idea if the geometry output is perceived as substantially different from other versions. To do this automatically, Keras (Chollet & others, 2015) deep learning model was used to extract features from the 2D image of the geometry model. Based on the features, elbow method (Thorndike, 1953) was used to determine the optimum number of clusters (k) and clustering is performed using K-means (Lloyd, 1982).

3.2. MICRO VIEW: METRICS OF A DESIGN VERSION AND ITS CHANGE

To quantify each design version, we use the Davis' (2013) existing metric for the parametric model (1 and 3) and Globa's (2016) for the geometry (4):

1. Number of Components in Parametric Model (*nComp*). This is the immediate proxy for the size of the parametric model.
2. Number of Unique Components (*nUniqueComp*). This is used as a proxy of how versatile a designer is and how unique a design is. We assume that expert designers would know how to use more component types to create more diverse designs.
3. Parametric Model Complexity (*graphComplexity*). Based on the number of link and components in the model, this is a measure of the amount of work to understand the parametric model.
4. Number of Meshes in the Geometry (*nMesh*). This is used as a proxy for the geometric complexity of the generated model.

Further, we look at design versions as time-series data to analyse the design change process, to see if we can learn any general or distinct patterns. Each design version is compared to its parent (previous) version. In every version data, there are three components: parametric model definition (*XML* string), parameters and performance values (as key-value pairs), and geometric output (3D objects). Upon observing that the participants were not taking performance values into account and were more interested in exploring visually unique geometrical shapes (topology), we decided to disregard performance differences in this experiment.

3.2.1. Parametric Change (Δ param)

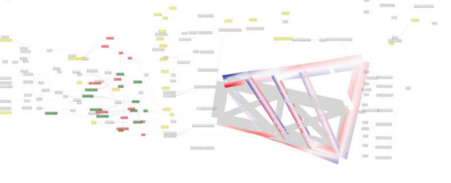


Figure 3. To change from original (grey shaded) to current geometry (coloured), parametric components were deleted (red), added (green), and changed (yellow).

As a parametric model definition is XML text-based, we performed parametric model 'Diff'-ing, inspired by Diff (Myers, 1986), the standard software code versioning's difference detection algorithm. As a parametric model's building block is its components, *Δparam* is defined as the total number of components added, deleted, or changed in its attributes.

3.2.2. Geometric Change (Δ geom)

Geometric change can be the extent of design space explored (Brown & Mueller, 2019) and is often attributed as a measure of design creativity as it means designers are not fixated on a particular design (Nathan, 2015). To measure this, Hausdorff distance calculation from Meshlab library (Cignoni et al., 2008) was used. This distance (*Δ geom*) is defined as the maximum distance of a set to the nearest point in another set. Hence, the higher the distance value is, the more dissimilar the two geometries are (see Table 3). The *nMesh* metric mentioned previously was not used because the change in the mesh count does not necessarily represent the change geometry topology.

Table 3. Δ geom values for three level of geometric changes.

rib → rib_12 *Δ geom : 0.116*	rib_14 → rib_30 *Δ geom : 0.368*	rib_14 → rib_54 *Δ geom : 0.742*

4. Results & Discussion

Below we present our findings in question and answer format for easier discussion.

4.1. HOW DO THE METRICS FARE ACROSS THE COHORTS?

- *nNode*: G1 has the largest nNode, as it had double the student size compared to G2 and G3. On average, the number of design versions submitted per student for all groups is between 3-5. G1-B had more design versions as compared to G1-A, as the students were required to submit minimum 5 design versions each.
- *branchingComplexity*: for all groups, it ranged between 5-6, except for G2-A where it is 8. This higher value is encouraged by the experiment settings where the students had to continue their own or other's design in the 30 minutes iteration, as compared to the other groups where there was no time limit. It is also higher than G2-B as G2-B can only choose the highest rated versions.
- *maxtree_Depth* : The longer development time in G1 and G3 contributed to maxtreeDepth as high as 10 in G1-A and G1-B, and 8 in G3-A, as compared to G2-A's 6 or G2-B's 7. the *avg_treeDepth* of G1, G2, and G3 are 4.5, 3.3, and 4 respectively.
- *graphComplexity*: from the radar plot, it can be seen that G1 has a wider range of *graphComplexity* as compared to its initial value. As it has the lowest *nComp* and only 5 *nUniqueComp* related to its topology, it appears that its base model simplicity (and also the longer duration of exploration) gave room for more complex modification.

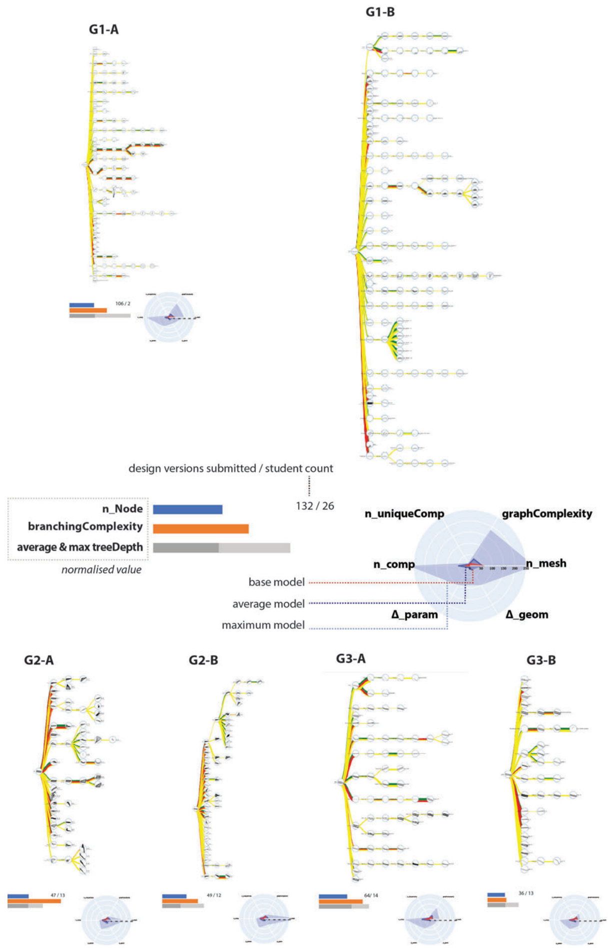


Figure 4. Design change tree and metrics visualisation from 3 cohorts. Radar areas are indicative of the initial metrics value and the extent of the students design space exploration.

4.2. WHAT ARE THE DESIGN CHANGE PATTERNS OBSERVED FROM THE DESIGN CHANGE TREE?

Yellow, green, and red lines and their thickness in Fig. 4's design change tree represents the count of modified, added, and deleted components respectively. Many versions submitted early in the tree has more yellow lines, signifying students started exploring by changing components' parameters. Some students also started adding and deleting components (creation modification) right away. Either they had an idea right off the bat, or the initial parametric changes were not uploaded. As the design progressed, we can observe two distinct continuous development paths: (1) refining (yellow lines only), or (2) idea exploration (thick red and green lines across). For many design paths, it is a combination of these.

4.3. ON N_IDEAS METRIC, HOW DOES AUTOMATIC DEEP LEARNING IMAGE CLUSTERING FARE COMPARE TO MANUAL REVIEWERS?

Figure 5 displays the resulting clusters taken as *nIdeas* metric on G2-B's dataset (based on the method explained in 3.1 above). There is no significant 'elbow' or turning point from the image features can be observed, implying that no optimum number of clusters were identified given the maximum of 20 clusters. It is possible that the images were hard to cluster - many individual unique design idea does not belong to any clusters. While all reviewers could agree that most design ideas can be found in G1, followed by G2 and G3, the number identified varied a lot depending on the reviewer (see Table 4), confirming the challenge in clustering even when performed manually.

Figure 5. G2-B's 13 clusters of design ideas from the design versions.

Table 4. Number of design ideas found by reviewers and automatic image clustering.

	G1-A	G1-B	G2-A	G2-B	G3-A	G3-B
Reviewer 1	19	23	17	13	8	6
Reviewer 2	71	70	43	29	33	18
Reviewer 3	35	37	31	15	13	8
Image Clustering	13	14	13	11	6	8

4.4. ON COLLABORATION: ARE THERE ANY DIFFERENCES WHEN STUDENTS MODIFIED THEIR OWN DESIGNS VERSUS OTHERS'S ?

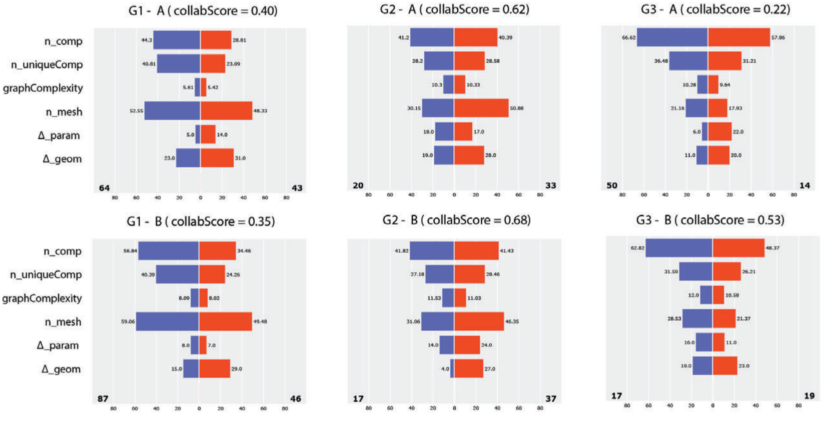


Figure 6. Metrics comparison of the cohorts. Blue: own design modification, red: other's.

- Without a specific experiment setting where they had to modify the highest rating designs - which might not be their own (G2-B case), students mostly tend to modify their own design versions (lower *collabScore*).
- As students work on their own designs, they tend to create and modify larger models (higher *nComp* and *nUniqueComp*). This is observed more significantly in G1 than G3. Perhaps when modifying other's models, it is easier to modify simpler models, such as the earlier developed models.
- *nComp* and *nUniqueComp* between self and others are comparable in G2. We suspect this is due to the half-hour time constraint which limits how much can be done.
- Despite this, *nMesh* is higher when other's models are modified in G2. It is possible that time constraint factor plays a part in a quicker idea exploration (White et al., 2010), and that students achieved higher *Δgeom* by simply modifying sliders or parameters (will be further discussed in 4.6).

4.5. ARE THERE ANY DIFFERENCES IN HOW EACH STUDENT MODIFIED THEIR DESIGNS ?

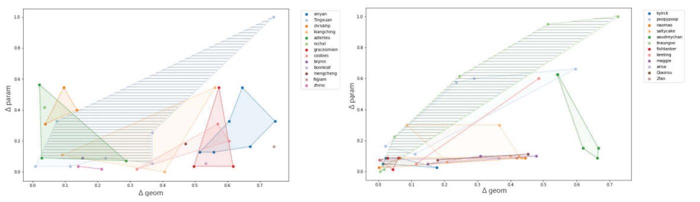


Figure 7. G2's design versions' Δparam and Δgeom plotted and connected per user. Each user occupies a 'zone'.

We plotted *Δparam* and *Δgeom* values from each user in G2 using a different colour (see Fig. 7). When each user's data points are connected, they occupied certain 'zones' in the plot. Some users' 'change zone' spanned to cover almost the entire plot, while some only covered small area in the plot. The data points signify specific parametric models modifications each user is most familiar with, resulting in various geometric change outcomes. We hypothesise that the bigger the zone spans represents users with higher parametric modelling proficiency and thus a wider range of design exploration; such as shown by G2-A's *Tingxua* (left) and G2-B's *tnaungo* (right) (shaded in Fig. 7 above).

4.6. HOW CAN WE CATEGORISE THE TYPES OF DESIGN CHANGES?

Based on *Δparam* and *Δgeom*'s value, four categories were recognised (see Fig 8 below). This categorisation could potentially help design researchers to better understand users' design modification behavior and designers to be more structured/intentional in their modification. For example, if high geometry change value is a goal, an automatic design assistant can nudge them towards that.

1. High *Δparam* & low *Δgeom*: Despite the high count in parametric changes, the geometry did not change significantly. It is possible that the design direction

was unclear, or it is intrinsic that the target design geometry does not vary much geometrically.

2. High *Δparam* & high *Δgeom*: High count of parametric changes (often signified by a mixture of adding, deleting, and changing component modification) and the geometry drastically changes as well. This typically happens when a new design direction is explored.
3. Low *Δparam* & low *Δgeom*: Only a few components change, typically this happens when a user wants to understand how geometry changes if a parameter attribute is modified.
4. Low *Δparam* & high *Δgeom*: Despite the lower count of parametric changes, the geometry changes drastically, revealing parametric 'surprises' (Woodbury, 2010), and thus, a potentially interesting design direction.

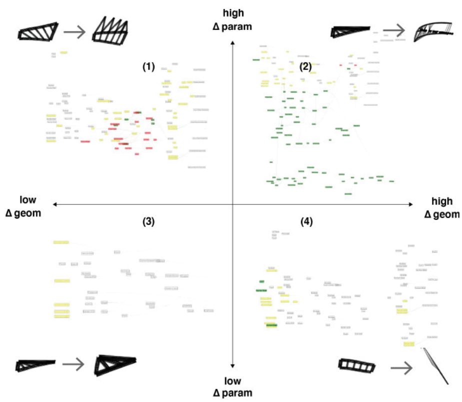


Figure 8. Four change clusters identified by Δparam and Δgeom.

5. Summary and Conclusion

In this paper, we have demonstrated how collaborative parametric design exploration process can be (1) captured through the practice of versioning and (2) interpreted through the proposed metrics. At the macro level, history tree-related metrics such as the number of nodes, branches, and depth of the tree are used as proxies to describe the design space explored in terms of its size, diversity, and development of ideas. At the micro-level, design change metrics for both parametric and geometry models were established to evaluate and categorise the modifications performed. For example, the change metrics were useful to see how some students are more versatile in their designs through the wider range of metrics extracted from their design versions. In the collaboration context, time appears to be a crucial factor: little difference was observed in the change metrics when one was modifying his/her personal design vs others' in the shorter given time. In contrast, larger and more complex parametric model modifications were observed with own models when longer time is allowed.

Finally, while in this paper we have started utilising data to develop metrics towards understanding the design process better, the availability of such design progression data opens the door to wider possibilities for digital and parametric design. In software engineering, where versioning was initially used, version data is also used to identify which programmers introduce more bugs (Kim et al., 2006). A similar approach can be used to determine which designers contribute significantly to design development. For example, in a pedagogy context, this can be used to support students who are lagging and support them. Data collected from multiple years can inform teachers of unique or perhaps shared struggles students face in learning parametric design. Additionally, as the field of architecture continues to adopt various AI technologies, we believe that capturing design process data can play a significant part in bridging the cognitive gap towards building autonomous AI design assistants.

References

Achten, H. and Beetz, J.: 2009, What happened to collaborative design?, *eCAADe*.

Brown, N.C. and Mueller, C.T.: 2019, Quantifying diversity in parametric design: a comparison of possible metrics., *AI EDAM*, **33**(1), 40-53.

Chollet, F.: 2015, “Keras” . Available from <https://github.com/fchollet/keras>.

Cignoni, P. and al, initials missing: 2008, “Meshlab: an open-source mesh processing tool” . Available from <https://github.com/cnr-isti-vclab/meshlab>.

Crilly, N.: 2015, Fixation and creativity in concept development: The attitudes and practices of expert designers., *Design Studies*, **38**, 54-91.

Cristie, V. and Joyce, S.C.: 2018, GHShot: 3D Design Versioning for Learning and Collaboration in the Web, *Extended Abstracts of the 2018 CHI Conference*.

Cristie, V. and Joyce, S.C.: 2019, ‘GHShot’: a collaborative and distributed visual version control for Grasshopper, *37th eCAADe and 23rd SIGraDi*.

Cross, N.: 2004, Expertise in design: an overview, *Design Studies*, **25**(5), 427-441.

Davis, D.: 2013, *Modelled on software engineering: Flexible parametric models in the practice of architecture*, Ph.D. Thesis, RMIT.

Dean, B.: 1915, An Explanatory Label for Helmets, *The Metropolitan Museum of Art Bulletin*, **10**(8), 173-177.

Eastman, C., Newstetter, W. and McCracken, M.: 2001, *Design knowing and learning: Cognition in design education*, Elsevier.

Globa, A.A., Donn, M. and Ulchitskiy, O.A.: 2016, Metrics for measuring complexity of geometric models, *Scientific visualization*, **8**, 74-82.

Kim, S., Zimmermann, T. and Whitehead, E.: 2006, Automatic Identification of Bug-Introducing Changes, *21st IEEE on Automated Software Engineering*.

Lawson, B.: 2006, *How designers think: The design process demystified*, Routledge.

Lloyd, S.P.: 1982, Least squares quantization in PCM, *Information Theory*, **28.2**, 129-137.

Meagher, M., Bielaczyc, K. and Huang, J.: 2005, OpenD: supporting parallel development of digital designs, *Proceedings of Designing for User eXperience*.

Myers, E.W.: 1986, AnO(ND) difference algorithm and its variations, *Algorithmica*, **1**, 251-266.

Sakai, Y. and Tsunoda, D.: 2015, Decentralized Version Control and Mass Collective Collaboration in design, *Proceedings of eCAADe 33*, 207-214.

Steele, B.: 2006, The AADRL: Design, Collaboration and Convergence., *AD*, **76**(5), 58-63.

Thorndike, R.L.: 1953, Who Belongs in the Family?, *Psychometrika*, **18**(4), 267-276.

Todd, S.P. and Latham, W.: 1992, *Evolutionary art and computers*, Academic Press, Inc..

Wenz, F. and Hirschberg, U.: 1997, Phase (x) Memetic Engineering for Architecture, *Proceedings of the 15th ECAADE Conference*, Vienna.

Wojtowicz, J.: 1995, *Virtual Design Studio*, Hong Kong University Press.

Yu, R., Gero, J. and Gu, N.: 2014, Cognitive effects of using parametric modeling by practicing architects: a preliminary study., *Proceedings of CAADRIA 2014*, 677-686.

CAPTURING INTERPRETATION SOURCES IN ARCHITECTURAL DESIGN BY OBSERVING SEQUENCES OF DESIGN ACTS

YU CAO[1], YUVAL KAHLON[2] and HARUYUKI FUJII[3]
[1,2,3]*Tokyo Institute of Technology, School of Environment and Society*
[1]*georgenamedcy1@gmail.com* [2,3]*{kahlon.y.aa|fujii.h.aa}@m.titech.ac.jp*

Abstract. Prototyping is important for design exploration. While various computer-aided conceptual design systems (CACD) aim to support this practice, they are somewhat limited in their ability to suggest interpretations in-context. To improve these systems, we need a better understanding of how designers interpret things when designing, and what factors influence this activity. We observe architectural designers' design process, and conducted a deep analysis of the activity at several levels, to capture interpretative events. The analysis of these reveals interesting patterns of design interpretation, which may be used to enhance future CACD systems.

Keywords. Design process; Design computing; Reinterpretation.

1. Introduction

Compared with CAD systems, prototyping in the early design stages (via sketching, using physical models etc.) consists of a dynamic communication between the design representation and the designer (Schon and Wiggins 1992). This communication, which can be seen as a 'seeing-moving-seeing' process, allows the designer many opportunities to reinterpret ambiguous forms and generate new ideas.

CACD systems, which target the early design stages, aim to support this practice. Specifically, systems focusing on interpretation can help designers in changing their perspective of the design, when designing (see for example, "The Creative Sketching Apprentice" by Karimi et al., 2019). However, current systems are limited in their ability to suggest interpretations based on the design situation.

Since design can be seen as a sequence of situated acts (Gero 1998), interpretations should not be discussed in isolation. In short, the situation affects our knowledge and view of the world (Kelly 2011), and thus our interpretations. Therefore, to enable computational systems to realistically support interpretation in conceptual design, it is important to understand interpretation in context. One important aspect is the following - how do past events affect the representation and interpretation of future designs?

This paper sheds some light on how designers get inspiration from past events, to interpret design representations based on the design situation. Designers

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 141-150.

generate interpretations by constructing representation of the artifact, and attributing a meaning to the artifact (Tversky et al., 2003). This can provide a new way of understanding and observing the design process.

The structure of this paper is as follows: we first introduce the relevant background regarding interpretation in design. Then, we describe our design task and its analysis. Next, we introduce results extracted from our analysis regarding interpretation. Finally, we discuss their implications with respect to CACD systems.

2. Background

2.1. INTERPRETATION IN DESIGN

Interpretation plays a central role in design (Goldschmidt 1988), for two main reasons: first, it is the bridge between reality and imagination (*figure 1*), shaping 'the way that the external world comes to be represented internally by a designer' (Kelly 2011, p21). Since design can be regarded as 'seeing-moving-seeing' process (Schon and Wiggins 1992), the two-way communication between designers and design representations depends on interpretation. Second, interpretation aids in design exploration, since design representations are ambiguous (Jowers and Earl 2014) - for example, a designer can give the same sketch many different meanings in different situations.

Figure 1. Interpretation is the way that the external world comes to be represented internally by a designer (based on Kelly 2011).

The process of generating interpretations can be divided into two parts: first designers reconstruct their mental representation of the artifact (perceptual reorganization), and then they attribute a meaning to a part of the artifact itself (Tversky et al., 2003).

We redefine these two steps with the help of the situated FBS ontology proposed by Gero and Kannengiesser (2004). Perceptual reorganization takes place on "structure" (the artifact's components) and the meaning assigned is often related to their "function" (purpose). Since in our study we focused more on low-level of observations to discover general phenomena of interpretation, so we did not include the notion of "behavior", which is a part of the above model.

2.2. ANALYZING DESIGN PROCESSES

Design can be seen as a sequence of situated acts (Gero 1998), so it is necessary to observe interpretation within design situation. Before analyzing specific interpretations, it is useful to visualize the entire design process, to see the big picture.

Linkography is a method for visualizing design processes, developed by Goldschmidt (2014). It shows the process as a series of events referred to as "design moves". A "linkograph" are is a graph constructed from design moves ('an act which transforms the design situation', Kan and Gero 2017, p24) and "links" ('the connection between moves using domain knowledge and common sense', Kan and Gero 2017, p25). Linkographs can serve two purposes in our work - helps in searching critical moves in the entire process, and find other moves which are related to these.

To form Linkographs, researchers use protocol analysis - a method that records the externalization of thoughts in real time. In this analysis, researchers transfer the data into transcript, then categorize the transcript using specific rules. Categorization enables a common language for identifying important patterns. Some protocol studies focus on design collaboration process. For example, Christensen and Ball (2016) have examined the effects of background knowledge on the ability to analogize in teams. In another world, Song et al. (2003) have found that teams with high semantic variation explored design solutions broadly. These have broadened our horizons when constructing our analysis method.

We list some shortcomings in existing analysis methods for observing interpretations in design processes. First, designers do not just communicate verbally, they also use design representations like sketches to express their ideas. Hence verbal and visual data cannot be discussed separately. Linkographs do not propose a clear way to integrate these. Second, because interpretation links the external and internal worlds (Kelly 2011), we need to distinguish between these, when analyzing interpretation. However, Linkography does not make this distinction, and therefore cannot account for the interaction between different worlds.

3. Method

3.1. APPROACH

To observe interpretation during a design process, we devised a design task, in the context of architectural design. We began by conducting an initial experiment, in which two designers were asked to co- design a building complex of a design office and residence (face-to-face). They were asked to come up with a complete set of floor plan sketches. We video recorded their conversations, and documented their sketches and notes.

In the initial experiment, we observed how designers assigned meaning to design representations, based on previous events in the course of design. We relied on Gero's original definition of "structure" (Gero and Kannengiesser 2004), and further defined it as visual representation including a shape or a group of shapes. Further, based on Gero's definition, we further identified a narrow definition of "function" - the purpose of architectural elements as a component of a structure in architectural design. A function could be specified using either an architectural element (for example, a door) that contained many sub-functions, or introduced verbally using phrases like 'through it we can see outside' (a general function).

By comparing the work done by the designers at the initial experiments, we found that the initial experiments lacked constraints, making the design process difficult to compare between different groups. Based on these initial findings, we have improved the experiment, as explained below.

3.2. DATA COLLECTION

First, we decided regarding the skill-level of the participants. We chose architectural design students who had at least a bachelor's degree in architecture, and in the age range of 22-30 years old, because they would have a shared expertise and an ability to use language and shape to express their ideas. To let the participants express their thoughts naturally, they were asked to work in pairs. The maximal duration for the task was 45 minutes. We conducted five sessions with the help of 10 participants (in 5 groups).

Second, due to the effects of COVID-19 the experiment could not be conducted face to face. However, we wanted to ensure that the participants from each team could communicate and design in real time. As a solution to this, we resolved to use Google Meet to have a voice call and Figma (a co-design platform) to share design in real time. The participants connected via their personal computer with a microphone in a stable internet environment. The entire design process, including the conversation was video recorded.

It is worth noting that such platforms, designers can only share their ideas through shapes and conversations. This is in contrast to face-to-face designing, where we can quickly show notes, sketches of relevant cases, and express ourselves in body-language, to convey our ideas - all of which facilitate smooth communication. On the other hand, using Figma allowed designers to focus more on the expression of ideas in form, which is important for this work.

Third, we revised the design task. The new task (*figure 2*) focused on designing a facade of an architectural office for three architects. Several design requirements, the surrounding buildings and the boundary of the site, were given as initial information. We chose the facade as the focus of our design task because it reduced the amount of work involved in drawing floor plans, but allowed the designers to design while imagining the entire building, its function and its relationship to its surroundings.

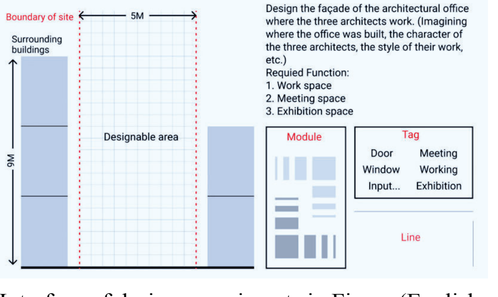


Figure 2. Interface of design experiments in Figma (English version).

To make the design more realistic and facilitate creativity, we started by asking the designers to imagine a specific site, the work styles of the three architects, etc. In order to control the complexity of the design and to ensure comparability, the designers had to complete the design by using a predefined set of modules. We provided the designers with four sizes of modules and presented them in two gray-scales and two orientations. The original modules did not have any meaning, and the designers could assign meaning to the modules freely during the session (however were not instructed on how to do so). The site was divided using a 10 x 21 grid, which constrained the location for placing modules. Finally, to observe and record architectural elements more clearly, we provided designers with editable tags and lines, for easy annotation.

3.3. DATA ANALYSIS

3.3.1. Analysis of design process

Each design session was timed at 45 minutes. We first converted the recorded conversation into a transcript. Phrases like 'Yeah', 'emm', 'I see', etc. which didn't have a clear meaning in the conversation were omitted. The transcript was segmented into design moves based on the number of acts and points raised by the designer in the recording, and links were created between the design moves based on the current topic mentioned in the conversation, and the current action performed in the video. Additionally, when seen as useful for getting further insight, we also drew a Linkograph.

3.3.2. Selection of episodes

We revisited five design sessions, and extracted critical episodes which were rich in interactions between designers and design representations. For considerations of understandability, we selected two examples from different degrees of complexity, which reveal some common findings.

3.3.3. Relating Structure and Function

To create a rich representation of the interactions in the episode, we divided the world into 'internal' and 'external' worlds (Gero and Kannengiesser 2004). Notice that we treated the two designers in each group as having a shared interpretation space. For clarification, we only use interpretation in a symbolic way. Therefore, when one designer proposes some interpretation and make his/her collaborator aware of it, we regard them as having a shared interpretation (which appears in the internal world). To present the interaction of design ideas over time, we added an additional category of 'previous'. We placed the events and relations in these three dimensions (*figure 3*).

We extracted the design moves in which meanings were assigned, and combined these with the current structure, as a basis for forming our diagrams.

In the external world there are 'structures' that represent design representations ['S(x)'], in the internal world there are 'architectural elements' that represent collections of functions ('E(x)') and 'functions' that represent a specific function ['F(x)']. Additionally, in the category of 'previous' there are 'previous events' that represent design requirements, past design moves and past experiences etc. ['(P(x)']. In all cases, x is a serial number assigned to these. We used lines to represent the relationships between these entities, and arrows to indicate the possible direction of causation. Each line was labeled with a number, indicating the order in which it occurred (identical numbers indicate simultaneous occurrence). When two related entities are in the same world, they were connected by solid lines; if not, they were connected by dashed lines. Finally, we took a screenshot of the designer's design process, and framed the part of the drawing that corresponds to the current structure.

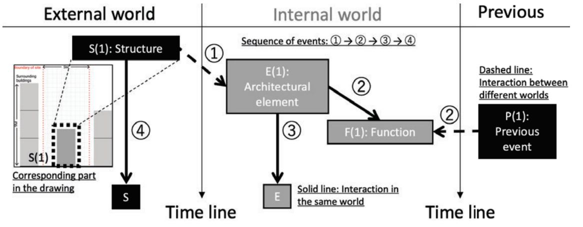


Figure 3. The way to read the diagrams with structure and function.

4. Result and discussion

4.1. EPISODE 1 - 'DESIGN FACTORY'

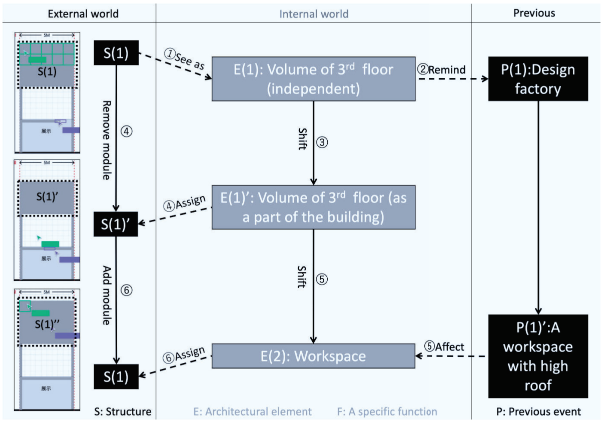


Figure 4. Sequence of events in episode 1.

The designer created S(1) by accident, when copying and pasting modules. Sequence of events: 1-The designer interpreted S(1) as the volume of the third floor E(1) and discussed the size of the volume independently; 2-The large volume of the third floor E(1) reminded the designer of a familiar place called 'design factory' P(1); 3-When the designer considered the third floor volume as part of the building E(1)', he found it was too large; 4-He reduced one layer of modules to create S(1)', and assigned E(1)' to S(1)'; 5-The designer said that the 'design factory' was a workspace with a high roof P(1)', and he thought it would be good to design the third floor to be a workspace E(2), with a high roof; 6-The designer added the removed modules back to create S(1) again and said that the third floor could be used as a workspace like the design factory, which has a high roof (*figure 4*).

Pattern 1-1 (*figure 5*): *structures and functions interact to produce new interpretations and structures*. The designer initially interpreted S(1) as the volume of the third floor E(1). However, when the designer saw the volume as part of the whole building E(1)‘, he felt that the volume was too large. So he removed some of the modules and transformed S(1) into S(1)’.

Pattern 1-2 (*figure 5*): *functions and past events interact to produce new interpretations*. The designer initially interpreted S(1) as the volume of the third floor E(1). The large size of S(1) reminded the designer of a place called ‘design factory’ P(1). The designer remembered the ‘design factory’ as a workspace with a high roof P(1)‘. This memory P(1)’ led the designer to reinterpret the volume of the third floor E(1)‘ as a workspace E(2), then the designer thought the original large volume S(1) was ideal and enlarged the S(1)’ back into S(1).

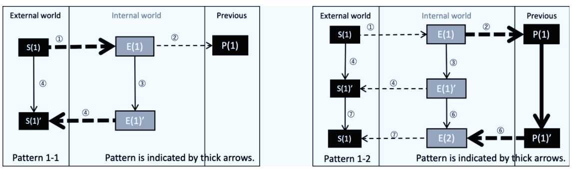


Figure 5. Patterns in episode 1.

4.2. EPISODE 2 - ‘ROOF FIELD’

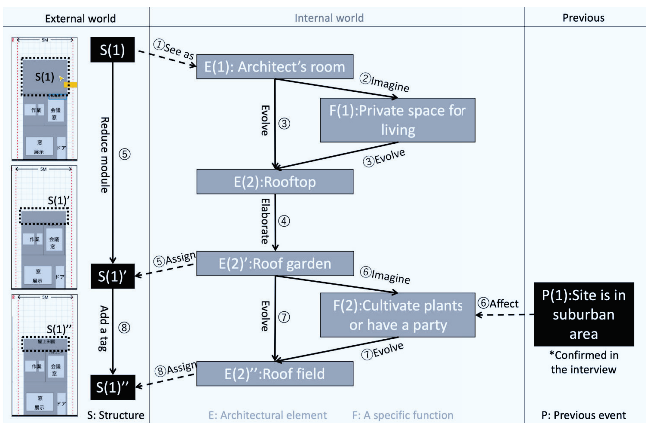


Figure 6. Sequence of events in episode 2.

Sequence of events (*figure 6*): 1-The designer discussed the use of S(1), suggesting that it could be used as the architect’s personal room E(1); 2-The designer began to imagine the specific functions for the architect’s personal room, thinking it could be a space for living F(1); 3-The designer suddenly felt that F(1) is not necessary, thereby suggestin that the third floor could be turned into a rooftop E(2); 4-The designer said the roof can be used as roof garden E(2)'; 5-The designer felt that the current S(1) was too large for a roof garden E(2)', so he removed some of the modules to create S(1)'; 6-While imagining the specific functions of a roof garden E(2)', the designer was inspired by the idea of a site in the suburbs P(1), and felt that cultivating plants and having a party F(2) on the roof would be more suitable for an idyllic landscape; 7-The designer felt that a 'roof field' E(2)" was more suitable for this building than the rooftop garden E(2)'; 8. The designer added a tag 'roof field' to create S(1)".

Pattern 2-1 (*figure 7*): *the combination of architectural elements and their specific functions lead to an innovative interpretation*. Based on the architect's personal room E(1), the designer imagined the specific function F(1) of the room, which led the designer to realize that a personal room E(1) was not necessary for the building, thus proposing a rooftop E(2) instead of personal room E(1).

Pattern 2-2 (*figure 7*): *past events may influence the formation of interpretations and help the designer to imagine a specific function*. The designer set the site in the suburb P(1), at the beginning. When he imagined the specific function of the roof garden E(2)', he felt that cultivating plants F(2) was more in line with the idyllic landscape of the suburb. And, *the combination of the architectural elements and their specific functions has lead to an innovative interpretation*. Under the combined influence of the roof garden E(2)' and cultivating plants F(2), the designer transformed the roof garden E(2)' into the 'roof field' E(2)''.

Pattern 2-3 (*figure 7*): *a new interpretation is based on past interpretation*. The designer initially designed a rooftop E(2), then elaborated it into the roof garden E(2)' which finally evolved into the 'roof field' E(2)". These three architectural elements are all about the roof and quite similar. This shows a possible tendency to keep previous interpretations and apply them to the new situation.

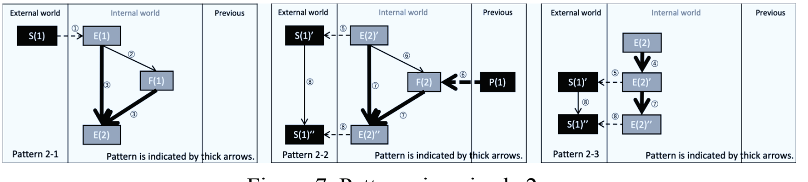


Figure 7. Patterns in episode 2.

4.3. DISCUSSION

Several findings arise from this study. First, we observed two fundamental interactions: one between structure and function (Pattern 1-1), and the other between function and past events (1-2), which are difficult to observe in Linkographs. This implies that our method can enhance inquiries into interpretation. Second, we found that the current structures and functions (2-1), and past events (2-2) are all possible sources of interpretation, and can individually or collectively influence the formation of interpretations. Third, based on the patterns we have found, we identified two main categories: patterns that apply original architectural elements to new situations (2-3), and patterns that combine architectural elements and their specific function to create new interpretations (2-1 and 2-2).

Finally, we have identified interesting relations with existing models for implementing human-like memory in computational design agents, such as the "constructive memory" (Gero and Fujii 2000), and specifically with the notions of "push" and "pull" from memory, proposed by Kelly and Gero (2015) as basic components for design agents. 'Push' refers to the act of remembering something via being affected by the environment (for example, I hear my pet cat calling which reminds me that I need to feed it) and 'pull' refers to intentionally remembering something (I try to recall the name of an old friend).

In our experiment, we observed the occurrence of both 'push' and 'pull' in interpretation. In episode 1, S(1) was created accidentally by the designer while copying and pasting the modules. This unexpected structure was interpreted by the designer as the volume of the third floor, 'pushing' the designer to remember a place called the 'Design Factory'. The way that the designer stopped designing and thought about the 'Design Factory' more deeply seems related with the idea of 'reflection-in-action' (Schön 2011), which is important for designing professionally. The moment of reflection allowed the designer to transform the 'Design Factory' into a workspace with a high roof, and had driven the designer to change the modified structure back to its original S(1), and interpret it as a workspace with a high roof.

In second-order cybernetics (Herr and Fischer, 2019), Stafford Beer (1972) proposed a five-layer model for organizational structure that balances survival demands in an environment, named the viable system model. We have identified interesting relations between our design episode and this model, specifically with respect to layers 4 and 5.

In episode 2, the designer suddenly felt that the space for living F(1) was not necessary, so that the original idea of an architect's personal room E(1) had lost its importance. However, the visual representation S(1), related to E(1), still existed in the external world, letting the designer create rooftop E(2) to replace E(1). This process corresponds with layer 4 (a system responding to the external world). In another example, the designer began by setting the site in the suburb P(1), and the idyllic landscape became one of the design themes. This drove the designer to expect to cultivate plants on the rooftop F(2), transforming the current roof garden E(2)' into the roof field E(2)". This process corresponds with layer 5 (a system dealing with internal policy decisions), considering that a theme can be seen as a loose policy in architectural design.

5. Conclusion & Future work

Nowadays, more and more efforts are made to build CACD systems that can flexibly and actively support designers, like the system by (Karimi et al., 2019). Such work is naturally expected to draw on research in design cognition (Ashok et al. 2012), towards understanding and modeling human design capabilities.

This study has proposed a method to systematically observe interpretations, by relating structures and functions, and demonstrated its use for extracting patterns of interpretation in designing. These can be used to deepen our understanding of interpretation in design. Furthermore, they provide a basis for discovering specific rules for implementing interpretative processes in CACD which engage in interpretation.

We now know of certain factors shaping interpretation, however the actual their interaction should be studied in depth. It is as if we have identified several of the unknowns in the equation, but have not clarified their coefficients. For future work, we aim to refine and generalize such patterns of interpretations, as we observe the process in greater detail. For example, we wanted to trace what kind of things reminded the designer of past events. Additionally, we intend to focus on key patterns, and search for more specific rules associated with them.

References

Ashok, G., Vattam, S., Wiltgen, B. and Helms, M.: 2012, Cognitive, collaborative, conceptual and creative - Four characteristics of the next generation of knowledge-based CAD systems: A study in biologically inspired design, *CAD Comput. Aided Des.*, **44**, 879–900.

Beer, S.: 1981, *Brain of the Firm*, Wiley.

Christensen, B. and Ball, L.: 2016, Creative analogy use in a heterogeneous design team: The pervasive role of background domain knowledge, *Design studies*, **46**, 38–58.

Gero, J.S.: 1998, Conceptual designing as a sequence of situated acts, *Artificial Intelligence in Structural Engineering*, **1454**, 165-177.

Gero, J.S. and Fujii, H.: 2000, A computational framework for concept formation for a situated design agent, *Knowledge-Based Systems*, **13**, 361-368.

Gero, J.S. and Kannengiesser, U.: 2004, The situated function–behaviour–structure framework, *Design Studies*, **25**, 373-391.

Goldschmidt, G.: 1988, Interpretation: its role in architectural designing, *Design Studies*, **9**, 235-245.

Goldschmidt, G.: 2014, *Linkography: Unfolding the Design Process*, MIT Press.

Herr, C.M. and Fischer, T.: 2019, Design Cybernetics and CAAD Research: Aspects of our shared interests, *Proceedings of CAADRIA 2019*, 541-550.

Jowers, I. and Earl, C.: 2014, Shape interpretation with design computing, *Design Computing and Cognition '12*, 343-360.

Kan, J.W.T. and Gero, J.S.: 2017, *Quantitative Methods for Studying Design Protocols*, Springer.

Karimi, P., Grace, K., Davis, N. and Maher, M.L.: 2019, Creative Sketching Apprentice: Supporting Conceptual Shifts in Sketch Ideation, *Design Computing and Cognition '18*, 721-738.

Kelly, N.: 2011, *Constructive interpretation in design thinking*, Ph.D. Thesis, The University of Sydney.

Kelly, N. and Gero, J.S.: 2015, Situated interpretation in computational creativity, *Knowledge-Based Systems*, **80**, 48-57.

Schön, D.A.: 2017, *The Reflective Practitioner: How Professionals Think in Action*, Routledge.

Schön, D.A. and Wiggins, G.: 1992, Kinds of seeing and their functions in designing, *Design studies*, **13**(2), 135-156.

Song, S., Dong, A. and Agogino, A.: 2003, Time Variation of Design 'Story Telling' in Engineering Design Teams, *Proc. Int. Conf. Eng. Des. (ICED 03)*.

Tversky, B., Suwa, M., Agrawala, M., Heiser, J., Stolte, C., Hanrahan, P., Phan, D., Klingner, J., Daniel, M.-P., Lee, P. and Haymaker, J. 2003, Sketches for Design and Design of Sketches, *in* U. Lindemann (ed.), *Human Behaviour in Design*, Springer, 79-86.

TOPOLOGY GENERATED NON-FUNGIBLE TOKENS

Blockchain as infrastructure for a circular economy in architectural design

THEODOROS DOUNAS[1], WASSIM JABI[2] and
DAVIDE LOMBARDI[3]
[1]*Robert Gordon University*
[1]*t.dounas@rgu.ac.uk*
[2]*Cardiff University*
[2]*Jabiw@cardiff.ac.uk*
[3]*Xian Jiaotong Liverpool University*
[3]*Davide.Lombardi@xjtlu.edu.cn*

Abstract. The paper presents a new digital infrastructure layer for buildings and architectural assets. The infrastructure layer consists of a combination of topology graphs secured on a decentralised ledger. The topology graphs organise non-fungible digital tokens which each represent and correspond to building components, and in the root of the graph to the building itself.The paper presents background research in the relationship of building representation in the form of graphs with topology, of both manifold and non manifold nature. In parallel we present and analyse the relationship between digital representation and physical manifestation of a building, and back again. Within the digital representations the paper analyses the securing and saving of information on decentralised ledger technologies (such as blockchain). We then present a simple sample of generating and registering a non-manifold topology graph on the Ethereum blockchain as an EC721 token, i.e. a digital object that is unique, all through the use of dynamo and python scripting connected with a smart contract on the Ethereum blockchain. Ownership of this token can then be transferred on the blockchain smart contracts. The paper concludes with a discussion of the possibilities that this integration brings in terms of material passports and a circular economy and smart contracts as an infrastructure for whole-lifecycle BIM and digitally encapsulates of value in architectural designPlease write your abstract here by clicking this paragraph.

Keywords. Blockchain; Tokenisation; Topology; Circular Economy; decentralisation.

1. Introduction

Building information Modelling has been presented as a whole-lifecycle paradigm that encompasses all aspects of the life of a building asset, from conception, to design to construction and then operations. While there has been massive progress

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 151-160.

in the past twenty years in terms of the information that is digitally available to architects and designers, to optimise building design and construction, the impact of the existing problems has been accentuated: building waste (Adams 2017), the impact of the embodied carbon in built environment on climate (Anderson 2014) and the need for integration of digital and physical systems in architectural design (Dounas et al, 2020). Building Information Modelling platforms have the tendency to have a high computational footprint, further increasing complexity within the information space that an architect needs to navigate and process (Aish 2018). However recent examples of lightweight, modular, computational design processes provide an alternative view towards reducing the information complexity needed in architectural design, in a computational paradigm that resembles the Unix tools chain set.

2. Background

2.1. TOPOLOGY, GRAPHS AND TOPOLOGIC

Central to the idea of relational architectural representation is the idea of topology. Within that one distinguishes between manifold topology (Kantor 2005) and non-manifold topology (AIsh et al 2018). Within the birth of topology by Euler, when he asked whether a person could cross all bridges of today's Kaliningrad by crossing each bridge only once, lies the elegance of topological representation: one uses topology to represent an object, economically. Libraries for Non-Manifold topology, such as Topologic, (Jabi 2019) allow the connection of topology with energy or structural simulations, massively reducing the computational footprint and complexity of the building representation. At the core of the Topologic idea lies the notion that "Buildings enclose and partition space and are built from assemblies of connected components" (Aish et al 2018). For each cell in a building, one can generate a non-manifold topology where a cell is analysed into 12 edges, 6 planes of 4 walls and 2 horizontal planes, plus at least one opening. [Figure 1]

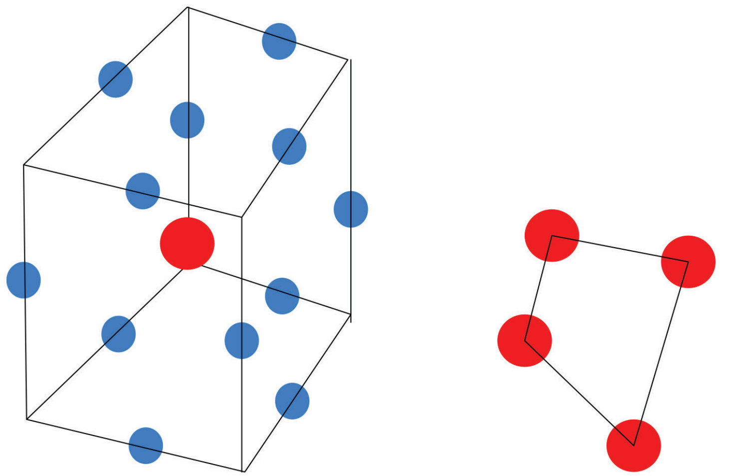


Figure 1. Figure 1: Topological representation of a cell complex- each blues dot represents a cell face or edge, while the red dot represents the cell. The four dots represent then a cell-complex of four cells.

2.2. BLOCKCHAIN, SMART CONTRACT AND TOKENS

Distributed ledgers are essentially distributed databases where participants in the database hold copies of it and there is a mechanism to synchronise and achieve consensus between these copies. The difficulty to achieve consensus in a decentralised ledger is due to the possibility that at least two copies of the ledger might have values that are different added to it. Consensus mechanisms follow in many cases scenarios of the "byzantine Generals problem" (Nakamoto 2009). Blockchains are a special version of distributed ledgers which got initially invented to facilitate the idea behind digital cash in Bitcoin (Nakamoto 2009). Inspired by the Bitcoin blockchain, where the blockchain operates additions and subtractions, A subset of bitcoin programmers created the Ethereum blockchain which acts as a decentralised, global, distributed computing platform capable of any Turing Complete computation.

A blockchain is a decentralised database, where multiple nodes on a computer network hold part of the data or the full data set. Due to its decentralised and distributed nature, Blockchains require a mechanism to synchronise the nodes, and have a single version of the data emerge. Thus algorithmic measures have been implemented that are based on difficult to solve cryptographic problems, or in a collective signing of the next version of the data using again difficult to tamper with cryptography. He former consensus mechanism is called Proof of Work, since the miners, i.e the validators of the data solve and algorithm, while the latter Proof of Stake since the validators signing the data “stake” an amount of cryptocurrencies as incentive for participation. After validation of the chain, a new block is “minted”, I.e created, which is cryptographically connected with the previous block, as each new block contains a cryptographic hash of the previous one. This ensures that no single node can re-edit the data contained in the transactions but also incentivises the network participants to strive for truth, as each true block minted is rewarded with new cryptocurrency. Beyond tallying cryotcurrencies transactions blockchains can also automatically execute pieces of code called “smart contracts” and it is this feature that makes blockchains compelling in a design and computation context.Our main implementation is based on the Ethereum blockchain [Antonopoulos 2018] because it offers currently various advantages: it has a full toolset to develop smart contracts on, excellent tooling for developers, and full features for the user interfaces tools, where one can write code in javascript frameworks or on python, taking advantage of the respective libraries. From a computational design point of view, we use the Ethereum blockchain as a state machine, i.e a Turing complete machine that allows external input to alter its state. As such, with the feature of smart contracts it is perfectly possible to record and execute code on the Ethereum blockchain, either using python, or the native, purpose built language of Ethereum, solidity. Beyond the hype, reports have described the potential of Blockchain (Cooper 2018) to profoundly affect the digital infrastructure (Kinnaird et al 2017) that runs the build environment but also the digital tools that we currently use to design architecture. Ethereum smart contracts are essentially the equivalent of classes of code that execute specific functions. They are inheritable, can act as factories or libraries for other contracts, and normally one would need a collection of smart contracts to build complex software constructs. Each contract resides in a distinct Ethereum address and is addressable by sending a transaction to that address, with or without invoking a specific function of the contract.

With the use of Smart contracts and the immutability of the blockchain, the creation of digital currency in the form of digital tokens is possible, for example by using the ERC20 standard on Ethereum (Vogelsteller et al. 2015). In parallel, the creation of distinguishable, non-funglible, unique tokens, is possible as well by using the ERC721 standard (Entriken et al. 2018). We present both token standards so that the distinctiveness and uniqueness of ERC721 can be made clear to the reader.

2.2.1. ERC20

ERC20 tokens issued by a smart contract can be interchangeable between them, in the same manner that currency has: An ERC20 Token of type A is equal and indistinguishable with another Token A, and there is no manner in which one can distinguish on the blochchain betwn ERC20 tokens of the same type. The Ethereum foundation that governs the standards for the Ethereum blockchain, has defined three optional and six mandatory rules that ERC -20 tokens should follow so they can adhere to the standard. The optional are the Token name, Symbol, and allowing for decimal subdivision, up to 18 decimal places. The mandatory rules are:

1. The “totalSupply” i.e the designer of the token has to define how many tokens all together will exist and this has to be a finite number.
2. The “BalanceOf” records how many tokens an account has
3. The “Transfer” allows for the transfer of the token
4. The “TransferFrom” records the initialling account
5. The “Approve” cross-checks a transaction against the total number of tokens recorded in the blockchain
6. The allowance checks the balance of an account before a transaction takes place and will cancel a transaction before it takes place

2.2.2. ERC721

ERC721 Tokens are the non-fungible tokens (NFT) that are encapsulated inside a smart contract. Non-Fungible means that one token is not exchangeable with another. Within a smart contract ERC721 are represented using “structs”, a computational entity that can contain a series of other properties in the form of variables. The ERC721 specification itself describes that one of the potential uses of the standard is the representation of physical objects, such as houses or unique artwork, where one ETH address on the blockchain network has ownership of the token, including the potential for an ERC721 token to be owned by a contract. ERC721 use a unique numerical identifier in the form of an unsigned integer. The combination of the contract address and the unique identifier (ETH Address, uint) stands for a global identifier for the token, as ETH addresses are also unique. Key property of the ERC721 is that it is transferable (Openzeppelin 2020).

3. Topology and ERC721: Implementation.

Within our computational analysis, we use a series of encapsulated graphs to represent buildings, using the topology library topologic.app. Each node in the root graph corresponds to a space in an existing building or a building under design. The second layer of graphs stems the initial graph, and in a series of layers and connections of nodes to components of the building, represent in graph form the whole ontology of the building. Consequently a series of tokens that represent the nodes to the graph get created on a contract we control on the Ethereum Blockchain. While tokens that represent building components can be interchangeable, the tokens that represent unique nodes in the building, and the root of the graph, are non-fungible, and unique, i.e. not interchangeable. [Figure 2]

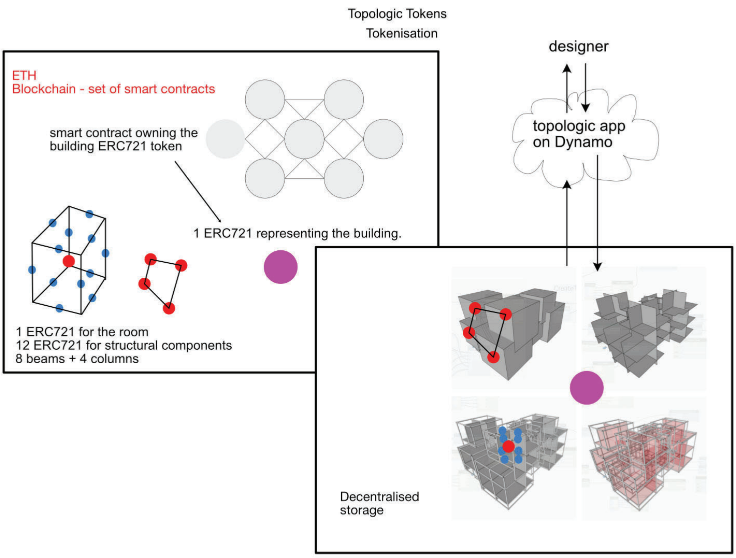


Figure 2. Figure 2 : Conceptual representation of the Topologic Token prototype.

Our prototype implementation involves executing a simple topologic definition in Dynamo that generates a cell complex of nine cubes, side-10, and then topologically analysing each of the cells into the faces and edges that comprise the cell. [Figure 3]

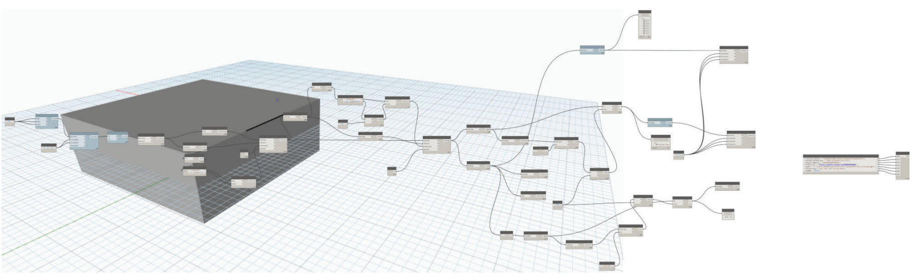


Figure 3. Figure 3: Generating a 9-cell complex on dynamo using topologic-analysing the cell into edges.

We then upload the topology definition on the interplanetary filesystem, a decentralised file repository that is used in decentralised applications, since saving whole files on the blockchain is both difficult but also computationally expensive to the point that it becomes impractical. Files on IPFS are connected with a cryptographic hash generated by the SHA256 algorithm. This hash is a unique representation each file stored on the IPFS storage. By uploading the dynamo definition on IPFS it is assigned thus a unique hash, based on the nature of the file.We then upload the topology definition on the interplanetary filesystem, a decentralised file repository that is used in decentralised applications, since saving whole files on the blockchain is both difficult but also computationally expensive to the point that it becomes impractical. Files on IPFS are connected with a cryptographic hash generated by the SHA256 algorithm. This hash is a unique representation each file stored on the IPFS storage. On the Ethereum Ropsten Test network we have deployed a Token Minting contract. The tokens generated have beyond their unique number, the following variables: a hash in the form of a string, a price and an address that owns the token. [smart contract code]

```
  uint256 public _tokenIds;
  uint256 public _buildingItemIds;
  mapping (uint256 => buildingItem) private _buildingItems;


///@dev: creating the buildingItem as a struct, toeknURI is the IPFS URI
  struct buildingItem {
    address seller;
    uint256 price;
    string tokenURI;
    bool exists;
  }
```

To connect the Dynamo software to the Ethereum blockchain we use an intermediary library written in Python, Web3.py and a script that essentially writes the hash to the smart contract. We confirm through the remix.ethereum.org interface that the IPFS hash of the topologic dynamo definition has been minted into a token in our contract. [Figure 4]

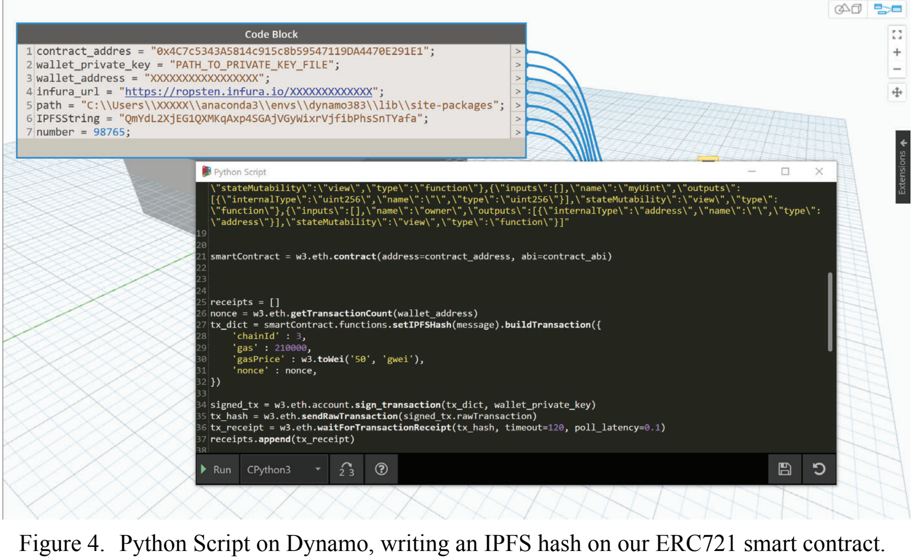


Figure 4. Python Script on Dynamo, writing an IPFS hash on our ERC721 smart contract.

Thus, we are able to encapsulate a topological representation of a building unto a unique non-fungible ERC721 token. This allows a bidirectional connection between topological representation of buildings on dynamo and smart contracts on the blockchain.

4. Computational Design Scenarios in Architecture using NFTs -opportunities and constraints

The NFT representation of building components and their topological interdependence using Topologic opens a variety of avenues for architectural design. On a new building "A", the design of the building will be already represented on the blockchain, along with the topologic interdependence of the components. This creates immediately the possibility for collective ownership of the building, by multiple addresses on the Ethereum blockchain. It also creates the first step for the creation of a circular economy of components, as a future designer that requires to re-cycle the building will have at her disposal, the full, immutable record of all components, and their topological interrelationship. Furthermore, if our technique is extended to include existing buildings, the token representation can be used to use buildings as material banks in a circular economy, with the blockchain providing the data provenance layer, i.e the designer can query the blockchain for components needed for her design. In terms of operations the token representation on the blockchain can be used both as a digital twin but also as an asset that funds decentralised finance applications. While our prototype currently is basic and simple we are working on creating templates and scripts for designers that will allow the tokenisation of their building designs in an easy manner. In parallel we believe that the creation of smart contract NFTs for architecture will contribute to jumpstarting the creation of a creative economy for architecture with blockchain(s) as infrastructure, where designers will be able to have better control of their intellectual property, but also where new methods of procurement will foster innovation in design. For this to happen, we would need better tools for connecting designs to the blockchain, the establishment of certain blockchains as the optimum infrastructures for design, and adoption of our tools by a number of architects.

5. Discussion & Future Possibilities

The work we present conceptually and practically connects non-fungible digital artefacts on a blockchain with the topological representation of physical buildings, where the non-manifold topology of the building is key to the generation of the non-fungible token. Within the Blockchain and the smart contracts universe, this NFT is unique, and an address account can own it. This is the equivalent of legal ownership of an artefact. Through a careful orchestration of the equivalence the smart contract to legal contracts, the digital representations that architects use achieve a unique function: the representation is the building and the building is the representation. This analogy opens a wide variety of applications including value management and the creation of a digital economy, where optimisation of structure, embodied carbon, energy, material and real estate management have direct currency on blockchain and decentralised ledger technologies. For example, ownership of a NFT could be used as legal proof of ownership of a building, or within the architectural design, of a particular design solution. One can imagine global smart contracts that act as registries of ownership of buildings, where complex transactions are simplified by simple transfer of ERC721 tokens between accounts on the Ethereum blockchain.

Within our prototype we only have tokenised a topology file, however each building component of a topology dynamo definition can be an ERC721 token. This greatly reduces the computational burden and complexity of establishing material passports for their use in circular economy applications of the built environment, and simultaneously provides an elegant and immutable manner of transferring and tracking ownership of building components. One easy extensibility of the system is the addition of various other variables that define the material properties of a component uniquely identified on the topology of the building. This directly solves the problem of the provenance of information in circular economies (Debacker et al. 2017) by directly storing information about a building component, creating trust within the value network through the blockchain, by providing transparent and traceable information, and augmenting potential further applications where the value of a component can further by monetised by financial applications on the Ethereum blockchain. A further potential application of our bi-directional prototype is the provenance of information on digital twins. On can construct digital twins directly on the blockchain securing the operational maintenance of building components and the informational provenance of such operation and maintenance. Thus our cryptographically secured mechanism allows the generation of a representation of a building component, and the management of its lifecycle from birth to end of life, including all phase of the lifecycle of a building, from concept to decommission. We believe that our prototype is significant in the sense that provides a two-way, unique, safe, accurate manner of translating between physical and digital environments, where information is validated, and additionally creates the infrastructure to allow a decentralised management of the built environment. It is original in advancing the state of the art of blockchain in construction, providing for the first time a manner to align physical assets with digital assets in a manner which is unique and singular. The methods and prototypes are developed rigorously, stemming from already well-established practices, within a sociotechnical framework that responds to challenges of the fourth industrial revolution.

References

"Platform for Smart contract development and validation" : 2020. Available from <www.remix.ethereum.org> (accessed December 2020).

"Smart Contract Address on the Ethereum Ropsten TestNetwork:" : 2020. Available from <0x4C7c5343A5814c915c8b59547119DA4470E291E1> (accessed created and accessed December 2020).

"OpenZeppelin (2020), ERC721 contract template implementation" : 2020. Available from <https://docs.openzeppelin.com/contracts/2.x/erc721> (accessed December 2020).

Adams, T.K., Thorpe, T., Osmani, M. and Thornback, J.C.P.: 2017, Circular Economy in construction: Current awareness, challenges, enablers, *Proceedings for the institution of*

civil engineers, waste and resource management, vol. 170, 15-24.
Aish, R., Jabi, W., Lannon, S., Wardhana, N. and Chatzivasileiadi, A.: 2018, Topologic: tools to explore architectural topology, *Advances in Architectural Geometry*, Chalmers University of Technology, Gothenburg, Sweden, 22-25.
Antonopoulos, A. and Wood, G.: 2018, *Mastering Ethereum*, O Reilly Media Inc, Sebastopol .
Cooper, H.: 2018, Blockchain Feasibility and opportunity assessment, *BRE report prepared for the BRE trust*, London.
Debacker, W., Manshoven, S., Peters, M., Ribeiro, A. and Weerdt, Y.: 2017, Circular economy and design for change within the built environment: preparing the transition, *International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste*, Delft, The Netherlands.
Dounas, T.: 2020, "Contract Deployment on Etherscan" . Available from <https://ropsten.etherscan.io/tx/0x6b9ffa539b59314b425f444f6933c47dc4be98f6924b52ffc62aff9b4b0f6efc> (accessed December 2020).
Dounas, T., Lombardi, D. and Jabi, W.: 2020, Framework for decentralised architectural design BIM and Blockchain integration, *Journal of Architectural Computing*, **Architecture in the Age of Fourth Industrial revolution vol. II**(https://doi.org/10.1177%2F1478077120963376).
Entriken, W., Shirley, D., Evans, J. and Sachs, N.: 2018, ERC-721 Non-Fungible Token Standard,, *Ethereum Improvement Proposals*, accessed Dec 2020: https://github.com/ethereum/EIPs/blob/master/EIPS/eip-721.md.
Jabi, W. and Chatzivasileiadi, A.: 2020, Topologic: exploring spatial reasoning through geometry, topology, and semantics., *Presented at: 5th International Symposium Formal Methods in Architecture (5FMA)*, Lisbon, Portugal.
Kinnaird, C., Geipel, M. and Bew, M.: 2017, Blockchain Technology, How the Inventions Behind Bitcoin are Enabling a Network of Trust for the Built Environment, *Arup Report*, London.
Vogelsteller, F. and Butterin, V.: 2015, ERC20: A standard Interface for Tokens., *EIP: Ethereum Improvement Proposals*, Accessed Dec 2020: https://github.com/ethereum/EIPs/blob/master/EIPS/eip-20.md.

Virtual/Augmented/Mixed/ Interactive Environments, Human-computer Interaction

DESIGNING FOR HUMAN-VR INTERACTION

How VR interaction can be designed to bring better design participation

XUANNING QI[1], TIAN TIAN LO[2] and YUNSONG HAN[3]

[1,3]*School of Architecture, Harbin Institute of Technology, Harbin, China; Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, Harbin, China*

[1,3]*{michelle|hanyunsong}@hit.edu.cn*

[2]*Harbin Institute of Technology (Shenzhen)*

[2]*skyduo@gmail.com*

Abstract. The research in human-computer interaction (HCI) has been ongoing for years until present-day to observe how humans interact with computers and digital technologies. Then comes the development of virtual reality (VR), one where it allows users to be immersed in the virtual environment for various kinds of experiences. This paper takes a close reference to the research method in HCI and brings the examination to the context of VR to understand the user behavior towards human-VR interaction (HVRI). A workshop is done based on the new HVRI method, and students are given the task to explore what are the elements of architecture that can be interacted and how they can be performed in the immersive environment. This paper will describe the HVRI designed and analyze how the new interaction method helps to bring about closer relationships between the human and the virtual model beyond just visualization.

Keywords. VR; Interaction; Design Participation; HVRI; Design Studio.

1. INTRODUCTION

The arrival of the artificial intelligence has brought new possibilities for human-computer interaction design. Before *AutoCAD* appeared in 1942, architects needed to use a pencil and rubber to draw design plans in drawing paper. The whole process costs a lot of human resources and material resources. In 1950, the gradual rise of Computer-Aided Design (CAD) made the architectural design transition from paper and pen drawing design stage to computer drawing design stage. Since then, architects have gradually got rid of the shackles of paper, pen, and board on scheme design, and presented their design ideas to the world through computer graphics(Lo and Gao 2020). Although the two-dimensional drawing method can accurately express the architect's design idea, in the era of the rapid development of information technology, this method has been unable to

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 163-172.

meet the needs of the architect for the presentation of the scheme. The emergence of three-dimensional (3D) modeling technology provides architects with a better visual effect of space. However, since 3D design software is usually based on the interaction of plane, pen, computer screen and multiple interfaces of the model, users can not fully understand the spatial scale of the model only through the computer screen or software interface. In addition, converting a two-dimensional solution design into a three-dimensional space design is a relatively complicated operation process. The designer needs to perform corresponding operations according to the requirements of the software system, which affects the expression of the designer's creative thinking (Dorta, Kinayoglu and Hoffmann 2016). However, the architect needs to evaluate the architectural scheme in the space in order to get a more accurate evaluation. Therefore, virtual reality technology has gradually entered the vision of architects.

In the Virtual Simulation Laboratory of Strathclyde University in Scotland, Maver et al. realized the immersion of the scene by projecting images on the curved screen to achieve the simulation of the remote environment, dangerous environment, and nonexistent environment (Maver, Harrison and Grant 2001). Although this kind of equipment can bring real experience effect to the experimenter, it is not ideal because of its huge size, complicated operation, and human-computer interaction. Schnabel et al. used a Hybrid Virtual Environment 3D (HYVE-3D) system to restore and present the environment of narrow alleys in Kashgar (Schnabel et al. 2016). This practice not only provides a new situation for the spread of historical heritage buildings but also achieves a breakthrough in the process of immersive collaborative 3D sketch drawing. Lo and Schnabel discussed how students can make full use of software and virtual display devices in the process of architectural design to achieve a breakthrough in architecture teaching methods (Lo and Schnabel 2018). Virtual reality devices can provide users with a visual operation platform through real-time interaction. Users experience the spatial scale through virtual reality devices, increasing the feasibility of human-VR interaction (HVRI).In this paper, the application of HVRI in the field of architectural design will be studied. By analyzing the design process of each group of students in the workshop, we explore how this new interaction method can help make the relationship between people and virtual models closer within the immersive environment. The results of the study will provide a new scheme design process for the field of architectural design.

2. FROM HCI TO HVRI

In the 1980s, the concept of model human processor was proposed, which gradually opened the prelude to human-computer interaction methods. Although interaction is only a simple process of information transmission, there are many ways of information transmission (Dix, Finlay and Abowd 1998). The application of human-computer interaction in the field of architectural design starts from the use of CAD by architects, but it is gradually optimized and updated with the continuous development of virtual reality technology. Dorta et al. used hybrid virtual environment 3D technology to operate 3D cursors and used digital board to sketch on hand-held tablet computers, so that the experiencer can experience the concept scheme directly in the immersive display (Dorta, Kinayoglu and Hoffmann 2016). By studying the application of virtual reality technology in architectural education, Sorguç et al. put forward the concept of virtual learning environments (VLE), and proved that this kind of education can help improve students' cognition of spatial relationship and creativity (Sorguç et al. 2017).

In recent years, due to the extensive use of scientific research, virtual reality technology has developed rapidly in software and hardware. According to the different moving range, the HMDs can be divided into mobile head-mounted displays and stationary head-mounted displays. In general, the mobile HMD is realized by adding a smartphone which can process the display information into the spectacle bracket. The technology of stationary HMD is similar to the smartphone, which combines the external environment information recorded by sensors with optical tracking technology. HTC Vive and Oculus Rift two typical stationary HMDs. HTC Vive has a similar display effect with Oculus Rift, but HTC Vive can provide an interactive experience with different room sizes. Wearing a head-mounted display can completely isolate the user from the real world (Lindeman et al. 2004).

The traditional HCI process is the user's interactive application with the virtual equipment in the real environment, and the real world has strong interference to the interactive process. Restricted by the external environment conditions, the tester can only complete the relevant activities in the virtual environment through the controllers, tracking positioner and other control equipment. HVRI is the process of immersive simulation interaction, which places the tester in the virtual environment, without the interference of the real environment and space restrictions, and can provide users with more real scene experience. HVRI method can not only use the controllers handle and other devices, but also complete the scene interaction process through the gesture tracking or posture capture(Lo and Gao 2020).

This workshop provides the desktop holographic projection equipment for students. In the dark test environment, 3D images can be regarded as the interaction activities in the virtual environment. By examining various types of VR equipment and how its system could assist the design process, this research will study the various aspect of the interaction method; from the presentation of the building information to the comfort level of using the equipment to the degree of design collaboration among users. This paper will then introduce a new interaction method between the human and the virtual reality that can push beyond the current design capabilities within the immersive environment.

3. THE WORKSHOP

A design workshop is held to explore how VR interactions can be designed for better virtual engagement (Figure 1a). Based on computational design methods and virtual reality technology, this workshop was organized to help students understand the application of VR interaction design in the field of design. It is one of the 'computational design 2019' series activities held by the computational design committee of the Chinese Architectural Society. There are nineteen student participants with one workshop instructor who is also the principal researcher for this paper and a technical workshop assistant to aid with any technical problems. These nineteen students are from the first-year undergraduate to the second-year graduate students majoring in architecture, urban planning, landscape, or visual communication design. The students are evenly divided into three groups, each with a different year and study major to balance the group in terms of experiences and their knowledge and all students can complete basic design modeling.

During the workshop, each group of students was asked to explore how architects can VR to design the scheme. They are also introduced to an AEC software call *Fuzor*. *Fuzor* is a virtual reality interactive platform that can realize real-time and bidirectional synchronization with *Revit*, *AutoCAD* and other modeling software. Through its own 3D game engine, *Fuzor* can realize the real-time rendering of the model and the real-time VR scene experience, and can support multiple people to work together in the cloud server. Ample time was given to the students to discuss among their members in the groups to design the simulated scenarios. They were free to create or choose existing simulated scenarios. A digital model is generated using their familiar 3D modeling software, which they will then import into *Fuzor* to insert their desired HVRI. During the process, they aim to achieve the goal of human-computer interaction in the virtual environment and explore the problem in presenting their design through interaction practice. They also observed if such architecture details can be easily understood by laypersons through their designed interaction. In the whole design process, a series of VR equipment are provided for students to explore the availability of HRVI, such as HTC Vive, Table-top VR projection, and other controller devices such as gamepad and *leapmotion* (Figure 1b).

(a) (b)

Figure 1. (a)Task arrangement and software training; (b)Demonstration of different human-computer interaction practice.

4. EXPLORATORY RESULTS

4.1. GROUP 1: GAMIFIED ENVIRONMENT

The first group of students took the game "Monument Valley" as the design prototype to build a gamified interactive scene (Figure 2). Firstly, they designed a background based on their interests: in a quiet night, a little boy has to overcome many difficulties to climb to the top of the lighthouse and obtain the key to the future. Secondly, they used *SketchUp* to create a basic model of the whole scene. In the process of modeling, they not only considered the unique properties of geometric shapes such as cubes and cones, but also adopted parametric modeling to improve the accuracy and complexity of the scene model. Finally, they carried out the creation of simulation scene special effects, audio, and video import and interactivity test in the *Fuzor* platform.

In order to make the whole game scene more vivid, they added a rotation mechanism in the scene. When the tester approached, the mechanism would be triggered, the geometry obstructing the path would rotate, and then the stairs would appear in front of him. In the stage of scene improvement, team members have tested in virtual reality scenes many times to explore the experience of different trigger mechanisms in response to distance and rotation speed of the obstruction. In addition, they also tried to add scene animation effects and model elements to enhance the fun of the tour process. They selected scene elements by actions and gestures of the testers when they first entered the immersive scene and combined with participants' subjective feedback. In the end, they decided to introduce water and cave elements into the scene.

In the actual operation process, how to make the scene vivid and interesting and let the participants successfully complete the whole process is the main difficulty they face. Therefore, they tried to give the scene a vivid story background and introduce the corresponding background music and special effect sound in different scenes. In the course of HVRI testing, they found that although the testers can successfully complete all the hurdles, due to the interference of the surrounding environment and the narrow size of the moving path, the testers cannot quickly and accurately determine the moving path. Therefore, during the post-debugging process, they optimized the spatial proportion of the scene and added prompt information to assist the passers-by to complete the game. In the process of the experiment, some members were responsible for observing the behavior activities of the experimenter. They took the expression and language feedback of the experimenter in different scenes as the criteria to evaluate the quality of the scene design. If the scene design was successful, when the scene passed through dangerous stimulation, the experimenter would scream or the body would produce defensive action, and vice versa. They took the feedback of the behavior and expression of the tester as the focus of interaction design research, explored the action and expression feedback of the tester in the game scene, and hoped to use it as the basis of HVRI in architectural design, and provided the evaluation basis of subjective feedback for the designer. It can be seen that HVRI method can be implemented in an immersive interactive scene, combining the physical activities of participants in the virtual scene and subjective feedback results to improve the construction of the architectural space scene.

Figure 2. Design process and outcome by Group One.

4.2. GROUP 2: SMART ENVIRONMENT

The second group of students had an in-depth discussion on the construction of the indoor scene of the building, and tried to introduce their idea of the interior design, and try to realized it in this workshop (Figure 3). Firstly, they choose to design a smart environment in the small villa building, and construct the typical scene. In *SketchUp* platform, the existing building model was refined, and tables, chairs, sofas and other indoor furniture were introduced. They also considered the outdoor landscape, adding outdoor fountains, flower beds, lawns and other architectural sketches. Then, they imported the completed building model into the *Fuzor* software simulation platform, and design the scene animation. The music effect corresponding to the instrument was added in the piano room, and a series of triggering actions were set. When the reader came to the piano room, clicked on the instrument, the indoor light and music could be turned on at the same time. Finally, the scene was optimized in the virtual reality device. In order to let visitors fully understand the overall situation of the building, they also designed the outdoor environment of the whole building according to the changes of the four seasons of the year. When observing the night effect of the building, they found that the experience effect of the building was very different from the real environment, so they added the trigger switch of the indoor light.

This group of students explored the application of virtual reality technology in the interior space design of buildings by using the HVRI method. Due to the participation of students majoring in visual communication design, the scheme of this group was more inclined to scene design and display. Therefore, how to let the experimenter quickly understand the design of the whole interior scene and attract their attention was the main difficulty they face. They chose to add scene sound effects and trigger sound effects in special scenes to gradually bring users into the scene through the sound environment.

In the process of HVRI method pre-test, they found that a single outdoor environment could not accurately express the lighting changes of indoor space. Therefore, during the later debugging process, they added the outdoor environment of rain and snow, day and dark days, and the experimenter could automatically switch to different weather as required. This group of students used the form of questionnaire feedback to evaluate the interior space design. After completing the whole scene experience, the tester would fill in the questionnaire according to his real experience results. The questionnaire includes four aspects: spatial layout, spatial color, interior furnishing layout and outdoor landscape layout. They hope to explore the subjective feedback of the tester in the virtual reality scene to the indoor and outdoor space according to the simple architectural space layout, and provide theoretical support for the site experience of the complex architectural space in the future.

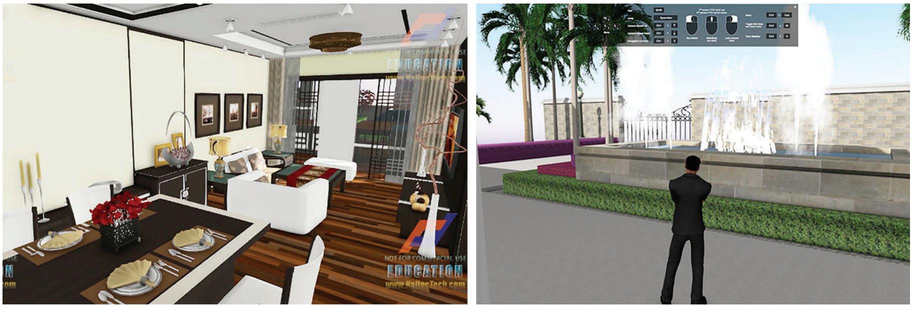


Figure 3. Design process and outcome by Group Two.

4.3. GROUP 3: OPEN-CHOICE ENVIRONMENT

The third group of students used virtual reality technology to explore the interior layout of the existing building space and how they can allow user participation to design the space to state their needs (Figure 4). Firstly, they used rhino parametric modeling method to build the spatial model of the office area. In the process of modeling, they try to restore the characteristics of building space as accurately as possible. They then imported the model into *Fuzor* and added scene special effects in the room. When approaching the glass door, through the interface prompt, the experiencer can click the trigger button to enter the room. When the experiencer approaches the model display rack, the display model will generate corresponding action special effects and play related introduction content. At the same time, an introductory video of the office area will be scrolled on the display in the conference area. Finally, they designed a scene that allows the experiencer to arrange the building space to focus on the purpose of human-computer interaction.

With the help of the *Fuzor* platform, the tester can arrange the interior furniture according to his ideal office space, making the tester not only the visitor of the environment but also the designer of the space. Through the pop-up window, the tester can gradually complete the construction of all space scenes in accordance with the order of the tour. How to create a model base containing a large number of furniture models in the system without affecting the fluency of software operation was their main technical problem. In addition, in the process of importing *Sketchup* models into *Fuzor*, they also need to continuously adjust and modify the proportion of furniture through HVRI method.

In the process, the testers not only designed their favorite scene space, but also had a deep understanding of the proportions of furniture. This group of students use questionnaires and interviews to determine the satisfaction of the testers with the building space. They considered that the layout of interior space is a flexible way of architectural space design, so it was difficult for the tester to express his real feelings with several options in the questionnaire. Therefore, their questionnaire was only the evaluation of furniture types and space forms. The team members will interview the testers to discuss the technical difficulties in the process of space design and the testers' ideas when placing furniture. They hope to use the simple office building space design as the basis to explore the needs of different groups for office space use, and provide a theoretical basis for future office space design.

Figure 4. Design process and outcome by Group Three.

5. ANALYSIS AND DISCUSSION

Based on the analysis result, this paper will contemplate future trajectories for the novel strategies to improve HVRI, that one day may lead to genuinely immersive design interaction. By observing the students' application of virtual reality technology and tools to the project design, we believe that the design mode of human-computer interaction design feedback is gradually promoted. The full application of virtual reality software and equipment shows the feasibility of application and promotion of HVRI in the field of architectural design. In the scheme preparation stage, design stage and later practice verification stage, virtual reality tools provide decision-making support for designers in the form of architectural space. But to use virtual reality equipment better, architects need to study software operation and equipment operation.

In the scene design process, all groups of students used the HVRI method to optimize the design of scene, but the focus of each group was different. The first group of students put the focus of the test on the creation of scene immersion effect, hoping that each game scene will give people a unique or vivid and interesting effect. They try to use sound effects and story scenarios to bring the testers into the game. Therefore, they built the basic space in the computer, and the team members tested the built space with HTC Vive equipment and explored the possibility of more changes. After debugging, they use the desktop holographic projection equipment to let more users in the workshop participate in the test process, so as to optimize the whole game plan. They adopt the design idea from HCI to HVRI. The second group of students focused on the display effect of the scene, they want to let the tester fully understand the layout of the building space and the surrounding environment. Therefore, in the process of testing, they introduced seasonal and temporal changes to provide more possibilities for the tester to observe. Since the design purpose of this group is to intuitively show the space scene to the testers, they need more real experience data than the other two groups, so they directly import the built space model into the desktop holographic projection device for debugging. The third group of students is to focus on the open design form, through continuous testing to optimize the proportion of furniture and space size, to bring better experience for the tester. Therefore, this group of students needs to conduct preliminary research and evaluation on the size and placement of furniture and the actual office scene in the early stage of design. After obtaining accurate survey data, they imported the completed spatial model into a desktop holographic projection device for debugging. The design idea of this group of students is to combine the survey results with the HVRI method to design the scene. From this point of view, HVRI is an immersive interactive experience technology that can work closely with other research methods. Through the close cooperation of various research methods, the designer can realize the optimization of scheme design.

Each group of students pay close attention to the experience of testers, actively collect the opinions of testers and feedback the effect of field experience, so as to achieve the effect of HVRI. Since the first group of students is to test and evaluate the game space, they mainly focus on the interest of the tester in the game process and whether there are common operation difficulties in the experience process. They record the time required for each tester to break through the barrier, and deleted the route and content of the scene according to the time when the tester had visual fatigue during the experience. They judge the success of the scene construction based on the tester's language and action behavior feedback during the experience, and use this as the criterion for the tester's behavior judgment in the future HVRI. The second group of students is about the design of the exhibition space, so they pay more attention to the interest of the tester in each space and whether they are willing to complete the whole space tour. Therefore, they not only record the time spent by each tester in the whole experience process, but also record the time spent by the tester in a certain space, and interview the tester after completing the test to ask the space they are most interested in. According to the interview results and the actual experience time of the participants, they show more details of the rooms with higher interest points. They use a questionnaire survey to conduct a post-user evaluation of the constructed architectural scene, and the results provide theoretical support for the future experience of the complex architectural space.The third group is to explore the open space, so they spend more time on the feasibility of the furniture layout in the space and the fluency of the tester's operation process. Different from the other two groups, in the process of experience, the team members try to discuss the possibility of indoor furniture placement with them, so that the team members can be clearer about the needs of the tester, and pass the operation and technical guidance to the tester when appropriate. Therefore, they integrate the time required by the tester to complete the whole process, and set prompts under the key options node to improve the fluency of the interaction experience. They use questionnaires and interviews to comprehensively understand the satisfaction of the testers with the architectural space, and provide a theoretical basis for the future design of office space. In conclusion, HVRI method not only provides more possibilities for interaction design, but also provides more options for users to evaluate and feedback.

6. CONCLUSION

This paper believes that HVRI, a new human-computer interaction method, can help to make the relationship between human and virtual model closer and provide decision support for all stages of architectural design. It provides an innovative and efficient design method for architects. So that the designer can experience the real building scene and display the image of the two-dimensional interface in the three-dimensional immersive space. It can complete the construction and design of the relevant content of the scheme in the virtual scene, and truly realize the collaborative interaction between the experiencer and the virtual reality device. This method makes the form of architectural design more diversified, and the design results closer to the needs of users.

ACKNOWLEDGEMENTS

The authors would like to acknowledge that this paper was financially supported by the National Natural Science Foundation of China (Grant No. 51908158). The corresponding author of this article is TianTian Lo.

References

Anthes, C., García-Hernández, R. J., Wiedemann, M. and Kranzlmüller, D.: 2016, State of the art of virtual reality technology, *2016 IEEE Aerospace Conference*, 1-19.

Dix, A., Dix, A. J., Finlay, J., Abowd, G. D. and Beale, R.: 2003, *Human-computer interaction*, Pearson Education.

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.

Lindeman, R. W., Page, R., Yanagida, Y. and Sibert, J. L.: 2004, Towards full - body haptic feedback: The design and deployment of a spatialized vibrotactile feedback system, *Proceedings of the ACM symposium on Virtual reality software and technology*, 146–149.

Lo, T.T. and Gao, X.R.: 2020, FROM HCI TO HVRI: How different will the interaction of digital architecture design be?, *CAADRIA 2020*, Hong Kong, 253-262.

Lo, T.T. and Schnabel, M.A.: 2018, Virtual & Augmented Studio Environment (VASE) - Developing the Virtual Reality Eco-System for Design Studios, *CAADRIA 2018*, Beijing, 443-452.

Maver, T. and Harrison, C.: 2001, Virtual Environment for Special Needs: Changing the VR Paradigm, *Proceedings of CAADFutures 2001*, Eindhoven, 151-160.

Schnabel, M.A., Aydin, S., Moleta, T. and Pierini, D.: 2016, Unmediated Cultural Heritage via HYVE-3D: Collecting individual and collective narratives with 3D sketching, *CAADRIA 2016*, Melbourne, 683-692.

Sorguç, A.G., Yemişcioğlu, M.K., Özgenel, C.F., Katipoğlu, M.O. and Rasulzade, R.: 2017, The Role of VR as a New Game Changer in Computational Design Education, *Proceedings of eCAADe Conference 2017*, Rome, 401-408.

EXPANDING THE METHODS OF HUMAN-VR INTERACTION (HVRI) FOR ARCHITECTURAL DESIGN PROCESS

CHAOHE LIN[1] and TIAN TIAN LO[2]
[1,2]*Harbin Institute of Technology, Shenzhen*
[1]*c1223536134@163.com* [2]*skyduo@gmail.com*

Abstract. The emergence of virtual reality technology now brings the possibility of new design methods. Virtual reality technology allows architects to feel space better and express design ideas more intuitively. With the interactive perception equipment and VR glasses, geometric shapes can be created and modified in a virtual environment, replacing the mouse and keyboard to complete the creation of space in the early stage of the design process. At present, the application of virtual reality in the architectural design process has some problems include unnatural interaction, low accuracy, high work cost. This paper will summarize the interactive methods of virtual reality technology in various current cases and compare the input and output of the device by analyzing the matrix method. We can explore interactions that are beneficial to architectural design. Using these interactive methods, we can expand the interface relationship between humans and the virtual environment.

Keywords. HCI; HVRI; Interaction; Digital Architecture Design; Virtual Reality.

1. Introduction

With the advancement and development of computer technology, virtual reality technology began to appear and apply in various fields. Virtual reality is a simulation in which computer graphics is used to create a realistic-looking world (Burdea & Coiffet, 2003).The characteristics of virtual reality are immersion, interaction, and imagination. Virtual reality technology breaks through the way people perceive the world in the past. It turns people's dreams of creating and experiencing virtual space into reality. In this context, using virtual reality technology in the architectural design process will be more effective. Virtual reality technology allows designers and users to immerse themselves in the virtual architectural space. It is conducive for the designers to improve the quality of architectural space.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 173-182.

2. The development of Human - VR interaction for architectural design process

2.1. THE APPLICATION OF VIRTUAL REALITY TECHNOLOGY IN THE ARCHITECTURAL DESIGN PROCESS

The introduction of design concepts used virtual reality at first. Virtual reality technology allows architects to express their designs freely (Schnabel et al. 2008). Virtual reality is a technology that adds immersion and interaction to the three-dimensional computer model. It can show the world that cannot express in traditional forms (Burdea & Coiffet, 2003). Therefore, VR is a powerful tool that can surpass reality.

The use of virtual reality technology can increase the collaboration of teams. By analyzing and evaluating two technologies, the 3D virtual world of remote design collaboration and the tangible user interface combined with AR. VR has increased the cooperation between design teams (Gu et al., 2011).

VR helps to understand the concept of space. VR-based 3D sketching interface can improve spatial cognition in the conceptual stage (Rahimian & Ibrahim, 2011). VR can also be used for three-dimensional interactive creation, modeling in design work. Users can experience the created space directly (Schnabel et al., 2008).

The combination of VR and BIM can lower the barrier of use. The technology allows users to interact in real-time and experience the virtual environment. It makes users experience a designed environment. It can have the function of simulating physical dynamics (Yan et al., 2011).

At present, VR has various applications in the field of architectural design, but there is a lack of further exploration in interactive methods. Due to the limitation of interactions, the application efficiency of virtual reality technology in the architectural design process is not high.

2.2. THE DEVELOPMENT OF INTERACTION FOR ARCHITECTURAL DESIGN PROCESS

Before the use of computers in architectural design, the way of architectural design was to draw drawings with paper and pen. At this time, people design buildings with the interaction of hands, drawing, and pen. In the 1970s, due to the development of computer hardware, specialized CAAD software was born. Architects used it for two-dimensional drawing work. Then from the mid-1980s to the 1990s, three-dimensional architectural model software began to appear. After entering the 21st century, parametric 3D design software has also started to use in the architectural design process. At this time, the process of architectural design bases on human-computer interaction. Architects use the mouse and keyboard to input parameters and design buildings on the computer. The emergence of virtual reality has expanded the way of architectural design. In the future, architects can no longer rely on the mouse and keyboard. Using perception devices, architects can design buildings in virtual reality with a variety of interactive methods.

2.3. RESEARCH OBJECTIVES

Due to the abstract and professional nature of traditional two-dimensional drawings, the communication between professionals and customers is impeded. Virtual reality technology can solve these problems. Virtual reality technology breaks the previous two-dimensional architectural design mode, and avoids the disadvantages of graphic design. The design can be constantly improved in the process and the virtual technology can make the design more perfect. At the same time, the immersion, interaction and imagination of virtual reality also provides convenience for users to participate in design. At present, interaction is one of the key problems of virtual reality in architectural design. This study attempts to find a natural interaction by sorting out different interaction modes. Improving the interaction mode of virtual reality technology in the architectural design process can make the architectural design process easier to be understood by people. As a result, it can reduce the communication barriers between professionals and non-professional users. Using virtual reality technology, non-professional users can participate in the design process, making the final building more suitable for use.

2.4. THE ADVANTAGES OF VIRTUAL REALITY TECHNOLOGY IN INTERACTIVE METHODS

Virtual reality technology can satisfy the natural interaction mode and reduce the difficulty of using the computer. It is still difficult for many non-professionals to use computers because of the cost of learning basic principles and operating skills. Better human-computer interaction will make computers easier to use, more enjoyable for users, and more productive. Ideally, people would be able to talk to the computer and control it in a more natural way than the current window, icon, menu, pointer (WIMP) interface. Using virtual reality to conduct human-computer interaction can make the computer easier to use. With virtual reality technology, the operation of the computer can be more in line with people's natural habits, and improve efficiency. Virtual reality technology can solve the problems the problems existing in the process of architectural design. In virtual reality, architects can feel the space and get more real feelings. Besides, architects can also get a multi-angle visual experience. The interaction between humans and the virtual environment can be more diverse and use body language. In short, virtual reality technology allows architects to experience the space they design. It can help architects to improve the quality of design.

2.5. THE PROBLEMS OF INTERACTION BETWEEN HUMAN AND VIRTUAL REALITY IN THE CURRENT ARCHITECTURAL DESIGN PROCESS

Virtual reality technology can enable users to better understand design, help to improve users' participation in design, and realize collaborative design. However, there are still some problems with using virtual reality in architectural design.

- Due to the difficulty of interacting with virtual objects, architecture visualization in VR system is limited (Camacho et al., 2019).
- Virtual reality technology equipment is not mature enough, and some people

will appear simulator sickness (Kreutzberg, 2014).

- In order to create a realistic digital environment, designers need to put more effort into defining objects in virtual reality (Lo & Gao, 2020).
- Multi-person interaction and long-distance collaboration in virtual reality are still being studied (Ishikawa et al., 2020).

All these problems increase the workload of designers and limit the application of virtual reality technology. It is necessary to reduce the cost of the designer's work and make it easier for the designer to operate in the virtual world. The improvement of the interaction is conducive for the popularization and application of technology.

3. Interactive methods of Human - VR interaction (HVRI)

At present, the main interactions of virtual reality technology are as follows.

3.1. THREE-DIMENSIONAL INTERACTION

Three-dimensional interaction refers to the operation of mapping spatial information or buttons of an input device into a virtual space to complete specific interactive tasks. According to different input methods, there are two types of mapping.

Direct mapping is mainly to input the spatial information of the hand or device directly. Ray casting uses virtual light. The virtual hand is a way of mapping by constructing the user's hand in the virtual world to achieve the purpose of interaction. Virtual hands have insufficient grasping accuracy. Based on the rules of threshold self-adaptation (TSA), virtual hands can achieve more accurate grasping (Zou et al., 2019) (Figure 1). Indirect mapping is mainly to map input information into gestures with the device. The users use these gestures to complete interactive tasks. In the WIM (world in miniature) system, users can control the mini-space. The change of the mini-space will affect the objects in the scene (Stoakley et al. 1995). Besides, the user can project three-dimensional space onto a two-dimensional plane and use the image plane to manipulate objects in three-dimensional space (Pierce et al., 1997).

There are three problems with 3D interactive technology. The space range is too small that it is difficult for the virtual hand to grasp the distant objects accurately. The three-dimensional interactive device provides more degrees of freedom, but it is hard to control. Interactive technology is lack multiple methods. In response to these problems, we propose to integrate existing technologies and develop new interactive methods. Besides, people's body language needs to be fully utilized, such as the use of hand interaction.

Figure 1. Virtual hands based on TSA rules (Zou et al. 2019).

3.2. GESTURE AND BODY INTERACTION

Gesture and body interaction refer to track the parts of the human body with the trackers or computer vision methods. The information in the real world is the input information of the virtual world, and then the recognition algorithm is used to analyze and give feedback. Gesture and body interaction is one of the current mainstream virtual reality input methods. Kinect uses computer vision recognition algorithms to analyze video and parse out gestures (Zhang, 2012) (Figure 2). The accuracy of recognition has been improved greatly. Leap Motion uses binocular visual recognition to collect user data and uses algorithms to analyze human body movements. The PS4 handle can obtain the movement information of the hand with the sensor worn on the hand. It recognizes the change of the spatial position and gets feedback. Google Project Soli uses radar to monitor air gestures and identify movement changes by transmitting and receiving feedback signals.

The problem of gesture and body interaction is that there are still problems with the recognition accuracy of gesture interaction. At present, only click gestures are recognized better. When using gestures, you need to stay for a certain time to switch the functions. The memory of gestures is complicated. To solve these problems, gesture interaction can first use click gestures to complete a series of operations before the accuracy meets requirements. The switching of gesture actions can be done with the help of a virtual interface.

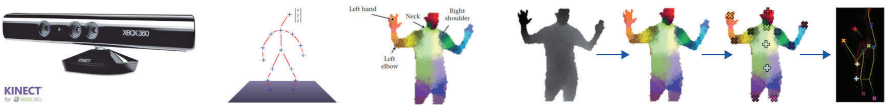


Figure 2. Kinect’s body recognition (Zhang, 2012).

3.3. HANDHELD MOBILE DEVICE INTERACTION

Figure 3. Compared with the VR scene rendering of FURION and other mobile devices, the FURION on the right has a better light perception (Lai et al. 2017).

With the development of the mobile device, people have begun to apply the three-dimensional interactive capabilities of these handheld smart devices to the field of virtual reality. The idea of the interaction between handheld interactive devices and virtual reality is to calculate the relative position of the device and superimpose the marked digital information on the captured image. Then the operations are on the 2D level. Currently, it is widely used in location navigation and collaborative games. FURION is a system architecture that can use wifi to support high-quality VR applications on smartphones (Lai et al., 2017) (Figure 3).

At present, the interactive mode of handheld mobile devices has problems that the display screen is too small and the computing power of the device is limited. When performing virtual reality operations on mobile devices, new interaction methods should be developed to adapt the restrictions.

3.4. VOICE INTERACTION

Voice interaction refers to the interactive mode in which users request the system to perform specific functions by voice commands. This way releases the hands. It can input a large amount of text accurately, and the interaction is very natural. Voice interaction has been applied to many smartphones. The voice recognition software is very diverse and has reached high accuracy. Google glasses, wearable devices, and Xiaomi speakers have integrated voice assistants to achieve voice interaction. Besides, creating virtual characters in the virtual world and performing voice interaction can also relieve anxiety (Yang et al., 2016) (Figure 4).

The problem with voice interaction is that when the voice interface needs to perform complex interactive tasks, the vocabulary is very demanding. When operating in virtual reality, if both hands are occupied, voice can be used as an auxiliary input to execute some simple commands.

Figure 4. Voice interaction system with virtual human (Yang et al.2016).

3.5. TACTILE INTERACTION

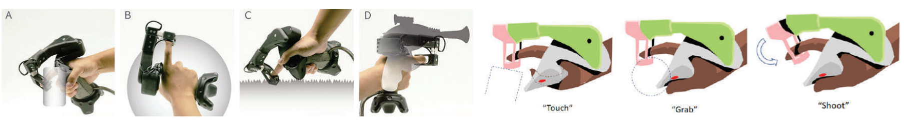


Figure 5. CLAW VR controller realizes tactile interaction (Choi et al. 2018).

When used as an input device, a tactile sensing device can capture user actions. When used as output devices, they can provide users with tactile experiences. With the widespread use of touch screens, tactile feedback technology has made fast progress in recent years. There are many applications on general touch screens and touch gloves. The CLAW VR controller provides force feedback and realizes the interaction of motion and touch (Choi et al., 2018) (Figure 5).

Tactile interaction is a mature method. However, in virtual reality, gloves and other equipment may be required, which has certain usage restrictions.

3.6. MULTI-CHANNEL INTERACTION

Multi-channel interaction refers to an interaction method that integrates two or more input channels. Multi-channel interaction makes full use of people's senses, making the interaction more natural and effective. Users can input information with gestures, voice, and so on. It improves the efficiency of input and the naturalness of interaction. MSVT system uses speech recognition and gesture input to complete the visualization of scientific data (LaViola, 2000). Multi-channel interaction can combine vision and touch. The portable visual-touch fusion VR software framework uses gloves and head-mounted devices to combine the sense of touch and vision, making interaction methods more diverse (Guo et al., 2020). Besides, the fusion of hearing, vision, and touch can further increase the immersion of virtual reality (Jadhav et al., 2017) (Figure 6).

Multi-channel interaction has some problems. First, we need to develop varied semantic models for specific operations. Second, it is difficult to organize different interactive devices. Finally, the information of different interaction channels should be fused.

Figure 6. Interaction that combines hearing, vision and touch (Jadhav et al. 2017).

4. Comparison of input and output of different interaction methods

Different interaction methods have different results of input and output. Firstly classify the input terminals in the form summarized above and add some interactions. Input methods divide into controllers, gestures, motion capture, voice, tactile, eye tracking, face recognition, brain waves, and multi-channel input. According to the various human senses, the output is classified into vision, hearing, tactile, body perception, and smell. Adding the different interaction methods mentioned above into the table, we can see that there are still many vacancies in the current interactions of virtual reality (Table 1). The main input focuses on gestures and speech and the main output is vision. Because of the characteristics of current virtual reality interaction methods, improvements can be made from four aspects.

- Use multiple sensory channels. Sometimes a single channel cannot accurately express the intentions of users, and the multi-sensory interaction can convey information more accurately.
- Operation in three-dimensional space. Operations in virtual reality should be based on three-dimensional. The operation in the space is more in line with the human natural operation mode.
- Two-way interaction. Interactive input and output can be carried out in both directions like eye-tracking and visual feedback, tactile input and tactile feedback, three-dimensional auditory localizer, and sound feedback. Two-way interaction can maximize the use of the senses and bring new experiences to people.
- The naturalness of interaction. A good interaction model should make people

unaware of the existence of an interactive interface. The user can naturally operate the virtual world. For example, users will naturally focus on things of interest in the virtual world.

Table 1. Comparison of different interaction methods.

Input / Output	Controller	Gesture	Motion capture	Voice	Tactile	Eye tracking	Face recognition	Brain waves	Multi-channel input
Vision	Ray casting、WIM、Image plane、HTC VIVE	Virtual hand、Kinect、Leap motion、Google Project Soli、Google Glasses	Kinect、Leap motion、	Voice recognition software、Google Glasses	Smart phone touch screen	HTC VIVE PRO EYE			MSVT system、Portable Vision-Touch Fusion VR Software Framework
Hearing				Voice recognition software、Mi Speaker					
Tactile			Exoskin coat		Touch gloves、CLAW VR controller 、Smart phone touch screen				Portable Vision-Touch Fusion VR Software Framework
Body perception			Exoskin coat						
Smell									

5. The direction of the interactive mode of virtual reality technology in the process of architectural design

This article summarizes the various interactive technologies of virtual reality. The methods need to be selected according to the needs of architectural design. There are three requirements in the field of architectural design.

- The way of interaction needs to be natural enough. If designers rely too much on a certain medium when performing operations, the thinking will be limited. For example, with too much use of the mouse, keyboard, and screen nowadays, it is difficult for architects to perceive the building space through the screen. The real feeling of the designed buildings will be biased.
- There must be a certain degree of accuracy. Architectural design has high requirements for scale. It is necessary to be able to input values accurately to control space design. Therefore, in the interaction of virtual reality, attention should be paid to the function that can define the value.
- Interactive learning and work costs need to below. If the time of learning is too long, the technology will be hard to promote and apply. The current design process schedule is very tight and it is difficult for designers to spend a lot of time learning new technologies. Therefore, to facilitate the application of virtual reality technology, it is necessary to make the interaction of virtual reality easy to study and close to nature.

In response to these three needs, combined with the advantages of various interaction methods summarized before, we propose three strategies.

- In the way of interaction, the interaction can use gestures as much as possible. The use of voice interaction can assist in the operation. This kind of method is the most natural. Switch gestures can use the function buttons of the virtual interface. Voice interaction can be used when both hands are occupied. Multi-channel interaction helps architects improve design efficiency.
- The accuracy of the interaction can be precisely controlled by inputting values through the three-dimensional virtual interface.

- We can consider using a graphical interface to represent the parameterized data logic. We can even control the model parameters by inputting body language directly. In the future, we can use natural interaction to realize parametric modeling and design work.

By analyzing the various existing interactive methods, we can see that there are some problems in the current virtual reality interactive methods. When virtual reality technology is used in the field of architectural design, it is necessary to change the interactions according to the needs. In the process of architectural design, we can use the device to capture gestures on the virtual reality interface to complete the creation of three-dimensional geometric objects. With the buildings created in this way, architects can directly roam inside the building to get a more real experience. The operation interface innovation of virtual reality will be a direction that can be improved.

Because virtual reality is multi-perceptual, immersive, and interactive, it is very effective to apply virtual reality to the communication between designers and users. In high-density urban areas, the development of residential buildings has three characteristics. First, to accommodate more people, the scale of residential construction projects is getting bigger and bigger. Second, the customer's needs are becoming increasingly diversified and the market is changing fast. Third, the industrialization of building components reduces production costs. Open architecture can meet such needs, but it requires users to participate in the preliminary design work. Using virtual reality technology can reduce the cost of communication between designers and non-professionals. Non-professionals can intuitively feel the residential space in virtual reality and put forward their own diversified needs. For designers, the participation of the user can improve work efficiency and reduce useless work. For developers, the participation of users can better meet the needs of customers and residential products have a higher competitive advantage. After non-professionals use virtual reality technology to intervene in the design process, the final product can be adapted to various needs while reducing costs.

6. Conclusions

This paper sorts out the various applications of virtual reality technology in the field of architectural design and analyzes the development process of human-computer interaction. It summarizes the advantages and problems of virtual reality technology in the architectural design process and analyzes the existing virtual reality interactions. The matrix compares the existing interactive methods of virtual reality. Finally, it is proposed that in the field of architectural design, gestures can be used as much as possible in virtual reality. The use of voice interaction can assist in the operation. The three-dimensional virtual interface can help to control the values accurately, and the interactive method can be improved to achieve easier parameterized construction and design work. Finally, the paper suggests that virtual reality technology can be used in the process of participatory residential design, allowing non-professionals to participate in the design process, improving design efficiency and meeting the diverse needs of users.

Acknowledgement

The authors would like to acknowledge that this paper was financially supported by the National Natural Science Foundation of China (Grant No.51908158).

References

Burdea, G. C. and Coiffet, P.: 2003, *Virtual reality technology*, John Wiley & Sons.

Camacho, D., Dobbs, T. and Fabbri, A.: 2019, Hands On Design - Integrating haptic interaction and feedback in virtual environments for enhanced immersive experiences in design practice., *Proceedings of the 24th CAADRIA Conference*, Wellington, New Zealand, 563-572.

Choi, I., Ofek, E. and Benko, H.: 2018, CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality, *the 2018 CHI Conference*.

Gu, N., Kim, M. J. and Maher, M. L.: 2011, Technological advancements in synchronous collaboration: The effect of 3D virtual worlds and tangible user interfaces on architectural design, *Automation in Construction*, **20**(3), 270-278.

Guo, Y., Tong, Q. Q., Zheng, Y. K., Wang, Z. Q., Zhang, Y. R. and Wang, D. X.: 2020, An Adaptable VR Software Framework for Collaborative Multi-modal Haptic and Immersive Visual Display, *Journal of System Simulation*, **32**(7), 1385-1392.

Ishikawa, D., Fukuda, T. and Yabuki, N.: 2020, A Mixed Reality Coordinate System for Multiple HMD Users Manipulating Real-time Point Cloud Objects - Towards virtual and interactive 3D synchronous sharing of physical objects in teleconference during design study, *Proceedings of the 38th eCAADe Conference*, Berlin, Germany, 197-206.

Jadhav, S., Kannanda, V. and Kang, B.: 2017, Soft robotic glove for kinesthetic haptic feedback in virtual reality environments, *Electronic Imaging*, **2017**(3), 19-24.

Kreutzberg, A., Mattias, R. and Tallgren, M. V.: 2014, New Virtual Reality for Architectural Investigations, *Ecaade Conference 2014*.

Lai, Z., Hu, Y. C. and Cui, Y.: 2017, Furion: Engineering High-Quality Immersive Virtual Reality on Today's Mobile Devices, *the 23rd Annual International Conference*.

LaViola, J.: 2000, MSVT: A virtual reality-based multimodal scientific visualization tool, *Proceedings of the third IASTED international conference on computer graphics and imaging*, 1-7.

Lo, T.T. and Gao, X.R.: 2020, From HCI to HVRI - How different will the interaction of digital architecture design be?, *Proceedings of the 25th CAADRIA Conference*, 253-262.

Pierce, J. S., Forsberg, A. S. and Conway, M. J.: 1997, Image plane interaction techniques in 3D immersive environments, *Proceedings of the 1997 symposium on Interactive 3D graphics*, 39-43.

Schnabel, M., Wang, X. and Seichter, H.: 2008, Touching The Untouchables: Virtual-, Augmented-, and Reality, *International Conference on the Association for Computer-Aided Architectural Design Research in Asia*, 293-299.

Stoakley, R., Conway, M. J. and Pausch, R.: 1995, Virtual reality on a WIM: interactive worlds in miniature, *Proceedings of the SIGCHI conference on Human factors in computing systems*, 265-272.

Wang, C. W., Gao, W. and Wang, X. R.: 1996, *Implementation and Application of Virtual Reality Technology*, Tsinghua University Press, Beijing.

Yang, W., Culp, C. and Graf, R.: 2011, Integrating BIM and gaming for real-time interactive architectural visualization, *Automation in Construction*, **20**(4), 446-458.

Yang, Y., Weng, D. D., Xue, S. and Su, M.: 2016, Study of Virtual Human Voice Interaction on the Soothing Effects of Anxiety, *Journal of System Simulation*, **28**(10), 2578-2585.

Zhang, Z.: 2012, Microsoft kinect sensor and its effect, *IEEE multimedia*, **19**(2), 4-10.

Zhu, N. K. and Zou, Y.: 2008, Appliance of Virtual Reality in Architecture Design, *Journal of Beijing University of Civil Engineering and Architecture*, **24**(1), 34-38.

DETECTING VIRTUAL PERCEPTION BASED ON MULTI-DIMENSIONAL BIOFEEDBACK

A Method to Pre-Evaluate Architectural Design Objectives

WANYU PEI[1], XIANGMIN GUO[2] and TIANTIAN LO[3]
[1,2,3]*Harbin Institute of Technology, Shenzhen*
[1,3]*{peiwanyu1|skyduo}@gmail.com* [2]*24904404@qq.com*

Abstract. In the information age, the attention to architectural design has gradually shifted from spatial aesthetics to the human's spatial experience. The situation of human perception becomes essential feedback information that designers can use to improve the design schemes. This research proposes an auxiliary method for pre-evaluating the architectural design goals and providing recommendations for architects to optimize the scheme. Specifically, by aggregating and quantitative analyzing electrophysiological signals and eye-tracking data, this research obtained the user's spatial perception with little effect of subjective consciousness as their feedback on the architectural environment. We took the campus outdoor space of an International School of Design as the research sample. By combining the architect's design concept and objectives, we constructed the contrast spatial schemes in virtual reality (VR) for users to experience and analyzed the usability of this method when pre-evaluate design objectives in a practical project.

Keywords. Multi-dimensional biofeedback; architectural design objectives; pre-evaluation; virtual reality.

1. Introduction

Essentially, under the changeable era, predicting the non-functional qualities like the relationship between space and human emotional perception is more critical than the function and economic benefits of a design. With the development and adoption of new technologies, the information exchanged between human and physical space has become more frequent than before. The mode of architectural design is gradually transferred from architect-oriented to user-oriented. However, related research (Yazdanfar et al., 2015) has shown significant differences in the perception of the same space between designers and ordinary users. Although designers try their best to propose the schemes from the user's viewpoint, it is still difficult to truly fit users' psychological needs.

Since architecture will have long-term impacts on users and will be irreversible once implemented, it is essential for decision-makers and designers to carefully

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 183-192.

evaluate whether the design proposals (alternatives) can achieve design goals before arriving at a decision. However, it is generally hard to collect and quantify the user's accurate perceptual and emotional feedback. On the one hand, a common finding in cognitive neuroscience research is that subjective feedback is easily affected by personal preference and professional level. On the other hand, it is difficult for non-professional users to comprehend the design schemes fully. The designers always cannot get users' feedback until completing the construction.

This study proposes a method for assisting design that combines virtual perception and multi-dimensional biofeedback in the detailed design stage to pre-evaluating the realizability of the objectives. By objectively comparing the quantifiable perceptions of users in a simulated environment, the designers can further optimize the schemes. When users experience a designed space in VR, the researchers collected users' physiological data including multi-dimensional electrophysiological signals (EDA: Electrochemical Activity, PPG: photoplethysmography) and eye-movement data which can reflect their visual perception emotional arousal.

2. Background

2.1. VIRTUAL REALITY AND ARCHITECTURAL SPACE EVALUATION

In 1993, Michael Heim proposed the feasibility of applying VR in architectural design. Some scholars subsequently use VR to assess the design projects and verify the availability of using in collecting feedback. For example, Frost et al. (2000) found that VR allows unprofessional users to figure out what they cannot comprehend through traditional visualization tools (2D and 3D drawings). Westerdahl et al. (2006) compared the VR model with the built environment and found the description of the VR model was entirely accurate. VR allows high-quality visualization of architectural space. It makes irregular space with complex shapes more intuitive and conducive for users to observe complex space' features.

Besides, designers can easily change space elements in VR and form contrast schemes for users to perceive. In 2015, Coronado et al. built three different simulation spaces in VR for evaluation. They showed that VR could bring higher efficiency in the improvement of design schemes. Norouzi et al. (2015) introduced a design platform to harmonize the communication between designers and users in VR. What's more, VR simulates a state of immersion feeling that is highly similar to the real. This VR feature allows researchers to measure psychological, physical, and behavioral responses in a controllable environment. Hence, some research used VR space to induce human emotions. Simultaneously, researchers obtain physiological data using physiological devices to recognize different emotional states according to nerve and cardiac dynamics. This research proved virtual environments could indeed awaken users' emotions such as relaxation or anxiety (Marín-Morales, 2018).

In conclusion, exist research proved physiological sensors could be used in VR experiments to detect the user's emotion when experiencing the space. VR has the potential to become an essential tool for studying the relationship between human perception and architectural space by providing a visual environment with immersion, interactivity, and the capability of inducing emotions.

2.2. MULTI-DIMENSIONAL PHYSIOLOGICAL PERCEPTION AND ARCHITECTURAL DESIGN

In the past, research mainly used subjective evaluation methods like interviews or questionnaires on the human spatial perception. The results may involve multiple psychological processes and can be affected by personal factors. Some other research tried to analyze the user's perception through overt behaviors, such as facial expression recognition (FER) and behavioral observation. However, the accuracy of overt behaviors is doubtful because it could be subjectively controlled. The environment can affect the visual perception system and lead to changes in physiological system variables. Physiological parameters are not easy to be controlled by human subjective consciousness and have higher credibility. Using portable physiological instruments and eye trackers can obtain the user's physiological indicators, helping designers objectively comprehend users' feelings of architectural space. According to existing research, skin conductance changes (SCC) and heart rate are nearly related to emotional arousal.

The relevant studies mainly include the following two categories: One uses perceptual measurement technology to identify the spaces that could bring negative emotional experiences (such as stress, anxiety, and fear). In 2020, Lee et al. integrated the on-skin electrophysiological data and location data of multiple people to identify the stress of the elderly caused by environmental obstacles. Some research (Engelniederhammer et al., 2019) observed the impact of crowding on the emotions of pedestrians in high-density urban areas by capturing EDA and skin temperature. The other kind of research used eye-tracking sensor technology to detect the user eyes' position and gaze points. Eye-tracking can get the user's objective feedback information of the designed VR spaces and quickly merge with the user's spatial behavior data to evaluate the scheme.

Since emotional perception and eye tracking can reflect the user's two aspects of "emotion" and "the cause of the emotion," combining these two technologies will help understand perception in a depth feedback mechanism. However, nowadays, little research has proposed applying the perceptual measurement to assist the pre-evaluation of design objectives, and the use of physiological data is relatively single.

3. Experiments, Methods and Data Collection

3.1. PROJECT BACKGROUND

The experiment sample of this research is the designed campus outdoor space of the ISD. Due to its essential campus location, there are many discussions and controversies regarding the design details during scheme improvement. This campus space designer proposed an axis response to the constructed campus texture and hoped the users could feel the campus spirit when walking along with the dynamic axis space. This axis space's central area spreading to the square in front of the main building is an exclusive space for pedestrians. The designer highlights a vital design objective: increasing the attention of the main building means that when users walk in the central axis space (fig.1), they can observe the main building from a better perspective. The designer hoped to create the depth of the landscape to achieve this aim. "The main building on the central axis becomes a visual focus of constant discovery and approach." Users in this space are expected to experience the solemn academic atmosphere and have a profound psychological feeling of this university which has a long history.

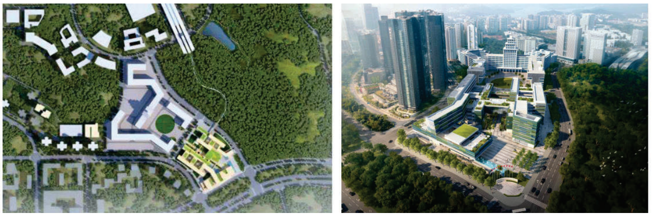


Figure 1. The general plan and aerial view of the ISD campus area.

At present, this design project is under the discussion and optimization stage. The stakeholders, including school directors, designers, constructors and experts, have launched multiple rounds of seminars, discussing design issues (tab.1) from various perspectives. However, there was some controversy regarding design objectives, which are a brake on the discussion. For one thing, most decision-makers can only predict the design results based on their experience and lack of objective evidence. Besides, due to the differences in multiple backgrounds and standpoints of stakeholders, it is not easy to reach a consensus. Therefore, we established a virtual environment and took this axis space as the testing example. Through analyzing users' biofeedback, we pre-evaluated design objectives and provided suggestions for resolving controversial design issues.

Table 1. The main argument points of the HITsz-ISD design.

	Semi-fixed features	**The point at issues**
Axis space	Building elevation	The entrance on the facade visually attractive.
	Corridor bridge	The axis space has the depth of field. Increase the attention of the main building. Generate emotional arousal in the axis space. Feel campus culture and arouse emotions during axis space roaming. Have an occlusion on the line of sight.
	Landscape belt	Is visually appealing. Lounge seats are easy to find.
	Signage system	Is visually appealing.

3.2. COMPARISON SCHEMES

During the multiple rounds of seminars, we collected the issues raised by decision-makers and generated comparison schemes for perception testing according to the project design goals and spatial factors. In this experiment, we set two kinds of comparison; one was a horizontal comparison, including ”experimental space” with corridor bridge and ”control space” without corridor bridge (fig.2). Through analyzing the perception results of the two groups, we can know the influence of the corridor bridge on users and whether the design of these factors can truly reflect the design intent. In the vertical comparison, we measured whether there are significantly different spatial factors’ attention levels to pre-evaluate the design goals.

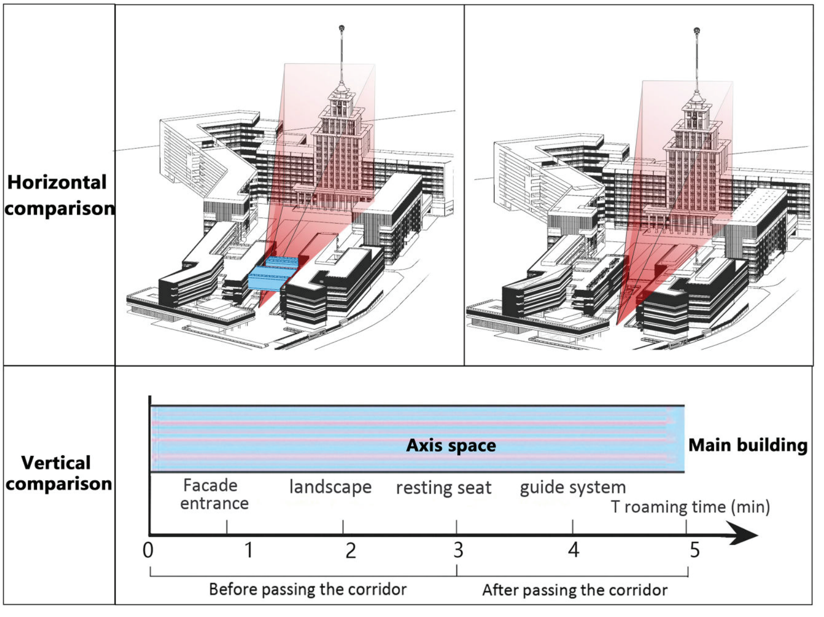


Figure 2. Horizontal and vertical comparison schemes.

3.3. EXPERIMENTAL DESIGN

This study adopted the within-participants experiment to reduce the differences between participants. The main disadvantage is that this type of experimental design can cause an accumulative error, which can be solved by balancing the experiment’s order. In this experiment, half of the participants experienced the “control space” first and the other half experienced the “experimental space” space first to offset the impact of experiment sequences.

3.3.1. Date collection

In this experiment, we set two kinds of comparison methods: horizontal comparison and vertical comparison. The horizontal comparison includes ”experimental space” with the corridor bridge and ”control space” without the corridor bridge. We analyzed the perception results of two different spaces to know the influence of the corridor bridge on the users and whether the design of these factors can truly reflect the design intent. In the vertical comparison, we measured the fixation count and duration to determine whether there is significantly different attention between spatial factors and pre-evaluate the design objectives according to the diversity. This research used the Ergo LAB platform (fig.3) to synchronously collect the participants' eye movement data (Tobii Pro Glasses 2), and physiological signals included PPG and EDA during roaming. Integrate collected multi-dimensional physiological data to understand the association between perception and designed environmental elements.

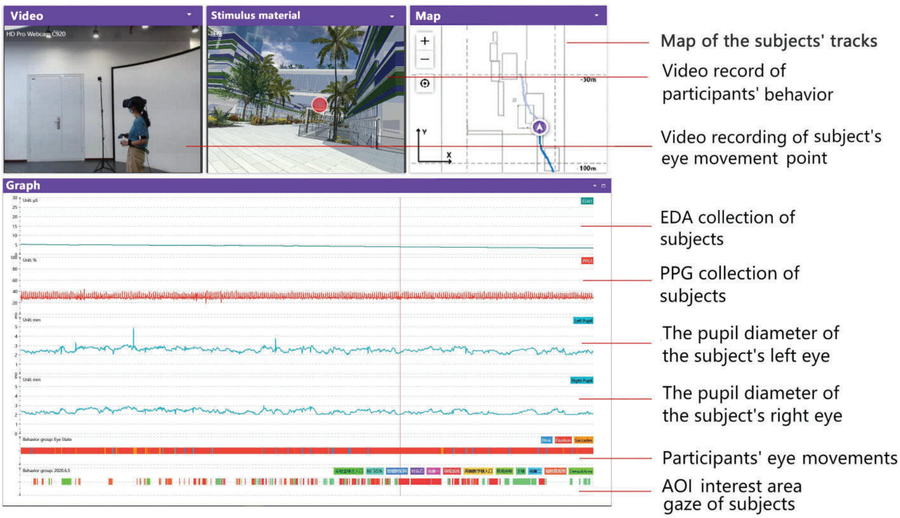


Figure 3. Synchronous collection of multi-dimensional physiological data.

3.3.2. Participants

Since this axis space will open up to social citizens after the building construction is complete (open campus). The type of users could be diversified. We recruited 30 laypersons with no professional design background (16 females, 14 males) by distributing ads on social and online platforms. Participants had not known or experienced this project space before this experiment. They could be potential users of this project and aged between 18 and 40 years old. They were told all possible risks of this experiment before the experiment.

3.3.3. Experimental procedure

The experimental process included the following six stages:

1. Pre-experiment: Invite two postgraduates major in architecture as participants to test the experiment flow and check whether VR spaces were a detailed simulation of the design scheme.
2. Prepare stage: Tell the experiment content and roaming path to participants and

help them wear the sensors and VR eye tracker. Participants need to calm down for about 5 minutes.

3. The first stage: Let participants roam in the "experimental space" for about 5 minutes. Collect physiological signals and eye movement data simultaneously.
4. Time for rest: The participants rest for 10 minutes.
5. The second stage: The second stage: Let participants roam in the "control space" for about 5 minutes. Collect physiological signals and eye movement data simultaneously.
6. Subjective questionnaire: Let participants complete the questionnaires which are used to verify the biofeedback.

4. Analysis of Data and Results

This research used basic statistical methods to analyze physiological indicators, including paired-samples T-test and Wilcoxon signed-rank test. We integrated multiple data to obtain feedback on the designed spatial factors by finding significant differences between the perceptions. All statistical calculations were completed in SPSS (version 20.0.0).

4.1. HORIZONTAL COMPARISON

4.1.1. Emotional arousal

This experiment collected participants' physiological signals, including EDA and PPG. For PPG signal analysis, we chose time-domain indexes containing Mean HR (bpm), SDNN (ms), RMSSD (ms), and frequency-domain index LF/HF. For EDA analysis, the index we chose was SC (μs). A comprehensive analysis of these indicators can better understand the user's emotional arousal status. According to the results of statistical analysis (tab.2), the users' emotional arousal in two kinds of axis space (with or without corridors) was not significantly different ($p>0.05$). The corridors had little impact on users' perception. The existing design objective proposed this axis space will improve the depth and dynamic of view through the design of corridors. However, the result of perception feedback proves that this design goal cannot be realized after is completing construction to a large extent.

Table 2. The analysis of biofeedback data.

		N	*MeanHR*(bmp)	*SDNN* (ms)	*RMSSD* (ms)	*LF/HF*	*SC*(μs)
Experimental group	Axis space	30	85.83±10.49	138.10±124.39	178.45±175.74	1.31±2.21	5.15±5.60
Control group		30	86.03±10.83	122.23±116.26	149.99±141.22	1.60±1.41	5.27±5.73
t/*Z*			*t*=-.505	*t*=.469	*t*=.328	*Z*=-1.656	*t*=-.672
p			.618	.642	.746	.0980*	.507

4.1.2. Visual attention to the main building

This research drew the front elevation of the main building as an area of interest (AOI) to collect eye movement data, including AOI Fixation Count (N) and

Fixation Duration (s), which can well reflect the user's attention to the spatial factors. The participants' attention to the main building was collected while roaming in the axis space. From the statistical analysis result (tab.3), When users experienced various spaces, the number of average fixation counts of the main building was different but was not significant ($p=0.05<0.094<0.1$). Besides, there is no difference in the total fixation duration ($p=0.797>0.1$).

Table 3. Statistical analysis of eye movement data.

	N	AOI fixation count (N)	AOI Total fixation duration (s)
experimental group	30	86.77±69.73	.16±.04
Control group	30	73.13±59.34	.16±.05
t/Z		t=1.729	Z=-.257
p		.094*	.797

The "experimental space" was the axis with horizontal corridors. Users cannot see the entire main building at first and gradually broaden the horizon during the roaming. From the eye-tracking feedback, the participants paid more attention to the main building when they roamed the "experimental space" (Fig.4). However, the differences in eye movement data were not significant enough. Designers need to further enhance spatial hierarchy by optimizing the horizontal corridor design or adding other spatial elements to enhance this effect of design further.

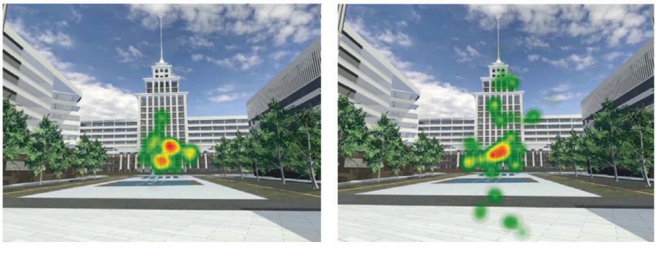


Figure 4. Heat map of users' fixation counts to the main building when walking in different kinds of spaces.

4.2. VERTICAL COMPARISON

The vertical comparison mainly analyzed the visual attention of the spatial elements that appear sequentially during the roaming. By analyzing the fixation information of 30 participants. By comparing the AOI data of each spatial element (Fig.5), we found that the main building AOI obtained the highest average fixation counts (N=79.95). Besides, 30 participants paid much attention to the guidance system AOI (N=49.92), even if they had been informed of the roaming path in advance. They spent a long time reading the guide system and bulletin board (Mean fixation duration=0.24s).

However, through replaying the experiment record video, we found that most participants overlooked the building's entrances. The entrances AOI had gain few fixation counts, and the fixation duration was short. This feedback information indicated that the entrance lacked visual appeal, but it may be the result that the participants were told not to enter the building before the experiment. The landscaping stone carving with famous quotes on the ground was a landscape element particularly designed by the designer. Many participants did not notice them when roaming. However, the landscaping stone got a long gaze duration because the participants will stop and read the stone inscriptions verbatim once they notice it. This design element had a particular role in cultural communication, but its' visual significance needs to be improved further.

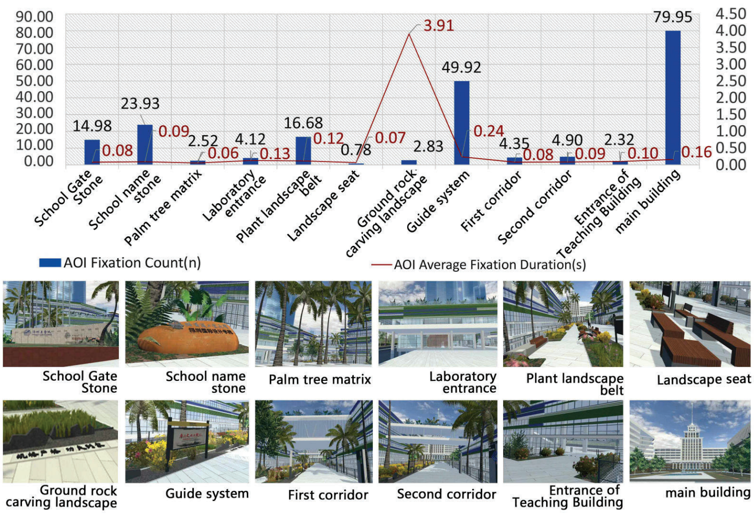


Figure 5. Statistics of eye-movement data on the attention of spatial elements.

5. Discussion and conclusion

Although the architects try to design the spaces from the user's perspective, this research found that some design effects may not reach architects' objectives. Architects and ordinary users have a significant difference in their understanding of the same space. Users without experience or professional knowledge have limited knowledge and expression ability of architectural perception, making it difficult for architects to obtain feedback from users and evaluate the objectives of the design scheme. This research collected users' biofeedback in the virtual environment. On the one hand, it provides users with an intuitive presentation to explore and understand the architectural scheme. On the other hand, the designer can flexibly and economically change the environmental factors in VR and obtain feedback from users by constructing the comparison schemes. In the process of improving the actual project, designers no longer need to rely on their empirical judgment or users' vague and non-quantified subjective description to judge whether a design scheme can achieve the design objectives. Physiological data and biofeedback can provide more scientific and objective evidence for scheme optimization. Simultaneously, the evaluation process will not require users to understand professional knowledge or imagine 3D space based on 2D drawings. It can be much easier and more convenient for users to participate in design.

Besides, there are still some shortcomings in this research. Firstly, since the perception of detection requires sensing devices' support and controlled environmental conditions. The laboratory is more suitable for the experiment, which brings inconveniences to users' and designers' participation. Also, most physiological signals can only objectively reflect the degree of the user's emotional arousal instead of accurately determining the emotional type. Therefore, this study could only use subjective questionnaires to verify the biofeedback. In the next research stage, some other physiological detection methods such as Electroencephalogram (EEG) and FER can be used to obtain the user's emotional type.

In conclusion, this research used sensor and computer technology to get biofeedback from users in an emulation VR environment and combine it with the objectives of the design proposal to pre-evaluate architectural spaces. This method is expected to aid in improving design schemes and providing evidence-based recommendations to designers.

6. Funding

This work was supported by the National Social Science Fund Later Stage Funding Project. Grant no: 19FXWB026 and the Guangdong Science and Technology Project, Grant no: 2017A020220011. Thanks to the "King far Research Support Program" of King far International Inc. for supporting this study and providing the necessary devices.

References

Coroado, L., Pedro, T. and D, J.: 2015, VIARMODES:Visualization and Interaction in Immersive Virtual Reality for Architectural Design Process, *Real Time-Proceedings of the 33rd eCAADe Conference-Volume 1*, Vienna, Austria, 125-134.

Frost, P. and Warren, P.: 2000, Virtual Reality Used in a Collaborative Architectural Design Process, *An International Conference on Computer Visualization and Graphics. IEEE*, 568-573.

Lee, G., Choi, B. and Jebelli, H.E.A.: 2020, Wearable Biosensor and Collective Sensing-Based Approach for Detecting Older Adults' Environmental Barriers, *Journal of Computing in Civil Engineering*, **34(2)**, 04020002.

Marín-Morales, J., Higuera-Trujillo, J.L. and Greco, A.E.A.: 2018, Affective Computing in Virtual Reality:Emotion Recognition from Brain and Heartbeat Dynamics Using Wearable Sensors, *Scientific reports*, **8(1)**, 1-15.

Norouzi, N., Shabak, M. and Embi, M.E.A.: 2015, A New Insight into Design Approach with Focus to Architect-Client Relationship, *Asian Social Science*, **11(5)**, 108.

Westerdahl, B., Suneson, K. and Wernemyr, C.E.A.: 2006, Users' Evaluation of a Virtual Reality Architectural Model Compared with the Experience of the Completed Building, *Automation in Construction*, **15(2)**, 150-165.

Yazdanfar, S.A., Heidari, A.A. and Aghajari, N.: 2015, Comparison of Architects' and Non-Architects' Perception of Place, *Procedia-Social and Behavioral Sciences*, **170**, 690-699.

CONTACTLESS AND CONTEXT-AWARE DECISION MAKING FOR AUTOMATED BUILDING ACCESS SYSTEMS

DJORDJE STOJANOVIC[1] and MILICA VUJOVIC[2]
[1]*University of Melbourne*
[1]*d.s@unimelb.edu.au*
[2]*University Pompeu Fabra*
[2]*milica.vujovic@upf.edu*

Abstract. In the current context of the COVID-19 pandemic, contactless solutions are becoming increasingly important to making buildings more resilient to the spread of infectious diseases in complementing social distancing and disinfection procedures for disease prevention. The presented study focuses on contactless technology and its role beyond automated interaction with the built environment by examining how it expedited space use and could improve compliance with sanitary norms. We introduce a conceptual framework for the intelligent operation of automated doors in an educational facility, enabled by the network of sensory devices and the application of computational techniques. Our research indicates how versatile data gathered by RFID systems, in conjunction with data extracted from occupancy schedules and sanitary protocols, can be used to enable the intelligent and context-aware application of disease prevention measures. In conclusion, we discuss the benefits of the proposed concept and its role beyond the need for social distancing after the pandemic.

Keywords. Human-Building Interaction; Interactive Environments; Responsive Environments; Occupancy Scheduling; Occupational Density.

1. Introduction

Contactless technology is rapidly finding applications in medicine, retail, and travel. In the current context of the COVID-19 pandemic, contactless solutions are also becoming increasingly important to making buildings more resilient to the spread of infectious diseases in complementing social distancing and disinfection procedures for disease prevention. To this end, public touchpoints in workplaces, lobbies, toilets, and elevators are being replaced with touchless interfaces. However, the cumulative impact of contactless solutions such as automatic doors, soap dispensers, taps, and electrical switches on how buildings are used is not fully understood. The potential of nascent technologies, enabling touchless interaction in the built environment is not adequately explored, and its relation to how buildings are designed and used is not fully discussed. Interactions

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 193-202.

between buildings and their occupants through multi-modal Human-Computer Interaction such as interactive speech and gesture recognition can dramatically enhance the way buildings are experienced, managed, and operated (Malkawi and Srinivasan 2005). The presented study focuses on contactless technology's purpose beyond automated interaction with the built environment, and it examines its role in expediting space use to improve compliance with sanitary norms.

We introduce a conceptual framework for the intelligent operation of automated doors that would be used in an educational facility, enabled by the network of sensory devices and the application of Computational Techniques (CTs). While focusing on a school building's needs, the paper shows how data capturing occupancy patterns, health and disease prevention measures, and learning environment requirements are coordinated to inform automatic doors‘ operation. The data is used to enable seamless entry to and trespassing across different areas of the school. The proposed framework would assist a 'return to the campus‘ as a tool for balancing between students' individual needs, social distancing measures, new sanitation protocols, class timetable, and curriculum specific requirements. In response to CAADRIA 2021 'Projections' topic of Interactive Environments, this paper contributes to computational design innovation by grounding a method for the application of CT's to enact evidence-based inquiry into architectural notions of context, access, and the relationship between people and buildings.

This paper outlines the research as follows. In the first section, a brief literature review establishes known technologies supporting contactless access systems and context-aware decision-making techniques relevant to the built environment and applicable to school buildings. The emphasis is placed on the use of Radio-Frequency Identification (RFID) systems. The aim is to create an information-rich decision-making context for automated access systems to the school building to help implement social distancing measures while maintaining efficient use of spaces. And to employ sensing devices to facilitate contactless interaction with the built environment. We propose and describe the use of an algorithmic framework to control the operation of automated doors across the school building, using the Melbourne School of Design building as a setting for our research. In the results section, we present a framework for data collection, processing, and structuring. Our research indicates that versatile data gathered by RFID systems, in conjunction with data extracted from occupancy schedules and sanitary protocols, can be used to enable the intelligent and context-aware application of disease prevention measures. In conclusion, we discuss the benefits of the proposed conceptual framework and its role beyond the need for social distancing after the pandemic.

2. Background Research

The investigation related to touchless interaction systems in the built environment is part of a broader and growing research scope on the use of sensing devices for data gathering and CTs for information processing. Sensing devices most commonly applied in capturing data from the built environment include Passive Infrared (PIR) sensors, Carbon-Dioxide (CO_2) detectors, Radio-Frequency

Identification (RFID), Wi-Fi counters, optical and infrared cameras, and a combination of devices to compensate for their individual insufficiencies (Hobson et al. 2019). At the same time, an increasing number of studies into advanced CTs shows how computation is employed to improve accuracy and robustness and reduce the operation cost of sensing devices (Dai et al. 2020).

RFID, as well as PIR based systems, are tried and tested solutions for automated access in buildings. While PIR sensors measuring infrared light radiating from objects in the field of view offer cost-effective and reliable solution for the operation of automated doors, RFID based systems permit wider application and can be used to collect diverse information from the built environment, such as location and identification of goods, animals, and humans (Irani et al. 2009, Oliveira et al. 2016). Advances in RFID technology first introduced in the 1990s are well documented by researchers in 17 190 papers published between 2006 and 2015 (Oliveira et al. 2016). The reduction of cost and the increase of longevity enable even more extensive use of this versatile technology. Systems composed of several readers, a large population of tags with an antenna and a server, are used in conjunction with information processing techniques to enhance their performance and structure data acquired by the system for multiple uses (Chen et al. 2018). For example, in the Architecture, Engineering, Construction, Owner and Operator industry, multi-level encryption is used to enable role-based access to data stored on tags attached to building components (Motamedi et al. 2011). In terms of access to buildings, the use of rules to override the system's binary operation is successfully linked with either PIR of RFID systems to either restrict or grant access at certain times (Aprilananda-Sujatmoko and Sujarwo 2020).

Moreover, the use of roles, i.e., for staff and students, with RFID systems, is developed for selective application of rules according to predetermined privileges (Rahman et al. 2019). Additional benefits to the security features of a door locking system can include a log containing check-in and check-out of each user along with basic information of use (Verma and Tripathi 2010), and can help attendance management by registering and tracking tags (Chiagozie and Nwaji 2012). Therefore, albeit some challenges to the implementation, such as those related to dealing with colliding tag responses and facilitation of the efficient tag identification (Wu et al. 2020) and factors such as attenuation and cross paths of signals or interference between systems (Ting et al. 2011), RFID systems provide a tool for harvesting versatile information from the built environment.

Recent research shows that the information gathered by RFID systems and other sensing devices, when processed and structured, can become valuable to understanding behavioural patterns (Guo et al. 2019) and intelligent management and operation of buildings (Duan and Cao 2020). Wireless sensor networks, groups of sensors linked with wireless media, have found diverse applications in the built environment linked to both optimising the use of resources and occupants' wellbeing (Wu and Noy 2010). Strides in miniaturization, wireless networking, and sensor technologies enable computers to be used in more places and have a greater awareness of the dynamic world they are a part of (Hong and Landay 2001). Recognizing context from the sensor data plays a crucial role in adding value to the raw sensor data, and therefore context-awareness is considered the core feature of ubiquitous and pervasive computing systems (Yang and Cho 2017).

Context is regarded as a key factor of computation, alongside the explicit input and output (Moran and Dourish 2001). Context-aware computing and computational frameworks are employed to automate and integrate context-aware sensing, data aggregation, information extraction and understanding, and qualitative decision-making through intelligent algorithms (Biswas et al. 2016). Recent research involving context-aware systems for home automation proposes the hierarchical model to reason from uncertain facts inferred from real sensor data (Chahuara et al. 2017) and adaptive decision-making systems for learning from data (Brenon et al. 2018).

The primary use of RFID-based automated access to educational buildings is driven by the need to improve the security of occupants and assets (e.g., Farooq et al. 2014, Rahman et al. 2019). However, in the context of the current COVID-19 pandemic, this study examines how the existing automated and RFID supported access systems can be enhanced using CTs to include context-aware decision-making and improve occupants‘ health and well-being while maintaining the efficient use of facilities. The proposed system aims to respond to occupants' needs and balance between efficient space usage and sanitary measures imposed by the current pandemic.

3. Research Aims

An automated access system's default role would be to open or close a door when an occupant approaches and passes through that door. From the disease prevention point of view, this helps minimize exposure to potentially contaminated door handles. The system can be put in operation at certain times of the day, which is also helpful as it can restrict access when there is no need for the use of individual facilities, and therefore, minimize further any unnecessary exposure. Significantly, the system could also facilitate the right of entry to only some users. For example, staff could be allowed to enter individual rooms while students may not be, which could also help minimize unnecessary contact. These features are achieved with well-known and frequently applied RFID systems in educational facilities, initially introduced to improve security in buildings identified in this paper's previous section. In the context of the current pandemic and much-expected return to campuses in Australia, these contactless interfaces have also become valuable as they minimize exposure to public touchpoints. However, the system's ability to selectively give access to some occupants offers itself as an effective disease prevention tool and forms this study's focus.

The aim is to define a decision-making context and develop an information processing framework to facilitate automated access to the school building's rooms to help implement disease prevention measures and disinfecting procedures while enabling efficient use of spaces. The proposed system's role is to open or close doors at certain times for certain users when certain conditions are met. The objective of this study is to help establish what users under what circumstances are permitted to enter individual rooms of the school. The study aims to answer the following research questions. What information is relevant, and how is it processed to create a disease prevention computing context? And what sensing tools and CTs can be employed to facilitate an intelligent access system within such a context?

The study addresses the Melbourne School of Design building's needs to examine the correlation between social distancing measures, disinfection procedures, and activity schedules to inform automated doors' operation. The study aims to provide intelligent and dynamic assistance rather than to apply generic disease prevention measures, insusceptible to human behaviour's unpredictability. Current disease prevention measures related to the use of buildings, namely social distancing rules, are generic and do not address the nature of activities and rooms. Moreover, current measures do not take many human-related aspects into account. Human behaviour varies, and it is difficult to predict, and therefore the application of uniform measures may not be adequate at all times

4. Framework for context-aware automated building access

The proposed algorithmic framework outlines a method for data harvesting to create a decision-making context. The computing context is built from the information gathered by RFID devices and extracted from occupancy scheduling. There are three relevant sets of data. First, the new sanitary protocols impose disinfection procedures in an individual room between occupational shifts, such as when one tutorial group leaves, and the other takes possession. Although cleaning slots are programmed and scheduled, restricting access to a room to students and staff while cleaning is in progress would enhance their safety by reducing unnecessary exposure to potentially contaminated areas or surfaces. Second, an RFID system controlling door operation at the entrance to a room provides the count of people entering and exiting the room. The count is translated into the number of people in a room and checked against social distancing norms, currently requiring 4 [m2] area per user to establish if more users can be allowed to that room. Third, timetabling and class schedules provide valuable sources of information for the operation of doors. For instance, access permission can be given selectively to students registered for a class unfolding in a specific room. In turn, this would also enhance their well-being by further minimisation of contact and the probability of breaching social distancing rules. At this stage, the proposed approach is to extract data from class timetabling and cleaning protocols to inform the system, while occupants count data is to be provided by RFID system monitoring access to individual rooms. We recognize that occupancy scheduling in educational buildings is becoming an increasingly complex field and identify the need to address how data gathered by RFID count could be used to inform timetabling in future studies.

Based on the occupant's alignment with one of the predetermined roles, the decision-making process is outlined in the second part of the proposed algorithmic framework (Figure 1). Such roles would typically be students, teachers, cleaners, maintenance, and security in school buildings. Moreover, within each role, subcategories would be used to further differentiate between occupants‘ privileges.

For example, students' access to individual rooms would be related to their enrolment in subjects or study programs. The use of roles is a well-developed feature of RFID systems whereby individual users are listed in sets and subsets with different access privileges, initially developed to enhance security and ease people's circulation through buildings. In this study, an RFID system with a role feature is used to exercise access control to individual rooms to improve disease prevention measures while maintaining efficient use of space in educational buildings.

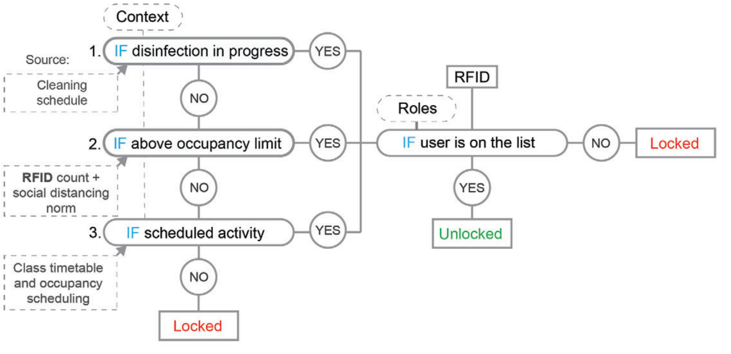


Figure 1. Computational framework for a contactless and context-aware building access system.

The proposed conceptual framework's significance is the ability to collect data across three levels of inquiry and evaluate if it is safe for a particular role to have access to that room, or if the presence of a specific role would compromise other occupants' safety, such as to students and staff during disinfection routine. The proposed concept's main benefits are enabling contactless interaction with the building, enacting intelligent and context-sensitive application of disease prevention measures rather than generic social distancing measures, and the capacity to act preventatively by minimizing overcrowding in buildings

The visible and tangible part of the proposed system, or the actuation, would be through a controlled operation of the automated door system, facilitating the right of entry to individual rooms if specific conditions are met. Four different scenarios are presented to examine the flow of information and demonstrate possible outcomes (Figure 2).

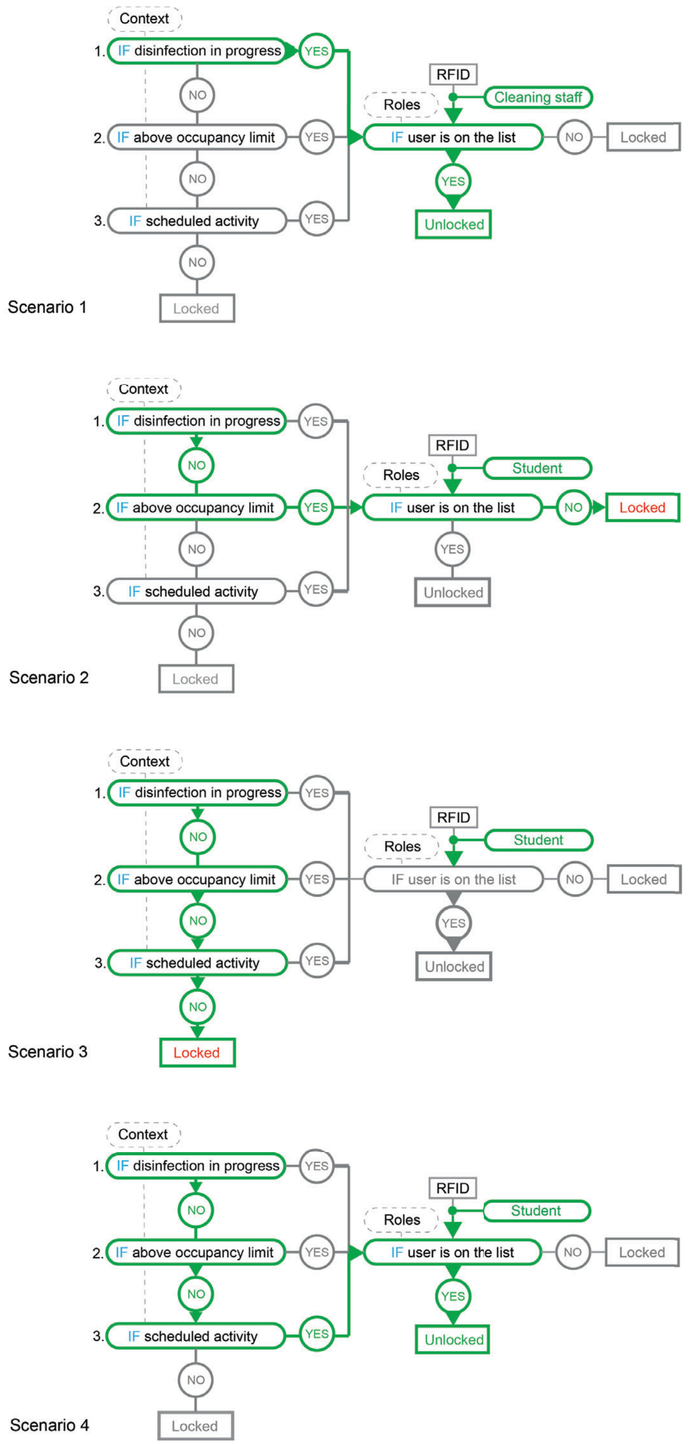


Figure 2. Four scenarios for information processing with outcomes.

Scenario 1 shows that when cleaning is in progress, doors are locked for everyone but specific user IDs, such as cleaners, maintenance, and security. In Scenario 2, it is not a cleaning time, but occupants count is high, and social distancing measures are compromised. The critical threshold or the number of people allowed to any room fluctuates according to prescribed sanitary norms. In the context of the COVID-19 pandemic, currently prescribed norms fluctuate between 2 and 4 [m2] area per user. The number of people allowed in the room is calculated when the room's floor area is divided by 4. If an RFID reader positioned at the room entrance records a critical number of occupants, the access is restricted to students, and everyone but personnel dealing with the emergency is meant to be out of the room. In Scenario 3, an occupant's tag is identified as a student, disinfection is not scheduled at this time, occupants' count is below the critical threshold, but the room is not booked through timetabling, and therefore, access to students is not granted. This inquiry line could be extended to establish if the occupant, student, or teacher is directly involved with scheduled activities. If the student is not enrolled in the study programme scheduled to occur in that room, their access to the room will be denied, giving priority to occupants enrolled in classes unfolding in that room. Scenario 4, all levels of inquiry are satisfied according to the occupant's ID, and doors are automatically unlocked and opened to grant access and avoid the use of public touchpoints such as door handles. The proposed system would facilitate a far greater number of scenarios, and four selected scenarios are to demonstrate the flow of information and possible outcomes.

5. Discussion and Conclusions

The proposed conceptual framework is an innovative use of the existing RFID based technology, enabling an automated and context-aware building access system to improve infection control measures. The primary use of RFID-based automated access to educational buildings is in improving security. However, in the context of the current COVID-19 pandemic, this study examines how the existing automated access systems can be enhanced using CTs to include context-aware decision-making to improve occupants' health and well-being and the efficient use of facilities. The proposed system is designed to maintain efficient use of space while responding to sanitary measures imposed by the current pandemic. The contactless human-building interaction is employed to minimise exposure to potentially contaminated surfaces and public touchpoints. It also expedites the use of space to improve compliance with the sanitary norms by granting access to individual rooms only when it is safe or when occupational density complies with social distancing rules and when disinfecting or cleaning protocols are not unfolding.

The research question, on what information is relevant, and how it is processed to create a disease prevention computing context is answered with a formulation of an algorithmic framework, identifying input information structured across three conditions or layers of inquiry before the actuation, lock/unlock door status could be granted. The second research question on what sensing tools and CTs are employed to facilitate an intelligent access system within the defined context is answered by structuring the relationship between conditions and occupants' identity, redacted and reduced to one of the predefined roles.

The proposed framework sets grounding for further research and developing a fully functional prototype that could be useful to the Melbourne School of Design building. At this stage, the study results with a concept seeking further development through evidence-based research. The study reported in this paper relies on known RFID techniques and explores the combined use of different data sets to establish a decision-making context. However, the correlation of data acquired by the network of sensory devices and data extracted from class timetabling and disinfection protocols is not fully resolved at this stage. The study's further limitations include dealing with a high flux of students and staff in the school, potentially resulting in colliding signals and interference between different systems in close proximity to each other

Beyond improving infection control measures in school buildings, this study's contribution is in expanding the architectural meaning of the context through sensing devices and CTs. It probes into human-building interaction and suggests a way to study the built environment through human behaviour. In the longer run, data acquired with the proposed wireless sensor networks could provide valuable insight into how buildings are used and help both researchers and designers explore context-sensitive and intelligent solutions to improve indoor environmental quality

References

Berry, J. and Park, P.: 2017, A Passive System for Quantifying Indoor Space Utilization, *ACADIA 2017: DISCIPLINES & DISRUPTION Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, Cambridge, MA, 138-145.

Biswas, P., Moon, S., Qi, H. and Dey, A.: 2016, Computational frameworks for context-aware hybrid sensor fusion, *International Journal of Image and Data Fusion*, **7**(1), 83-102.

Brenon, A., Portet, F. and Vacher, M.: 2018, ARCADES: A deep model for adaptive decision making in voice controlled smart-home, *Pervasive and Mobile Computing*, **49**, 92-110.

Chahuara, P., Portet, F. and Vacher, M.: 2017, Context-Aware Decision Making Under Uncertainty for Voice-based Control of Smart Home, *Expert Systems with Applications*, **75**, 63-79 .

Chen, H., Wang, Z., Xia, F., LI, Y. and Shi, L.: Efficiently and completely identifying missing key tags for anonymous RFID systems, 2018, *IEEE Internet Things Journal*, **5**, 2915–2926.

Chiagozie, O.G. and Nwaji, O.G.: 2012, Radio frequency identification (RFID) based attendance system with automatic door unit, *Academic Research International*, **2**(2), 171-183.

Duan, K.K. and Cao, S.: 2020, Emerging RFID technology in structural engineering – A review, *Structures*, **28**, 2404-2414.

Farooq, U., Hasan, M., Amar, M.A., Hanif, A. and Asad, M.: 2014, RFID based security and access control system, *International Journal of Engineering and Technology*, **6**(4), 309-314.

Gomez-Zamora, P. and Bafna, S.: 2019, Spatiotemporal Occupancy for Building Analytics, *Architecture in the Age of the 4th Industrial Revolution Proceedings of the 37th eCAADe and 23rd SIGraDi Conference*, Porto, Portugal, 111-120.

Guo, Z., Wang, X. and Yuan, P.: 2019, Sensing Human Behavior in the Built Environment, *Hello, Culture! Proceedings18th International Conference, CAAD Futures 2019*, Daejeon, Korea, 378-388 .

Hong, J. and Landay, J.: 2001, An Infrastructure Approach to Context-Aware Computing, *Human–Computer Interaction*, **16**(2), 287-303.

Irani, Z., Gunasekaran, A. and Dwivedi, Y.: 2010, Radio frequency identification (RFID): research trends and framework, *International Journal of Production Research*, **48**(9), 2485-2511.

Malkawi, A.M. and Srinivasan, R.S.: 2005, A new paradigm for human-building interaction: the use of cfd and augmented realit, *Automation in Construction*, **14**(1), 71–84.

Moran, T. and Dourish, P.: 2001, Introduction to This Special Issue on Context-Aware Computing, *Human–Computer Interaction*, **16**(2), 87-95.

Motamedi, A., Saini, R.S., Hammad, A. and Zhu, B.: 2011, Role-based access to facilities lifecycle information on RFID tags, *Advanced Engineering Informatics*, **25**(3), 559-568.

Oliveira, A., Oliveira, H., Gomes, C.F., Francisco, C. and Ribeiro, P.C.: 2016, Quantitative analysis of RFID' publications from 2006 to 2016, *International Journal of Information Management*, **48**, 185-192.

Rahman, S.N., Bashar, S.S., Al Mahmud, M.A., Miah, M.S., Karim, A.Z. and Marium, M.: 2019, A Security System for Kindergarten School Using RFID Technology, *Journal of Computer and Communications*, **70**(4), 21-30.

Aprilananda Sujatmoko, B. and Sujarwo, A.: 2020, Dual Security System for Room Access Control Using RFID at Islamic University of Indonesia, *Materials Science and Engineering Conference Series*, Yogyakarta, Indonesia, 012029-35.

Ting, S.L., Kwok, S.K., Tsan, A.H.C. and Ho, G.T.S.: 2011, The Study on Using Passive RFID Tags for Indoor Positioning, *International Journal of Engineering Business Management*, **3**, doi:10.5772/45678.

Verma, G.K. and Tripathi, P.: 2010, A digital security system with door lock system using RFID technology, *International Journal of Computer Applications*, **5**(11), doi:10.5120/957-1334.

Wu, S. and Noy, P.: 2010, A conceptual design of a wireless sensor actuator system for optimizing energy and well-being in buildings, *Intelligent Buildings International*, **2**(1), 41-56.

Wu, L., Sun, P., Wang, P. and Yang, Y.: 2020, Toward Efficient Compressed-Sensing-Based RFID Identification: A Sparsity-Controlled Approach, *IEEE Internet of Things Journal*, **7**(8), 7714-7724.

Yang, K. and Cho, S.K.: 2017, A context-aware system in Internet of Things using modular Bayesian networks, *International Journal of Distributed Sensor Networks*, **13**(5), 1-18.

VIRTUAL WORLD16

Virtual Design Collaboration for the Intersection of Academia and Industry

MARC AUREL SCHNABEL[1], YOSHIHIRO KOBAYASHI[2], YOANN PENCREACH[3], AMAR BENNADJI[4], DONGSOO CHOI[5], PAOLO FIAMMA[6], TOMOHIRO FUKUDA[7], TIAN TIAN LO[8], TARO NARAHARA[9], MARCOS NOVAK[10], RUTH RON[11], MATTHEW SWARTS[12], KOSTAS TERZIDIS[13], THOMAS TUCKER[14] and REBEKA VITAL[15]
[1] *Victoria University of Wellington*
[1] *MarcAurel.Schnabel@vuw.ac.nz*
[2] *Arizona State University*
[2] *dr.yoshihiro.kobayashi@gmail.com*
[3] *Forum8*
[3] *yoann@forum8.co.jp*
[4] *Robert Gordon University*
[4] *a.bennadji@rgu.ac.uk*
[5,14] *Virginia Tech*
[5,14] *{ds22|thomasjt}@vt.edu*
[6] *Universita di Pisa*
[6] *paolo.fiamma@ing.unipi.it*
[7] *Osaka University*
[7] *fukuda@see.eng.osaka-u.ac.jp*
[8] *Harbin Institute of Technology (Shenzhen)*
[8] *skyduo@gmail.com*
[9] *New Jersey Institute of Technology*
[9] *narahara@njit.edu*
[10] *University of California, Santa Barbara*
[10] *marcos@mat.ucsb.edu*
[11] *University of Miami*
[11] *rron@miami.edu*
[12] *Georgia Tech*
[12] *matthew.swarts@design.gatech.edu*
[13] *Tongji University*
[13] *kostas.terzidis@yahoo.com*
[15] *Shenkar College of Engineering and Design*
[15] *rebekavital@gmail.com*

Abstract. Over the past 13 years, the 'World16'-group has collaborated face-to-face on various challenges that architectural design faces within VR, architecture, urban design, and its delivery to the professional industries. The focus of the collaboration is to foster pathways of academic research and developments to industries and professions. In

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 203-212. © 2021 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

2020, due to the restrictions of the pandemic, the group had to rethink and redevelop how to collaborate meaningfully and become resilient: the World16 collaborated akin to the Virtual Design Studios (VDS) of the Nineties for the first time exclusively virtually becoming the 'Virtual World16'. The paper presents the group's various projects that are transformative to the praxis in VR architecture, design and urban design, and critically reflects on the lessons learned from VDS-paradigm.

Keywords. Virtual Design Studio (VDS); Human-Computer Interaction (HCI); VR, AR, XR; Collaboration; 3D City Modelling.

1. Introduction

The current academic framework of architectural research often thwarts Virtual Reality (VR) research and development. Most universities have only a few researchers in computational design, so it is not easy for them to find opportunities for development and collaboration. Conferences enable the sharing of conceptual knowledge, but not of VR technologies. Besides, there are many different VR instruments, so most researchers use different platforms to develop VR data and tools. As a result, it is difficult to verify each others' models, and it is hard to share a combination of knowledge and skills. It is a problem from the point of view of knowledge-accumulation (Kobayashi 2009). In particular, the collaboration and exchange with the industry and profession are challenging and often not well developed. World16 has set out to change this and actively connect internationally with researchers, industries in architecture, urban design, construction, and hard- and software developers who supply instruments for the field. Over the past years, there has been much development of VR-technologies, -modelling and -visualisations. The 'World16'-group has sixteen leading VR researchers (Stals and Caldas 2020) as permanent members on all continents matched by sixteen hard- and software developers. Additionally, adjunct members, guests-researcher or -practitioners offer fresh input to yearly changing research themes.

Since the modus of operandi of World16 is independently from research institutions, IP, methodologies and outcomes are shared openly. The close connection to industry partners offers World16 a timely grounding of their research and developments. World16 subsequently can operate in a unique realm that fosters novelty and transformative additionalities.

2. VR-Design Studio

Since 13 years, World16 uses and further develops the same common VR software platform *VR-Design Studio* (2020) to explore advances in city-modelling, VR visualisation, evaluation, narrative architecture, civil engineering, urban design, parametric modelling, computer graphics, digital art, and digital heritage. VR-Design Studio allows for a multitude of data types from industry-standard applications to be imported and simulated in a real-time 6D environment. The use of a common software platform enables World16 members to share data easily. Modification of the Software Development Kit (SDK) allows members to write their own computational tools when necessary. The Japanese software, developed around 2000 under the name *UC-win/Road,* can simulate traffic (moving agents), environmental conditions, and rich environmental data and visualisations in VR.

3. Virtual World16 Design Studio and Collaboration

In 2020, due to travel restrictions of the pandemic, World16 met for the first time exclusively virtually. First in July, for their annual 'hackathon' VR-symposium to co-develop, discuss and research novel avenues that can be implemented through VR-Design Studio. And again, in November, as part of the *14th Forum8's Design Festival 2020*, World16 showcased the outcomes of their research to industry- and sector-professionals at their yearly event, the (13th) *International VR Symposium* (F8DF 2020). Embracing the Virtual Design Studio (VDS) paradigm developed in the nineties (Kvan 2001), a 'Virtual *World16* Design Studio' (Vw16DS) was set up spanning over nine timezones from -13 UTC to +8 UTC. Three overlapping groups were set up to band members into most suitable time groups. Using the experiences gained by Schnabel and Kvan (2001) and Schnabel and Ham (2010) the Vw16DS worked and collaborated within an immersive social Virtual Environment (VE) to match the virtual realm of the research and development outcomes. Vw16DS used *Slack* (www.slack.com) as the main collaboration platform to facilitate collaboration, discussion and exchange. Video communication employed *Zoom* (www.zoom.us). Social- and dissemination-events were successfully held within *SpartialChat* (www.spatial.chat). Throughout the Vw16DS, various VR-plugins, -tools, -apps, and novel VEs such as *www.cluster.mu* were trialled, allowing to benchmark the research against recent developments in the field. Each symposia had at least two joint (virtual) activities for all group members, adjuncts and guest researchers to meet and critique their undertakings.

4. Virtual World16 Projects

The following twelve research projects were finalised in 2020, while others are still ongoing. They present a snapshot of the engagements of World16 over the past years. The research extends and builds upon the work presented in Kobayashi et al. (2010). Each of the research projects was led by one World16 academic who collaborated with one hard- or software developer. At the same time, the groups critiqued the work of each other at regular intervals to enrich the shared knowledge.

4.1. HUMAN-COMPUTER INTERACTION (HCI)

4.1.1. Eye-Tracking Voxel Environment Scultper (EVES)

Schnabel team's *Eye-Tracking Voxel Environment Scultper* (EVES) utilises eye-tracking to draw with one's eyes three-dimensionally within a VE (Wells et al. 2021). Within EVES, a ray is projected from the user's gaze data as the input method to sculpt voxels and navigate in-program menus. A guide-cursor follows the users' gaze indicating where they will sculpt. The guide-cursor takes the form of a selected brush, and by blinking - akin to a mouse click - voxels are sculpted and manipulated. Allowing eyes to draw, sculpt and manipulate form directly amplifies the capabilities of what the eyes can do, beyond that of which is typically possible. The eyes become actors in the design generation (Figure 1).

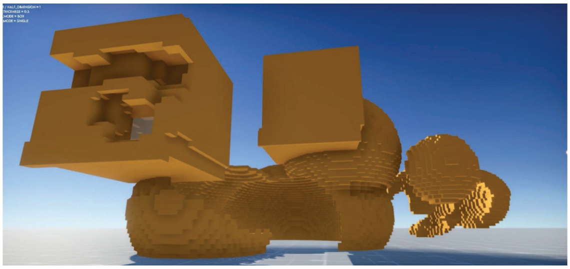


Figure 1. EVES' screenshot with Cube- and Box-tool as drawn with the user's eyes.

4.1.2. Interactive Mixed Reality Buildings

Tucker's project team utilizes physical scaled building forms overlayed with virtual reality. The interactive experience has the participant wear a *VIVE* head-mounted display (HMD) to engage with physical and VR buildings in real-time. The physical buildings have been modelled, and laser scanned to match the VR 3D buildings, so they are in sync when the participant grabs or moves a building form. To make the buildings interactive, VIVE Trackers have been placed on each building. Then the XYZ coordinates are fed into VR-Design Studio. The tracking is processed in the software to give real-time responses to movements and give responsive 3D visuals to the buildings' HMD participant in the VR space. The participant can manipulate both the physical and virtual objects and place them where desired (Figure 2).

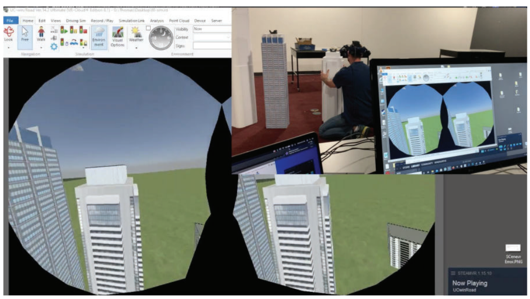


Figure 2. Interactive MR buildings, screenshot and physical models.

4.1.3. Interactive Virtual Sand Table (IVST)

VR has a highly simulated environment and efficient information interaction, pushing "human-computer interaction" to the level of "human-environment interaction". In participatory design, using this technology can reduce the operational burden of non-professionals and improve design efficiency. Lo team's IVST has a fixed viewing perspective. It duplicates the traditional physical sand table model and simply make it virtual and interactive. For non-professionals, it is easy to freely rotate the model and work with the virtual content by putting on 3D glasses and using hand gestures to manipulate the virtual objects intuitively (Lo and Gao 2020) (Figure 3).

Figure 3. System setting of the Interactive Virtual Sand Table (IVST).

4.2. VISUALIZATIONS TECHNIQUES

4.2.1. Point-Cloud Marker

Point-cloud data is useful for intermediate analysis within workflows, as they are relatively fast and contain attributes that model continuous data. Typical point-cloud colour data show either colour of the intensity value or actual RGB value if present; otherwise, it will be grayscale. To manipulate the colour of point cloud data is to reprocess each point cloud, save it out manually, and reimport into the point-cloud capable software, which is time-consuming and error-prone. Choi team's research altered this workflow by introducing a highlighting function. The area of interest in the point-cloud is changed by altering the existing or adding new colours to the data set via selecting the plane(s) in XYZ or boosting the current colour sets to a more prominent colour. The process allows for additional values and information to be added to the particular region (Figure 4).

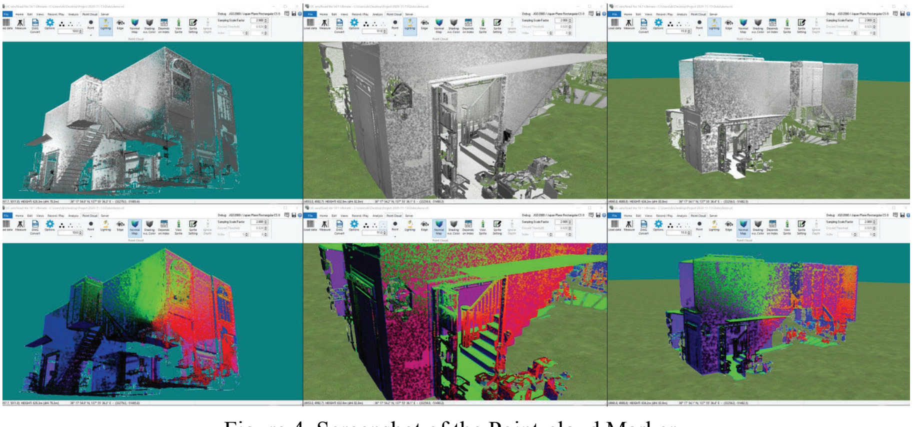


Figure 4. Screenshot of the Point-cloud Marker.

4.2.2. Motion Vector Visualization for Preventing VR Sickness

Increased uses of VR have resulted in a higher incidence of VR sickness. When a VR user along a predetermined walk-through path, audiences are forced to be presented with VR that involves movement and rotation. To prevent a VR sickness and ensure a VR content quality, a function is necessary to visualise movements within the VR space during the VR production process. Fukuda's team developed a rendering method of a VR camera's absolute velocity using a customised segmentation rendering (Fukuda et al. 2020). The absolute velocity values might be insufficient to evaluate a VR sickness. Their visualisation method of a VR camera's motion vector applies a customised segmentation rendering technique by calculating relative velocities on a VR screen at each frame. It overlays a colour on the screen according to the value to identify where in a virtual scene, VR sickness is likely to occur (Figure 5).

Figure 5. VR screenshots of motion vector visualization - normal and amended views.

4.2.3. Affordable Homes from Andragogy to Professional Tool

In collaboration with *Grampian Housing Association Ltd*, an affordable housing company, short design videos were produced. Due to the stakeholders' lack of interaction, a virtual self-guided exhibition was created to allow users to navigate virtually through the various designs. Bennadji's research team allowed future home buyers to understand better their home design and suggest changes they would like to see in their future home. Simultaneously, the transformative outcomes now allow housing procurement and commercial transactions to incorporate virtual procedures before a building is delivered to clients with higher satisfaction (Pleyers and Poncin 2020) (Figure 6).

Figure 6. Screenshot of one design of the Affordable Home Tool.

4.2.4. Artistic Interpretations of Point Clouds in VR

Vital's research team developed options for point cloud visualizations within the VR environment of VR-Design Studio. The visualization options go beyond the representation of points to points represented as different types of particles: i.e. brushstrokes, crystals, tiles, etc. and thus creating an artistic interpretation of the point cloud environments that can be experienced in VR (Figure 7).

Figure 7. Original point cloud and artistic interpretations (brushstrokes, hexagon particles).

4.2.5. Training of Tough Road Conditions for Drivers and Autonomous Systems

After developing solutions to simulate and visualise invisible urban environmental conditions (traffic noise, air pollution) (Grobman and Ron 2011),Ron's research team implemented into the driving-simulator the impact of reduced visibility (heavy rain, snow, fog (Figure 8), sandstorm, low sun angles) and increased stopping time/distance due to slippery roads conditions (wet, icy, oil-spill, unexpected obstacles). This included re-coding traffic algorithms to simulate car crashes.

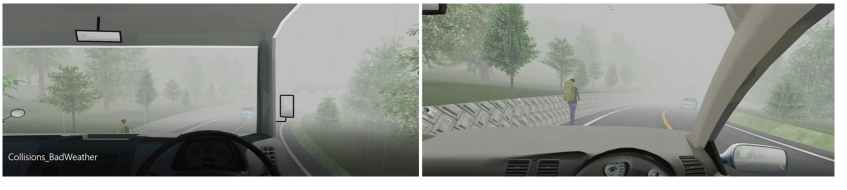


Figure 8. Simulation of a traffic collision in rain, fog and noise. Truck's and sedan's view.

4.3. INTELLIGENT MODELLING, DATA STRUCTURES, MACHINE LEARNING

4.3.1. Flexible Traffic Lights: Traffic Light Management using AI

Traffic lights are vital points of traffic managements as they can increase or decrease traffic flow depending on their timing. With the use of Artificial Intelligence (AI), it is possible to predict traffic flow. However, AI is often not transparent (a.k.a. 'black box'), stochastic, and therefore hard to rationalize (Lawe and Wang 2016). Terzidis' team constructed a system that uses permutations to optimize traffic lights' timing at intersections with AI prediction. It system replaces stochastic prediction with exhaustive permutations. Out of these permutations, patterns are sought that define the flow of traffic more accurately, making predictions more accurate, and impactful (Figure 9).

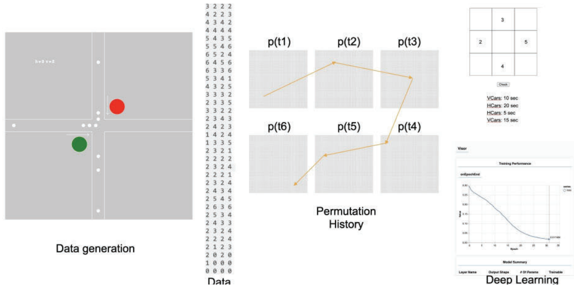


Figure 9. Flexible Traffic Lights System Map.

4.3.2. Recapturing Visions of Cities

VR is a time- and cost-effective pathway for data collection and annotating city images for machine learning (ML) (Narahara 2017). The acquisition of near-photo-realistic images and auto-generations of segmentation maps can be controlled by with ML algorithms rather than by web crawlers or costly outsourcing. Narahara's team used ML algorithms: images of various cities were extracted from VR models and used as data for the image-to-image translation model using *pix2pixHD*. Figure 10 shows examples of outputs transferred into "Tokyo style" from generic hand sketches with designated colours for some aspects of cityscapes as inputs. The use of larger datasets for higher quality and user studies are required to evaluate its feasibility.

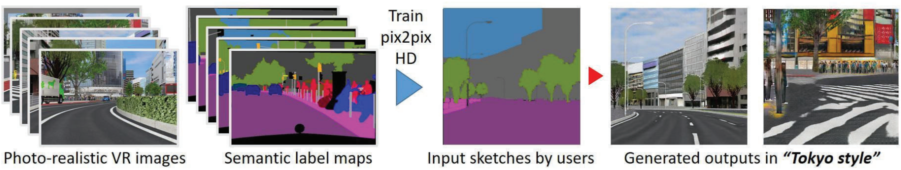


Figure 10. Sketches are transferred with selected cities' styles via datasets acquired in VR.

4.3.3. Selective Reality Substitution: 3D GAN and Latent Space Explorations

Autonomous vehicles, converging with XR, ML, AI, and HPC technologies, are enabling new possibilities for navigation through hyper-mediated urban spaces. Highly mediated environments are often boisterous and polluted by visual and spatial information. Just as sonic noise cancellation allows a focus on specific sonic signals, so can XR technologies replace undesirable aspects with other desirable visual and spatial information. Building on previous stages, Novak's research team explored how ML and AI techniques are used stereoscopically to generate alternate 3D *soft realities.* They are superimposed upon the real world to enable reliable *selective reality substitution* (transLAB 2020) (Figure 11).

Figure 11. Right: Picture of original space - Left: Soft Reality.

4.3.4. Designing sustainably using an IFC Parametric Development System

Fiamma's team combine data sets to IFC models and making these data and models parametric can combine different sets to a more sophisticated urban model. Akin to BIM, City Information Management (CIM) offers new lifecycle assessment pathways, design and planning. Parametric thinking means thinking about systems and subsystems, parts and entire, hierarchies of project and product. It leads actors to think (the construction design) like an organism made by connections (Fiamma 2014) (Figure 12). By bringing these CIM models into VR, diverse groups of stakeholders can understand the complexity of CIM and contribute to a process that responds to sustainability requirements (Venugopal et al. 2015).

Figure 12. Ontologies and parametric IFC objects as support to predittive design.

5. Conclusion

World16 has developed transformative research for and together with industry- and professional partners in the realm of XR in architecture, urban design, construction, heritage, city modelling, HCI, ML, and AI. In 2020 alone, World16 has innovatively collaborated in three main areas of HCI, visualisation, and intelligent modelling improving the simulation capabilities possible in XR. The professional virtual design collaboration - based on the VDS paradigm - between academia and industry has extended avenues to jointly advance virtual spatial simulations. The Vw16DS has evolved the VDS from an educational setting to a high-quality platform that intersects academic interests with those of the industry's and users' realms. Despite collaborating in real-time over several time zones is ambitious and challenging, World16 demonstrated successfully that the VDS paradigm can produce market-ready commercial solutions. The scheduled half-yearly touchpoints via joint symposia allowed all stakeholders to gain value from each other's developments, facilitated research validations, implementations, and dissemination to users. Over the next years, World16 will intersect XR with challenges of AI, blockchains, carbon neutrality, health and social-economical issues in the broader architectural and urban real and virtual realm.

Acknowledgement

World16 sincerely thanks the group of Forum8 software developer volunteers and acknowledges the financial support by Forum8 Co. Ltd.

References

"F8DF - 14th Forum8's Design Festival" : 2020. Available from <https://www.forum8.co.jp/fair/df/index-e.html> (accessed 1 December 2020).

"transLAB - Media Arts and Technology" : 2020. Available from <http://translab.mat.ucsb.edu/> (accessed 1 December 2020).

Fiamma, P.: 2014, About the Parametric Matter: is this [(x=x0 +at);(y=y0+bt)] Architecture?, *International conference on Innovative Engineering Technologies (ICIET'2014)*, Bangkok, 172-177.

Forum8, -: 2020, "VR-Design Studio" . Available from <https://www.forum8.com/technology/vr-design-studio/> (accessed 1 December 2020).

Fukuda, T., Novak, M., Fujii, H. and Pencreach, Y.: 2020, Virtual reality rendering methods for training deep learning, analysing landscapes, and preventing virtual reality sickness, *International Journal of Architectural Computing (IJAC)*, **18**(4), pgs 18.

Grobman, Y. and Ron, R.: 2011, Digital Form Finding: Generative Use of Simulation Processes by Architects in the Early Stages of the Design Process, *29th eCAADe*, Slovenia, 107-115.

Kobayashi, Y., Grasso, C. and McDearmon, M.J.: 2010, World16: Innovation and Collaboration in VR Technology, *Future Cities, 28th eCAADe Conference*, Zurich, 593-603.

Kobayashi, Y., Hawker, R., Terzidis, K., Narahara, T., Wael, A., Fukuda, T., Labarca, C., Calderon, C. and Jemtrud, M. 2009, World8: International Working Group for new Virtual Reality Applications in Architecture, *in* , *Joining Languages, Cultures and Visions: CAADFutures*, Les Presses de l'Université de Montréal, Montréal, 547- 556.

Kvan, T.: 2001, The Pedagogy of Virtual Design Studios, *Automation in Construction*, **10**(3), 345-353.

Lawe, S. and Wang, R. 2016, Optimization of Traffic Signals Using Deep Learning Neural Networks, *in* B. Kang and Q. Bai (eds.), *Australasian Joint Conference on Artificial Intelligence*, Springer, Cham, 403-415.

Lo, T.T. and Gao, X.R.: 2020, From HCI to HVRI - How different will the interaction of digital architecture design be?, *RE: Anthropocene, Design in the Age of Humans - 25th CAADRIA Conference*, Bangkok, Vol 2, 253-262.

Narahara, T.: 2017, Collective Construction Modeling and Machine Learning: Potential for Architectural Design, *ShoCK! - Sharing Computational Knowledge! - 35th eCAADe Conference - Volume 2*, Rome, 341-348.

Pleyers, G. and Poncin, I.: 2020, Non-Immersive Virtual Reality Technologies in Real Estate: How Customer Experience Drives Attitudes toward Properties and the Service Provider, *Journal of Retailing and Consumer Services*, **57**, 102175.

Schnabel, M.A. and Ham, J.J.: 2010, The Social Network Learning Cloud: Architectural Education for the 21st Century, *International Journal of Architectural Computing (IJAC)*, **12**(3), 225-242.

Schnabel, M.A. and Kvan, T.: 2001, Implementing The First Virtual Environment Design Studio, *Architectural Education for the Asian Century, 1st ACAE Conference on Architectural Education*, Singapore, 157-166.

Stals, A. and Caldas, L.: 2020, State of XR Research in Architecture with Focus on Professional Practice – A Systematic Literature Review, *Architectural Science Review*, **63**, pgs 9.

Venugopal, M., Eastman, C.M. and Teizer, J.: 2015, An ontology-based analysis of the industry foundation class schema for building information model exchanges, *Advanced Engineering Informatics*, **29**(4), 940-957.

Wells, C., Schnabel, M.A., Moleta, T. and Brown, A.: 2021, Beauty is in the Eye of the Beholder: Designing with One's Eyes, *Projections - 26th CAADRIA Conference*, Hong Kong, 10 pgs.

THE FOURTH VIRTUAL DIMENSION

Stimulating the Human Senses to Create Virtual Atmospheric Qualities

LIAM JORDAN SHEEHAN[1], ANDRE BROWN[2],
MARC AUREL SCHNABEL[3] and TANE MOLETA[4]
[1,2,3,4] *Victoria University of Wellington*
[1] *liam@sheehan.net.nz* [2,3,4] *{Andre.Brown|MarcAurel.Schnabel|Tane.Moleta}@vuw.ac.nz*

Abstract. In a move away from the ubiquitous ocular-centric Virtual Environment, our paper introduces a novel approach to creating other atmospheric qualities within VR scenarios that can address the known shortcoming of the feeling of disembodiment. In particular, we focus on stimulating the human body's sensory ability to detect temperature changes: thermoception. Currently, users' perceptions of a 3D virtual environment are often limited by the general focus, in VR development for design, on the two senses of vision and spatialised audio. The processes that we have undertaken include developing individual sensory engagement techniques, refinement of sensory stimuli and the generation of virtual atmospheric qualities. We respond to Pallasmaa's theoretical stance on the evolution of the human senses, and the western bias of vision in virtual engine development. Consequently, the paper investigates the role our senses, outside of the core 'five senses', have in creating a 'fourth virtual dimension'. The thermoception dimension is explored in our research. A user can begin to understand and engage with space and the directionality within a virtual scenario, as a bodily response to the stimulation of the body's thermoception sense.

Keywords. Virtual Reality; thermoception; sensory experience; immersion; atmosphere.

1. Introduction

Experience, more precisely Human Experience, is set against the backdrop of the perception of space. Yet, the concept of spatial comprehension is difficult to grasp - simply because we cannot place our finger upon it (Watts 2019). The relationship between our body and the spaces we inhabit is a fundamental part of any architecture experience, yet we often neglect the complete set qualities of space itself. Understanding the qualities of space is a difficult proposition for the western culture; primarily due to an ocular-centric paradigm which has provided us with our primary understanding of the world. However, the domination of vision within the human sensory experience has only originated throughout the last few centuries. The human sensory experience was primarily dominated by

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 213-222.

hearing; with a recent shift towards vision occurring gradually (Pallasmaa 2005 p. 24). The shift from hearing to vision is a change attributed to the western culture shifting from oral to written speech (Holl 2006 p. 30). A shift that is relevant in the research context as a shift from sound space to visual space.

The development of Virtual Reality (VR) systems over the last 50 years have allowed VR to become a global operation with a wide range of implementations from medical training to gaming. However, much like human sensory experience, VR systems are heavily ocular dominant, wherein tactile and auditory engagement is often treated as secondary functions to vision (Slater and Sanchez-Vives 2016). The prevalence of vision-based reality is a problem for VR systems as it limits the level of presence which a user can experience whilst inside a virtual scenario. Presence is a necessity for VR systems as it allows users to step into an immersive boundless reality. However, without an adequate sensory data substitution and an active engagement of the human sensory system, a user consciousness' can never be expected to completely embrace a virtual scenario (Slater and Sanchez-Vives 2016 p. 4, Ranasinghe et al. 2017 p. 1732). This absence of certain sensual stimuli in virtual environments has in the past have been characterised as a lack of ”otherness”. We represent a limited set of senses in VEs and consequently failed to represent the others, that in the real world, the human is fully aware of.

Our paper captures a new aspect of sensory experience within VR, which provides insights into the different ways the human thermoception sense, or the sense of temperature changes, can help enhance a VR users' experience of virtual space. Existing research within the sensory experience realm has often focused on auditory, tactility, scale, virtual bodies and positioning of the user within a virtual scenario (Bicchi et al. 2008, Cooper 2020, McCosh 2020, Rogers 2019a). Bailey (2020) discussed the importance of sensory perception in VR to achieve a 'synchronous reality' for users that enhances the immersion. The research carried out in these author's respective fields are explorative and provide insights into the different ways that the human body can be directly engaged whilst in a virtual scenario. The publication 'Reimagining Relativity' (Rogers et al. 2019b) highlights the importance of interconnected design processes when generating environmental inhabitation in VR. The reimagining of the body as a virtual inhabitant necessitates that VR systems must reproduce atmospheric qualities to create realistic virtual environments, and inherently virtual experiences (Rogers et al 2019b) (Figure 1).

The introduction of thermal systems within VR research is not unique to our paper and has been the subject of many previous studies. The primary application of heat within most of these studies has involved the placement of heating 'nodes' onto the user's skin, often on the rear of the neck or within haptic hand gloves (Kim et al. 2017, Ranasinghe et al. 2017, Ranasinghe et al. 2018). The research situates itself apart from these papers. It approaches the application of temperature by introducing 'spatialised heat'; treating temperature as a tactile response to virtual environments and as a critical atmospheric quality of the virtual environment. Through the production of a virtual atmosphere, this research produces what it defines as a 'fourth virtual dimension', an experiential medium which connects the 3-axial dimensions and allows a user to experience a continuous 360° understanding of the virtual environment.

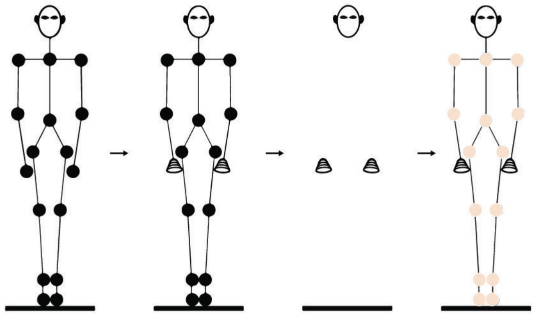


Figure 1. Re-Introduction of the body control points through thermoception. Adapted from (Rogers et al. 2019b).

2. Defining the Fourth Virtual Dimension

"By altering atmospheric conditions, the immaterial is materialised, the invisible becomes visible, what was absent becomes present. Space itself is rendered, not only visible but palpable, substantive"; Blau (2010 p. 106) suggests when considering Olafur Eliasson's artworks. Our research finds itself in a unique field of contemporary theory that attempts to bridge the fields of psychology and architecture. Through the critical review of relevant research papers and theorist's, a better understanding of how the human body perceives space through all of its senses simultaneously, and how no singular sense can act independently from the collective conscience can be generated (Montagu 1971 pp. 1-5, Hillier 1996 pp. 29-33, Pallasmaa 2005 pp. 16-21). The review provides the basis for our paper's methodology, where it becomes apparent that the balancing of individually engaged senses is crucial when creating a fourth virtual dimension that the user can experience.

The experience of space, or in this context 'the fourth virtual dimension' is an idea which has been explored predominantly through art during the previous century. James Turrell creates light works which allow his observers to experience the intangible. Turrell achieves this experience by carefully reproducing light within controlled environments. Turrell's works allow his audiences to visually observe an empty medium, or in fact; the empty medium of space (Adcock 1990 p. 220).

Our paper introduces Spatial Experience and Environmental Psychology's research fields to new technologies that can create or enhance our fourth virtual dimension experience. The three-axis' which we observe reality through is the primary subject of this research. The introduction of a thermal environment to the virtual realm is utilised to understand virtual space. It is also used to understand the extent to which a thermal environment creates a new non-visual form of directionality within the fourth virtual dimension. The three-axis we observe reality is the combination of our bodies location in space and the shape of that space, whilst Figure 2 demonstrates the fourth virtual dimension, as the connection between body and space.

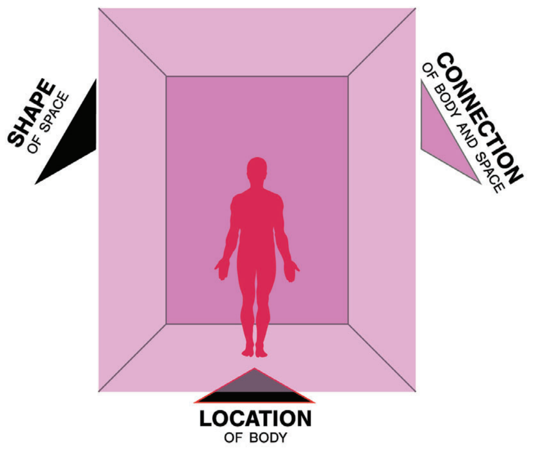


Figure 2. Illustration of 'fourth virtual dimension' connecting the 3-axial dimensions.

3. Methodology

Our methodology approaches the fourth virtual dimension as a problem of sensory refinement. This problem created a framework for our research approach; based on prior research, and relation to the fourth virtual dimension, four sensory inputs were selected (Visual, Auditory, Locomotion and Thermoception). Each sense was assessed individually at each stage of the research before the respective next stage of development occurred. Understanding each sense's role in creating and perceiving a virtual atmosphere and the extent to which each sense should be stimulated are the primary assessment criteria for the research.

The *HTC VIVE PRO* VR-headset was the device used for the testing of each research stage. This device allowed the user to move freely within each scenario as the VIVE PRO is a wireless VR unit. Initially, locomotion was implemented through an *HTC VIVE* controller, utilising the default teleportation mechanism discussed in Rogers et al (2019b). However, Initial testing with the thermal system presented an issue where the user could not effectively sense heat through the hand holding the controller. The integration of a *Microsoft Kinect 2.0* resolved this problem sufficiently. The Kinect has full-body tracking capabilities and allowed the user to move freely within the virtual space.

Each virtual scenario was developed through a combination of *Unity3D* and *C-sharp* coding techniques. Unity3D actively controlled the thermal environment, allowing it to respond to user action and changes in the *Head-Mounted Display (HMD)* position. The thermal environment is composed of *Magic Living's 375w Infrared Heat Lamps* connected to a *Theatrelight DMX dimmer. HOG 4 PC,* a PC based lighting console program, actively controlled the dimmer unit. Unity3D calculated changes in the HMD position, creating a percentage value for each heat lamp. Open Sound Control (OSC) protocols communicated this percentage value with HOG 4 PC, which allowed real-time updating of each respective heat lamps intensity value.

4. Stage One

Commencing the fourth virtual dimension experiment, the researchers began with a blanket engagement of all four selected senses. Each sense was equally stimulated through a dynamic abstract experience. The researchers decided to start with a blanket engagement, as it allowed a rapid understanding of each sense's role in creating and experiencing the fourth virtual dimension.

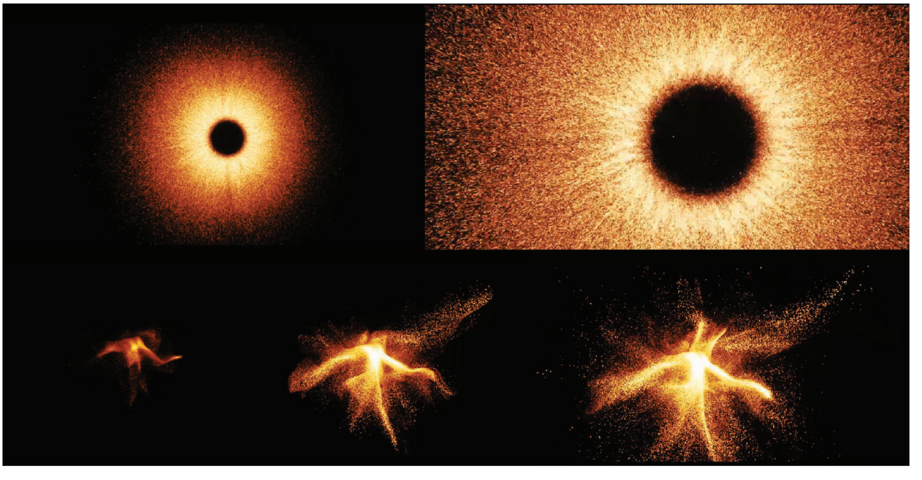


Figure 3. Multi-sensory testing through vfx driven simulations .

The VFX-graph tool in *Unity3D* can create high-quality particle effects for VR (Figure 3). The tools ability to create dramatic and dynamic visual stimulation in 3D environments allowed the rapid creation of stage one's virtual scenario. The orchestral music of Camo and Krooked (2020) controlled the particle effects, allowing the integration of the dynamic visuals and the auditory sense.

The Kinect 2.0 sensor has the capability of recognising recorded movements of the human body. Due to the cosmic scale of stage one's virtual experience, it became necessary to provide locomotion through a set of arm movements which would accelerate the user forward or backwards depending upon the action performed. The Kinect 2.0 also tracked the user's hands, allowing them to interact with the VFX particle effects, creating an inferred presence of body within the virtual scenario.

Finally, the thermal environment was produced through a singular heat lamp placed in front of the user. The heat lamp would increase and decrease its intensity depending upon its intensity and the user's proximity to each particle effect system.

The stage one virtual scenario provided the researchers with a clear understanding that a more delicate balance of sensory stimulation was necessary moving forward. Although this scenario was highly immersive, it became overwhelming at times, and what can be defined as sensory overload became apparent at stages of the scenario. The stimulation resulting from intense graphics, increased auditory engagement and thermoception incitement led to an overwhelming experience, which initially maintained immersivity. However, after about 30- 40 seconds, the users' engagement in the experience began to reduce. This lack of engagement between the user and the virtual scenario was a surprising finding which altered the approach to sensory interactions in future stages. The constant engagement of the senses and the single directionality of the heating system also did not help the user establish a 360˚ understanding of the virtual scenario. The research paper concluded stage one by understanding that if a fourth virtual dimension were to be effectively experienced, there would need to be more emphasis placed on the stimulation of the body's thermoception sense.

5. Stage Two

From the previous exploration of sensory engagement in a virtual scenario, the researchers wanted to better understand the qualities of heat itself. By understanding what qualities heat provided to a VR user, and what qualities were absent, the researchers could produce a more resolved understanding of how to create an experience of the fourth virtual dimension.

The researchers decided that the Kinect 2.0 sensor was not an effective means of delivering locomotion within this research context, as it created unrealistic expectations of heat and scale, which the heating system could not actively provide. As an alternative, the VR experience took place in a small room (3.5m x 2m), where the user could move freely within the bounds of the space.

Stage two replicated the sun's day-cycle, rising from the right of the user and setting to the left. To test the extent to which the thermoception sense can accurately perceive directionality and spatiality, the HMD displayed a black screen with no audio.

Four heat lamps were mounted around the user (Figure 4), and Unity3D calculated the sun's position to the user. The calculation allowed a percentage of angle for each heat lamp to be created and transmitted through the OSC-protocols.

By individually stimulating thermoception, this stage effectively demonstrated the role of heat in creating spatial perceptions of a virtual scenario. The introduction of the thermal system as the sun rises, caused the user to move towards the heat lamp, embracing the warmth and exploring the changes in temperature as they moved around the light. However, the absence of all other sensory stimuli created a virtual scenario that became unsettling and displaced the VR users' perception of space. It became possible to navigate the space throughout the virtual scenario; however, it was not easy to discern the room's bounds, nor was the user able to establish a complete 360° understanding of the virtual scenario. The stage highlighted an issue to the researchers, where the VIVE PRO headset effectively removed the perceptions of heat to most of the face and head. However, when the user turned around, the heat experienced on the neck's rear was highly effective and immersive. This stage's results allowed the researchers to approach the final stage of the research paper with a more comprehensive understanding of the role thermal changes can have on a VR experience.

Figure 4. Interconnected heating installation.

6. Stage Three

The previous stages of virtual scenario design provided our research with an understanding of sensory balance's significance in creating an experiential fourth virtual dimension. This research's final development stage built upon the findings so far and re-introduced visual and auditory senses to stage two's virtual scenario. The researchers created a 'meditative' alternate reality that provides the user with minimal auditory engagement and limited visual stimulation while focusing on a thermal system's refinement.

The researchers addressed the ocular sense by providing it with a minimal stimulus, an approach to emphasise thermoception. The HMD was placed in the centre of a slowly rotating night sky and an endless lake of lapping water. A forest of dark trees sat in the water around the user, which allowed the sun's visualisation to be displaced during sunrise and sunset. Limiting the auditory sensation to the sound of lapping water against rocks, combined with the minimal visual stimuli, allowed the thermoception sense to become the primary sensory input.

The auditory sensation was limited to a quiet sound of lapping water against rocks. The combination of dark, mysterious visual cues and auditory sensations was utilised to emphasise the warmth slowly introduced into the environment.

Much like the previous stage, the VR experience took place in the same room (Figure 5). The researchers placed a 700mm x 900mm platform on the floor for the user to stand on, which limited the users‘ movements within the room. Represented as a 3m high podium in the virtual scenario, the podium's introduction into the scenario engaged the users' sense of presence by creating a point of reference, connecting their physical and virtual movements.

Figure 5. Mixed Reality demonstrating the suns path of travel around the user, with heat lamp connection.

The introduction of acute visual and auditory stimuli proved effective in creating an experiential fourth virtual dimension. The displacements of light shown allowed the thermal sense to take a primary dominance within users. As a result of the carefully balanced stimulation of the Auditory, Ocular, Locomotion and Thermoception senses, users' comprehension of the virtual environment becomes three dimensional and occurs concurrently. An example of this was during sunrise, where users looked away from the 'sun' or heat source. Thermoception's engagement allowed the VR user to understand changes to the virtual atmosphere in real-time, often prompting a reaction to view and experience the temperature change. Due to the room's small constraints, implementing our heating system to VR experiences is limited to situations where an active engagement with the environment is not necessary, such as cinematic VR experiences.

7. Conclusion

The introduction of spatialised thermal atmospheres for VR systems proved highly successful in this research. By introducing an atmosphere of heat around a VR user, our research allows a greater understanding of the role that temperature changes can have on our comprehension of space, whether it is contained to the virtual. A strategically organised process was designed and implemented to create a multi-sensory experience that researched Thermoception stimulation's role in the virtual environment. By first understanding that a delicate balance of sensory stimuli must be maintained to create a presence within a virtual scenario. Our research encourages limiting selected sensory stimuli, in this case, visual and auditory, to allow new sensory inputs to take a primary sensory dominance within the human body. However, our research proposes that overloaded sensory design could have broader applications within non-architectural discourses such as education and simulation of high-stress scenarios, where heightened active sensory stimuli are common.

The significance of virtual atmospheric qualities and the role of heat in creating them has enabled us to understand more effective ways to experience a continuous understanding of a virtual scenario. Classically VR systems only allow a user to perceive what is occurring in front of their eyes. The introduction of spatialised audio allowed this perception to expand to virtual actions/events around the user. However, these events are usually caused by preset animations or as a result of the user's actions. By introducing a heating system, we can begin to allow users to perceive changes to the virtual environment itself. Changes could include the rising of a sun or the change in a thermal environment as the user enters a virtual building.

Exploring new processes like this within virtual environments stimulates new excitement for designers, clients and the public by creating better unison between VR scenarios and the human body. The virtual environment creates a richer picture of the human brain to process. It thereby creates an environment that is more fully furnished with the senses that humans possess and employ to understand the environment they are inhabiting. By implementing more comprehensive atmospheric qualities in VR, we begin to design more completely immersive and engaging virtual art and architectural design forms.

References

Adcock, C.E.: 1990, *James Turrell: The Art of Light and Space*, University of California Press, Berkeley.

Bailey, D.E.: 2020, Synchronous Reality: Enhancing Sensory Perception in Immersive VR, *Journal of Telecommunications and the Digital Economy*, **8**(1), 18-36.

Bicchi, A., Buss, M., Ernst, M.O. and Peer, A.: 2008, *The Sense of Touch and Its Rendering Progress in Haptics Research*, Springer, Berlin.

Blau, E.: 2010, *The Third Project. Olafur Eliasson: your chance encounter*, Lars Müller Publishers, Baden, Switzerland.

Camo, initials missing and Krooked, initials missing: 2020, "Red Bull Symphonic" . Available from <https://www.redbull.com/nz-en/films/red-bull-symphonic-film> (accessed 21 April 2020).

Cooper, Z.: 2019, *Unseen - Digital interactions for low vision spatial engagement*, Master's Thesis, Victoria University of Wellington.

Hillier, B.: 1996, *Space is the Machine: A Configurational Theory of Architecture*, Cambridge University Press, Cambridge, UK.

Holl, S.: 2006, *Questions of Perception: Phenomenology of Architecture*, William Stout, San Francisco.

Kim, M., Jeon, C. and Kim, J.: 2017, A Study on Immersion and Presence of a Portable Hand Haptic System for Immersive Virtual Reality, *Sensors*, **17**, 14.
McCosh, L.: 2020, *AMORPHOUS Towards a Sonic Architecture*, Master's Thesis, Victoria University of Wellington.
Moleta, T.: 2017, Digital Ephemera - Autonomous Real-Time Events in Virtual Environments, *Protocols, Flows, and Glitches - Proceedings of the 22nd CAADRIA Conference*, Suzhou, China, 13-22.
Montagu, A.: 1971, *Touching: The Human Significance of the Skin.*, Columbia University Press, New York.
Pallasmaa, J.: 2005, *The Eyes of the Skin: Architecture and the Senses*, Wiley-Academy, Chichester.
Ranasinghe, N., Jain, P., Karwita, S., Tolley, D. and Do, E. Y.-L.: 2017, Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions, *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, Denver, 1731-1742.
Ranasinghe, N., Eason Wai Tung, C., Yen, C.C., Do, E. Y.-L., Jain, P., Thi Ngoc Tram, N., Koh, K.C.R., Tolley, D., Karwita, S., Lien-Ya, L., Liangkun, Y. and Shamaiah, K.: 2018, Season Traveller: Multisensory Narration for Enhancing the Virtual Reality Experience, *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, Montreal, 1-13.
Rogers, J., Schnabel, M.A. and Moleta, T.: 2019b, Reimagining Relativity - Transitioning the Physical Body into a Virtual Inhabitant, *Intelligent & Informed - Proceedings of the 24th Computer Aided Architectural Design Research in Asia (CAADRIA)*, Wellington, 2, 727-736.
Rogers, J., Schnabel, M.A. and Moleta, T. 2019a, Digital Design Ecology to Generate a Speculative Virtual Environment with New Relativity Laws, *in* J.-H. Lee (ed.), *Computer-Aided Architectural Design. "Hello, Culture". Communications in Computer and Information Science (CCIS)*, Springer, Singapore, 120–133.
Schnabel, M.A. 2009, Framing Mixed Realities, *in* X. Wang and M.A. Schnabel (eds.), *Mixed Reality in Architecture, Design, and Construction*, Springer, The Netherlands, 3-11.
Slater, M. and Sanchez-Vives, M.V.: 2016, Enhancing Our Lives with Immersive Virtual Reality, *Frontiers in Robotics and AI*, **3**, 74.
Watts, A.: 2019, "Power of Space" . Available from <https://www.alanwatts.org/3-9-5-power-of-space-part-1/> (accessed 21 October 2020).

VRDR

An Attempt to Evaluate BIM-based Design Studio Outcome Through Virtual Reality

FAUZAN ALFI AGIRACHMAN[1] and MICHIHIKO SHINOZAKI[2]
[1,2]*Department of Architecture, Shibaura Institute of Technology, JAPAN*
[1,2]*{na19503|sinozaki}@shibaura-it.ac.jp*

Abstract. During the COVID-19 pandemic situation, educational institutions were forced to conduct all academic activities in distance learning formats, including the architecture program. This act barred interaction between students and supervisors only through their computer's screen. Therefore, in this study, we explored an opportunity to utilize virtual reality (VR) technology to help students understand and evaluate design outcomes from an architectural design studio course in a virtual environment setting. The design evaluation process is focused on building affordance and user accessibility aspect based on the design objectives that students must achieve. As a result, we developed a game-engine based VR system called VRDR for evaluating design studio outcomes modeled as Building Information Modeling (BIM) models.

Keywords. Virtual reality; building information modeling; building affordance; user accessibility; architectural education.

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic situation has forced architectural education institutions worldwide to arrange their academic activities differently. Institutions organize online classes, workshops, and design studios to avoid any viral community transmission within students and supervisors. Unfortunately, both students and supervisors have difficulties involved in an architectural design studio, a hands-on practice, and assessment by nature (Allam et al., 2020). Students cannot present their design works appropriately in front of their screen, and it is hard for supervisors to engage with students' works without any direct hands-on session. It needs a technology that can bridge them gearing verbal presentation, discussion, and assessment in a learning process (Lymer et al., 2009). By looking at the phenomenon, we are interested in investigating virtual reality (VR) technology utilization to help students and supervisors in the design learning process - especially in the design evaluation process, as part of the decision-making process.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 223-232.

In past years, researchers found that students get benefits that help their learning process understand the architectural space and design process using VR technology in architecture education. Dvorak et al. (2005) showed that VR helps increase students' speed and insight in learning architecture. They also found that VR is suitable for students to understand modeling and design faster because they focus on more prominent issues. Horne and Thompson (2008) found that VR technology can extend students' learning processes and improve their motivation and awareness. VR provides the sense of "being there" with immersive interaction between students and their design works. It is considered vital because behavior, cognitive outcomes, and users' subjective experiences must be taken into account by the architectural designer when evaluating a building design using VR (Kuliga et al., 2015).

Researchers also studied that the design evaluation process has become one of the important use cases of VR technology in the architectural, engineering, and construction sectors. VR provides a more efficient design review process and helps stakeholders identifying issues easier (Davila Delgado et al., 2020). VR is also able to assist architectural designers for space assessment ranging from spatial relationship, occupation comfort, visual and audio comfort (Berg and Vance, 2017; D'Cruz et al., 2014; Echevarria Sanchez et al., 2017; Liu and Kang, 2018; Sun et al., 2020). VR also can help non-designer to examine architectural design with ease (Serpa and Eloy, 2020). Even after the design development phase, VR can support stakeholders during the construction phase by providing improved communication between professionals, visualizing design review scenarios in construction, and analyzing building constructability (Bassanino et al., 2010; Boton, 2018; Dinis et al., 2020). Besides, VR usage for design evaluation in the operational phase is also explored. (Akanmu et al., 2020) Although there has been much research on VR for the design evaluation process, VR utilization for architectural design studio evaluation has not been explored much. Therefore, in this study, we explore VR utilization to help students evaluate their design outcomes in an architectural design studio course by developing a game engine-based VR system.

2. Research Method

This study uses a simulation research method (Groat and Wang, 2013) by transforming the design studio outcomes into a real-world setting as a virtual environment and drive individual perceptions of anyone who interacts inside it. We worked with students' design studio outcomes retrieved from the faculty archive. Since selected outcomes were authored as Building Information Modelling (BIM) models, we took advantage of them to enhance user experience inside the VE. This study aims to offer a VR system for evaluating design studio outcomes based on the design objectives assigned in terms of references (TOR) document of the studio course, focused on two components: building affordance and user accessibility.

3. Defining Design Evaluation Components

Before performing the design evaluation process, design evaluation parameters must be defined from both components: building affordances and user accessibility. First, the building affordance concept was derived from The Theory of Affordances, coined by Gibson in 1979 (Gibson, 2014). He described "affordance" as "what it offers the animal, what it provides or furnished, either for good or ill.". For example, in a house, a floor affords a person to walk from one room to another room, and a door affords a person to enter and exit a room. It means that the floor has an affordance of moving between rooms, and the door has an affordance of accessing a room in the house. Simultaneously, a thing can have more than one affordance, whether it is good or bad for a user. For example, a ramp affords a person to move from one place to another place with a different level of height, and at the same time, the ramp also affords a person to slip and fall to the ground. It shows that a ramp has one positive affordance and one negative affordance. Those affordances might be changed because Gibson mentioned that different places of habitat or a built environment might have different affordances.

From an architectural design point of view, Koutamanis (2006) pointed out that the concept of affordances has the potential ability to understand and utilize the different aspects of users. Architects and architectural designers can use affordance as a design approach to go beyond user-profile generalization and understand how people, as their works' end-users, will use the space. Different user has different affordances of the place that they belong. The architect maps the affordances within their design and eventually use them as feedback to improve the final design before it moves to the construction process.

In the design evaluation process, the concept of affordances clearly can be adopted for evaluating design works. An architect can learn and use affordances to determine appropriate goals that he wants to achieve as the final product, as Maier et al. (2009) described. Affordances can be used to understanding failures and unintentional design consequences, including unexpected human behavior. In the end, a design that affords users to do intended behavior and activities by an architect is considered a successful design. Especially when an architect can evaluate and confirm different intended affordances for different users existed in their design. It can be recognized from a large building or room-scale to a small interior scale, such as a ramp or door handle.

For this study, the design outcome's affordances were identified from design objectives mentioned in the TOR document using predetermination strategy. This strategy starts by determining artifact-user affordances (AUA) and artifact-artifact affordances (AAA). The desired studio outcome should have and not have from each design objective as an affordance structure. In short, AUA defines a relationship between a built environment and a human user situated in it. While in AAA, an affordance defines a relationship between an element and other elements in their respective built environment where behavior can exist in it. All identified affordances were mapped in the form of Affordance Structure Matrix (ASM) developed by Maier et al. (2008), as seen in Figure 1. The Matrix is used as an evaluation tool and combined with VR.

Affordance Structure Matrix			Room										Building Component									
			Retail	Atrium	Café	Gym	Karaoke	Minimarket	Toilet (Ladies)	Toilet (Gents)	Toilet (Disabled)	Circulation Area	Slab	Str. Column	Str. Beam	Ramp	Solid Wall	Glass Wall	Railing	Stairs	Ceiling	Facade
+AUA	G1	Safety in activities																				
	G2	Comfort in activites																				
	G3	Suitability of activities with the function of space																				
–AUA	H1	Getting in an accident																				
	H2	Getting lost in the building																				
+AAA	J1	Ability to support the load																				
	J2	Natural ventilation																				
–AAA	K1	Chances of getting hot easily																				
	K2	Excessive glare																				

Figure 1. Affordance Structure Matrix.

The second evaluation component that must be identified is user accessibility. For this study, we are considering a wheelchair user as a study case. Arlati et al. (2019) studied that wheelchair users' movement simulation using VR and HMD devices should be contextualized with the simulated living environment. This step will increase realism that contributes to the VR system's effectiveness for simulating the accessibility of wheelchair users in an environment. As a measurement standard, we use the standard maneuver diameter of a wheelchair user based on the Law of Ease of Building Standard released by the Ministry of Public Works and Housing of Indonesia (2017), as seen in Figure 2. The maneuver diameter of a wheelchair user is 152,5 centimeters in minimum.

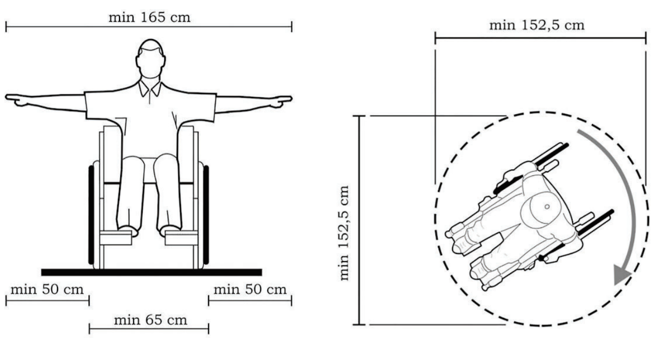


Figure 2. Maneuver diameter for a wheelchair user (Ministry of Public Works and Housing of Indonesia, 2017).

4. VRDR: An Attempt for Design Evaluation in Virtual Reality

After design evaluation parameters were specified, we developed a game engine-based VR system called Virtual Reality Design Reviewer (VRDR). The system was developed using Unity game engine technology and optimized for standalone VR head-mounted display such as Oculus Quest. This decision was made to have VRDR run without a need for high-end personal computer (PC) specification. VRDR lets the user himself explore design studio outcomes in a BIM model inside a VE.

VRDR consists of three system layers: BIM models as 3D geometric and building instance parameter data sources; design evaluation as a decision-making process, user interface (UI), and user experience (UX) layers, as shown in Figure 3. First, as mentioned above, all design studio outcomes used in this study are modeled as a BIM model. Three-dimensional geometries from the BIM model were imported into the .obj file and optimized for VR. We extracted essential parameters from several instances, such as name, area, and volume, to add an informative layer to UI and UX layers. More explanation on how those models and parameters are used in VRDR will be discussed in the next subsection. Second, we put design evaluation as the decision-making process of an architectural design at the center of VRDR. The design evaluation process will be focused on two main design evaluation components: building affordances and user accessibility. The third is the UI/UX layers, consisting of three sublayers: multisensory & spatio-temporal aspect of VR system; architecture design studio nuances in a VE; and positioning students and supervisors as system users.

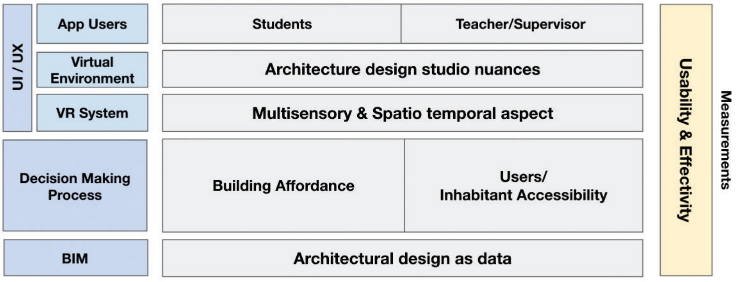


Figure 3. VRDR System Layers Diagram.

4.1. SYSTEM FRAMEWORK

VRDR system framework contained three main parts: Common Data Environment (CDE) of the BIM; VR model; and a standalone VR HMD device connected to the Internet, as shown in Figure 4. CDE worked as the back-end arrangement for VRDR, where the database needed for the system resides. VR model contained all optimized objects with embedded material textures and properties from the BIM models, a representative state transfer (RESTful) client as the connector to the database inside the CDE, and a world space-based UI UX to enable user working with the BIM model inside the VE. Then, the VR model is deployed to the standalone HMD device. It must be connected to the Internet for connecting with databases in the CDE.

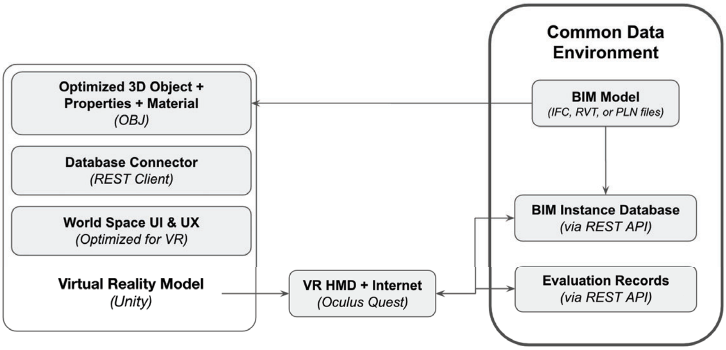


Figure 4. VRDR System Framework.

CDE or BIM repository collects and manages all BIM-based information and objects of individual projects (Sacks et al., 2018). We used a custom arrangement of cloud services and storage adapted from the previous preliminary study (Agirachman and Shinozaki, 2020). There were BIM models of design studio outcomes, instance database, and design evaluation records database in the CDE. The database was filled with the parameters and values extracted from the BIM models and connected to VRDR via RESTful Application Programming Interfaces (RESTful API). It allowed easy data request and storing process by VRDR to the databases.

After preparing the CDE, we developed the VR model in VRDR by exporting the three-dimensional objects from the same BIM models, including their materials. The objects were optimized by reducing their Level of Detail (LoD) and numbers of triangulations. This step is crucial to maintain the VR real-time rendering performance done by the HMD device. It is also helpful to reduce motion sickness that happened to a user when using the VRDR system. Unique object identifiers such as object identification number were also extracted from the BIM models to VRDR to link the object with the instance database set up in the CDE. So, each object could fetch related information via the RESTful API provided in the CDE.

Then, we developed UI inside the VR model to help the user interact with the models, both general and specific tools for the design evaluation process. General tools, such as input keyboard, show and hide buttons, environment adaptor panel; and project information panel, were placed in front of the user avatar for easier reachability. Specific tools such as object tags were placed near their respective object instance; questionnaire panel and scene switcher were placed in the same location along with the general tools. The questionnaire panel was designed to let the user load questions and record feedback to the CDE database. So, we can retrieve the evaluation response faster regardless of the VRDR user location.

For user accessibility evaluation, the system was equipped with a wheelchair simulator with a detector ring around it. The simulator will help the user evaluate the building design if it is suitable for a user with a wheelchair to easily maneuver.

The ring would react if it collided with nearby specified building components such as a wall or door. Ring interaction will be ignored if it has only collided for two seconds or less to avoid any false positive recorded.

4.2. SYSTEM WORKFLOW

In the beginning, the user will be asked to wear the VR HMD device and launch the VRDR application in it. Once the application is started, the user will see the general tools in front of him with the environment adaptor panel and scene selectors. Users will choose a scene of design outcome to evaluate by using a VR controller on their hands.

By default, the user will be in wheelchair mode, where the user can move slower, and the eye position is lower than the normal standing position. The user will be asked to explore all the building sections as a VR model to check whether its design complies with the wheelchair maneuver standard. The detector ring is enabled with green color by default. When it collides with a wall, the ring color turns yellow, and a warning panel appears in the general tools area, as seen in Figure 5. The ring also records the colliding duration and coordinates, which later can be regenerated as a heatmap. That is the workflow for user accessibility evaluation.

The user can then disable the wheelchair mode to move freely in the virtual environment to start building affordance evaluation. For this study, we put a room tag panel linked to the spatial properties of each room. Users can check the information of each room and type their feedbacks using the input keyboard available. After examining all rooms in the building, the user can answer all questions related to building affordance. All user inputs will be sent and stored in the database.

Figure 5. Wheelchair simulator ring turns green when the surrounding space affords the user to maneuver well (left) and turns yellow when the space doesn't (right).

5. Discussion

This section will discuss how the VRDR system works; the original features that make it distinctive; the advantages and disadvantages of the current systems; and opportunities that should be addressed in future studies. VRDR system combines the immersive of VR technology and the power of embedded information inside 3D geometries of a BIM model. It enables the student to get a sense of how his design would be built virtually on a scale of 1:1. By adding information layers from the extracted BIM database, the student can gain more spatial awareness of which area he is currently exploring. It is like playing a first-person video game, but the environment he explores is the building and site design he created by himself. In VRDR, students can evaluate if their designs afford the building users to perform activities mentioned in the TOR document of the design studio and comply with ease of building standard - more specifically for wheelchair users.

VRDR system offers original features that make it distinctive from others. The system has a RESTful client and API built-in, enabling both structured and unstructured data connection. A structured data connection is needed to access structured databases such as the instance database, which contains instance name, width, length, and location. Unstructured data connection availability lets us have a feedback feature where users can type textual feedback, send it to the CDE, and be accessed with other users for review. The system also has a wheelchair mode with a detector ring that helps student evaluate their design compliance with wheelchair maneuver standards. The ring also uses RESTful API to send location coordinate where it gets triggered. We can map the coordinate and check which part of the building has not complied with the standard.

There are advantages and disadvantages of the current VRDR system that we can identify. The VR model linked to the CDE database in the cloud enables the student to update the model information directly inside the virtual environment or outside with a separate dashboard. This advantage opens an opportunity to elaborate it with the design authoring modification process. The student can change specific building components or properties and record all changes to the CDE database. Students can send notes or feedback in text by typing them in the room tag panel and record it as part of their design logbook. Since the current system is in single-player mode, only one student or user can interact with the VR model at a time. Multi-player mode within the VRDR system is an opportunity in a future study. It would be helpful for students and even supervisors to evaluate design outcomes together in real-time.

In terms of the design evaluation process, user accessibility evaluation used in VRDR is still limited for wheelchair users and focuses on wheelchair maneuver radius compatibility. Other detailed factors such as small gaps between floors that can make a user with a wheelchair stuck in it or friction factor between wheels and floor material should be considered to add in the future to have a more realistic simulation. Building affordance evaluation in the study is still considered a self-evaluation where the user evaluates the design by filling the Affordance Structure Matrix. Unlike user accessibility evaluation, where users can use a technical standard to evaluate design compliances quantitatively, building affordance evaluation depends on the cognition skill of each user who experiences it. The evaluation still needs confirmation from third-party, i.e., other students or supervisors, to check if the design has the affordances shown in the Matrix.

6. Conclusion

VRDR system enables students to utilize VR technology to evaluate their design outcomes, mainly in user accessibility, building affordances, and design confirmation aspects. Student can use VRDR to check if his design complies with ease of building standard for wheelchair users and automatically record the spots in the rooms which do not comply with the standard for further analysis. Using Affordance Structure Matrix, the student can evaluate if building affordances based on the design studio objectives have existed in his design outcome. As the outcomes were authored as BIM models, students can get additional information about their design, such as room properties. The instance database provided information in the CDE and linked to each 3D geometry inside the virtual environment.

The next stage of this study is the analysis process of results recorded by the system. The authors will take the step to find out any differences between non-VR and VR system-equipped design evaluation processes, the advantages, and disadvantages of both methods for the student to get more insights into how the VR system can improve their design works. After that, further development of the system will be discussed based on the analysis result.

References

Agirachman, F.A. and Shinozaki, M.: 2020, BINDING DIGITAL AND PHYSICAL ENTITY: ASSEMBLING INTERACTION MODEL USING VIRTUAL REALITY AND BUILDING INFORMATION MODELING, *SEATUC journal of science and engineering*, **1**, 26-31.

Akanmu, A., Olayiwola, J. and Olatunji, O.: 2020, Automated checking of building component accessibility for maintenance, *Automation in Construction*, **114**, 103196.

Allam, Z., Siew, G. and Fokoua, F.: 2020, "How COVID-19 Will Shape Architectural Education" . Available from <https://www.archdaily.com/939423/how-covid-19-will-shape-architectural-education> (accessed 2nd November 2020).

Arlati, S., Colombo, V., Ferrigno, G., Sacchetti, R. and Sacco, M.: 2019, Virtual reality-based wheelchair simulators: A scoping review, *Assistive Technology*, **32**(6), 293-305.

Bassanino, M., Wu, K.C., Yao, J., Khosrowshahi, F., Fernando, T. and Skjærbæk, J.: 2010, The impact of immersive virtual reality on visualisation for a design review in construction, *Proceedings of the International Conference on Information Visualisation*, 585-589.

Berg, L. and Vance, J.: 2017, An Industry Case Study: Investigating Early Design Decision Making in Virtual Reality, *Journal of Computing and Information Science in Engineering*, **17**, 1-7.

Boton, C.: 2018, Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation, *Automation in Construction*, **96**, 1-15.

D'Cruz, M., Patel, H., Lewis, L., Cobb, S., Bues, M., Stefani, O., Grobler, T., Helin, K., Viitaniemi, J., Aromaa, S., Frohlich, B., Beck, S., Kunert, A., Kulik, A., Karaseitanidis, I., Psonis, P., Frangakis, N., Slater, M., Bergstrom, I., Kilteni, K., Kokkinara, E., Mohler, B., Leyrer, M., Soyka, F., Gaia, E., Tedone, D., Olbert, M. and Cappitelli, M.: 2014, Demonstration: VR-HYPERSPACE - The innovative use of virtual reality to increase comfort by changing the perception of self and space, *Proceedings - IEEE Virtual Reality*,

167-168.
Davila Delgado, J., Oyedele, L., Demian, P. and Beach, T.: 2020, A research agenda for augmented and virtual reality in architecture, engineering and construction, *Advanced Engineering Informatics*, **45**, 101122.
Dinis, F., Sanhudo, L., Martins, J. and Ramos, N.: 2020, Improving project communication in the architecture, engineering and construction industry: Coupling virtual reality and laser scanning, *Journal of Building Engineering*, **30**, 101287.
Dvorak, J., Hamata, V., Skacilik, J. and Benes, B.: 2005, Boosting up Architectural Design Education with Virtual Reality, *Central European Multimedia and Virtual Reality Conference*.
Gibson, J.: 2014, *The Ecological Approach to Visual Perception, Classic Edition.*, Taylor & Francis, New York.
Groat, L. and Wang, D.: 2013, *Architectural Research Methods*, John Wiley & Sons, Inc, Hoboken, New Jersey.
Horne, M. and Thompson, E.: 2008, The Role of Virtual Reality in Built Environment Education, *Journal for Education in the Built Environment*, **3**, 5-24.
Koutamanis, A.: 2008, BUILDINGS AND AFFORDANCES, *Design Computing and Cognition '06*, 345-364.
Kuliga, S., Thrash, T., Dalton, R. and Hölscher, C.: 2015, Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model, *Computers, Environment and Urban Systems*, **54**(November 2015), 363-375.
Liu, F. and Kang, J.: 2018, Relationship between street scale and subjective assessment of audio-visual environment comfort based on 3D virtual reality and dual-channel acoustic tests, *Building and Environment*, **129**, 35-45.
Lymer, G., Ivarsson, J. and Lindwall, O.: 2009, Contrasting the use of tools for presentation and critique: Some cases from architectural education, *International Journal of Computer-Supported Collaborative Learning*, **4**, 423-444.
Maier, J., Ezhilan, T. and Fadel, G.: 2007, The affordance structure matrix - A concept exploration and attention directing tool for affordance based design, *2007 Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007*, 277-287.
Maier, J., Fadel, G. and Battisto, D.: 2009, An affordance-based approach to architectural theory, design, and practice, *Design Studies*, **30**, 393-414.
Sacks, R., Eastman, C., Lee, G. and Teicholz, P.: 2018, *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, Third Edition*, John Wiley & Sons, Inc, Hoboken, New Jersey.
Echevarria Sanchez, G., Van Renterghem, T., Sun, K., De Coensel, B. and Botteldooren, D.: 2017, Using Virtual Reality for assessing the role of noise in the audio-visual design of an urban public space, *Landscape and Urban Planning*, **167**, 98-107.
Serpa, F. and Eloy, S.: 2020, How non-designers understand the architecture design project : a comparative study using immersive virtual, *Interaction Design and Architecture(s) Journal*, **45**, 287-301.
Sun, L., Tan, W., Ren, Y., Ji, X., Wang, Z. and Li, P.: 2020, Research on Visual Comfort of Underground Commercial Streets Pavement in China on the Basis of Virtual Simulation, *International Journal of Pattern Recognition and Artificial Intelligence*, **34**(3), 2050005-1-2050005-23.

POPULATING VIRTUAL WORLDS

Architecture, photography, sonic art and creative writing collide at "In the Forest with the Trees we Made".

TANE MOLETA[1] and MIZUHO NISHIOKA[2]
[1,2]*Victoria University of Wellington*
[1,2]*{tane.moleta|mizuho.nishioka}@vuw.ac.nz*

Abstract. This paper provides an original empirical study examining the engagement of artists, curators and virtual tools. The case focusses on a collaborative project called "In the Forest with the Trees we Made". Since the publishing of the project, many compelling findings have been made in reference to both CAAD design and contemporary curatorial and creative practices. They have been made possible, by allowing multi-participants, institutions and disciplines to project their specific creative acts into a single sharable portal. The paper describes the activities of the participants. It then offers a discussion of how these interactions are seated in the new digital realm. The skills of spatialisation, movement through space, generation of geometry and orientation are made accessible through this new digital tool. To conclude, a reflection on the changes in space perception and how 'space' becomes the 'matter' being exhibited is offered.

Keywords. Social Virtual Environments; Mozilla Hubs; Collaboration; Interdisciplinary.

1. Motivations for study

The motivation for generating this paper is to provide an original empirical record of a particular case and to contribute to the fledgling field of Social Virtual Environments (SVE's). The case explores a group of creators who have employed SVE's as an exhibition platform. The significance of writing up this case is that while virtual exhibitions are fairly well documented, the SVE as a phenomenon is relatively recent and novel development.

2. Methodology

The methodology employed in this paper tends toward naturalistic observation and co-creation in the write-up. The authors, who were also creators, try to string together, how the events, instruments and technologies brought together helped found new knowledge. The project has employed the collation of meeting notes, conversation recordings and has included an extensive period of screen recording, some of which have been converted into images for this paper.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 233-242.

3. Introduction

In late 2019 the CAADRIA Thailand local committee has accepted the authors proposal for an on-site exhibition. The goal was to exploring new media arts in the context of CAAD as a follow on to the exhibit at the previous conference held in 2019 in Wellington, New Zealand. The focus was intended to present a body of creative work based on Augmented Reality (AR) and to interrogate notions of digitally activated biophilia across a range of disciplines: Art, Photography, Poetry, Music and Architecture. However, the local committee announced sometime later that the conference would be postponed due to the pandemic, and CAADRIA20 would be held virtually.

The original plan had proposed to generate an internal forest planted in pots on the campus grounds. The project team had intended to create pathways and places to pause amongst the foliage and then set up a series of interventions using QR codes to activate visual, audio and tactile interactions with smart devices. The work was to span spatialised sound installations, augmented poetry readings and on-the-fly processing of photographs. The result looked in principle to leverage fascination with digital devices and technology against the backdrop of negotiating this relationship with a simulated natural environment. However, due to the unprecedented global pandemic, the whole plan needed a considerable to adjust to the virtual delivery of CAADRIA20.

A simple webpage or publication did not meet the project team's expectations. Presenting 2D images as a flat entity was discarded as an option, given the original proposal to exhibit within a physical space and design the exhibit in such a way that moves through and around the forest would not be an approximate shift or provide any conceptual linking between the team's intention and the proposed display. An alternative proposal suggested exploring a scheme using an RTVE. However, managing networking for multiple inhabitants was not something that appealed to the team or adequately matched their professions. A chance decision initiated the activity to explore the SVE known as Mozilla Hubs. Hubs seemed to answer the desires and limitations identified in this exploratory process. Prior research has established that Hubs is suited for use by conference delegates (Duc An Lee, 2020, pp).

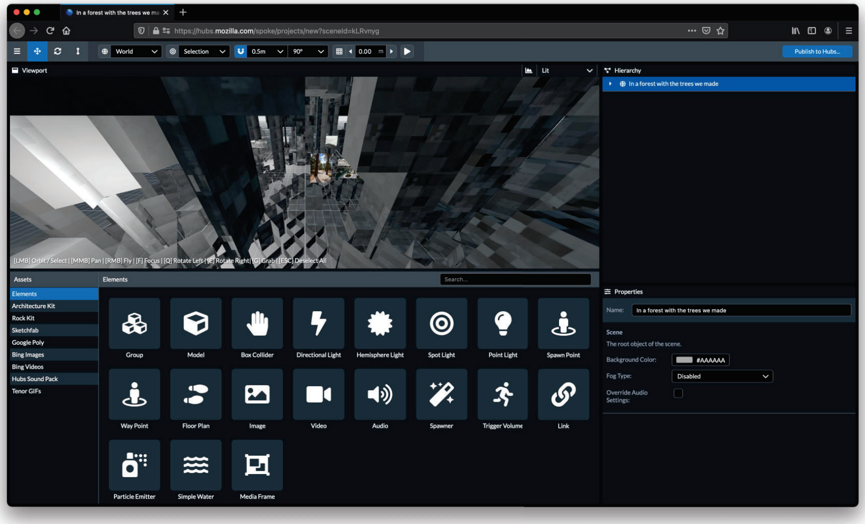


Figure 1. In the Forest with the Trees We Made in Mozilla Spoke for Hubs.

The platform boasts relative stability, and operability across many platforms and a range of devices - including HMD. Lee's study found that Hubs facilitated 'natural' communication (.ibid) between delegates and that moving from one conversation to another was facilitated by 'walking' from one group of colleagues to another. It was decided that this aspect of Hubs is crucial to the presentation of a body of creative work to an audience. Another feature that stands out is spatialised sound. It was noted that being able to inhabit a specific acoustic 'situation' would benefit sound-based works, and provide opportunity to explore the tool more generally. Finally, access to a Hub is pointed out as an especially low hurdle. 'Hubs' being an entirely web-based platform, means that access to the environment is achieved by clicking a single web link. These characteristics supported the project team to consider that an SVE hosted exhibition would support a broad engagement and participation of conference delegates in the work.

4. Creating a virtual forest in a SVE

Lingering feelings of wanting to simulate a forest for the project persisted and an environment was drafted. A philosophical position of interrogating 'digital biophilia' led the project team to explore, not an accurate representation of a forest, but rather, attempt to co-generate an artistic interpretation of what a forest might entail, if not only in the digital world. Inhabitation, enclosure, texture and scale were considered in the creation of the base model. A desire to generate a reasonably tight canopy and a vertical structure, hinting at trees trunks was decided upon. Finally, texture-map and lighting schema was developed to complete the scene.

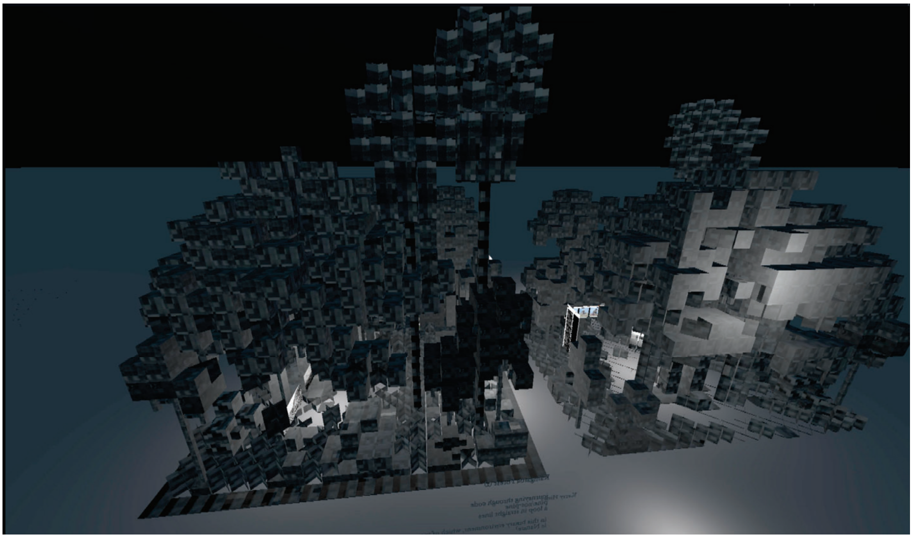


Figure 2. A virtual forest.

The modelling of the virtual environment was undertaken using the online tool TinkerCad. This tool was chosen to facilitate sharing of models with the team, who were predominantly non-architects; Photography, Poetry and Music and had no prior 3D modelling experience. The notion that design options could be viewed and discussed in the online portal Gallery of Things without downloading or needing to learn software was a key consideration. In a considerable departure to typical architectural modelling, no plans were generated. The first creative act was to download a series of components, make quick scalar adjustments and force the components together in what is termed in the game design field as a mash-up. The chosen elements were 'Tree and flower!!', 'Spooky Tree', 'Cycle Tree' and a creatively named, 'boss palm tree SKILLZ'. Beyond this, the items in the base model were all custom created for the environment. A conglomeration of simple cubes was arranged to simulate a grass-like texture, and a very pixelated 'S' shape was used to hint at a hanging vines. A series of intersecting panels were installed in the environment, a kind of crisscrossed effect was achieved, and the floor space was broken up in an ad-hoc manner. This happened to produce 'virtual clearing' in the forest, a small place of rest in an otherwise, increasingly geometrically complex space. These developments marked a fascinating departure from architectural design in a gallery setting as the co-creators articulated a desire to avoid generating walls, or doorways that may resemble their typical dissemination venue.

In this project, walls were exchanged for tall tree trunks, and a ceiling was replaced with a porous tree canopy that filtered a night sky. Hubs support a range of lighting tools; skybox, spotlight, point light and directional light. The lack of accuracy and comprehensive controls of these tools is offset by simple ease of use. In most cases, the only parameters are hue, direction and distance. A range of 'scenes' was explored daylight, sunset and night, however, a night setting was selected for fairly pragmatic reasons, which were mostly centred on providing an environment where the artists works would be as accessible as possible in the dense forest environment. For these reasons, the general setting is subdued, with moments of brightness.

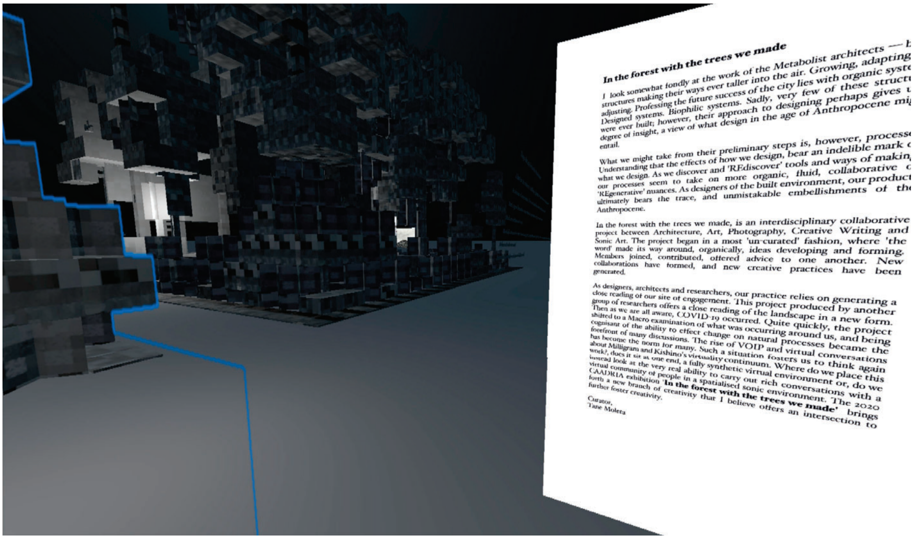


Figure 3. Virtual ‘Forest gallery’ and ‘Gallery text’.

Following the creation of an environment, a process to inhabit works within the ‘forest’ was undertaken. The original plan was to iterate and reconsider how to better design and accommodate the artist’s work within the environment, however, an interesting series of discoveries were made, that were primarily centred around the use of an SVE. The first of which was multiple artists inhabiting the SVE simultaneously and discussing the placement of work from varying different perspectives. One artist would be viewing the scene from above, while one from a lower angle and then one off to the side. This collaborative period of activity saw the time that was allocated for re-design and remodelling of the environment, being spent instead on collaboration, discussion and conversation in the SVE and directly testing work placement before locating the works in their final position. In this period of exercises, artists took multiple passes through a given space, considered how their works would be considered in sequence and how different pathways to exploring the work could be achieved by their audience.

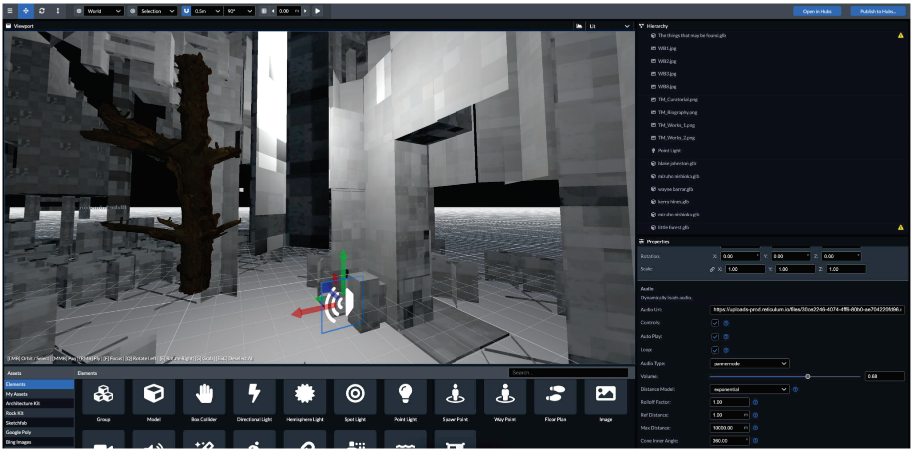


Figure 4. Sonic Artwork by Blake Johnston and sound controls.

The inclusion of a sonic artist in the project team brought a series of new and rich considerations. This work displayed below in (Fig 3) is a work that employed photogrammetry and included an audio file. Unlike sound in a physical environment, it was noted that the sound could be as large, or as small as was needed to produce a compelling virtual experience. There was a degree of frivolity and playfulness to the placement of the work, and also the permeating audio track which would eventually be set to a volume that could be heard from within the entire project. Upon nearing the single-coloured tree stump generated in photogrammetry, the audience is overwhelmed with a rich series of acoustic tones. The considered difference of this means of engagement with an audience is that the audience is able to quickly traverse away from the point of sound, either horizontally or vertically. The positioning of the work does, however generate a rich dialogue on modes of representation, simulation and generation. The model is highly edited digitally, yet in a second reading, is, without doubt, a capture of the natural environment, albeit experienceable only in the virtual.

A suite of poems was prepared for the exhibit. The decision-making process of this work was again collaborative and co-generated using the SVE. The author was able to inhabit the virtual environment, select locations and make adjustments to the positioning of the work within the environment, taking care, that the text was legible, and that a degree of blending with the environment was achieved.

The author of these works was especially driven to experiment and arrive at an outcome that would exploit the abilities of the CVE. The author was aware of their digital engagement in the opening lines of 'Kaingaroa Forest (2)' offers something to consider in the terms, "journeying through code, pine-not pine, a loop in straight lines". In contrast to an artist with a career based in printed material, there was an interest to explore and to generate written work in a manner that was immersive and inhabitable. The work prepares a serious nod to the looped audio pieces explored in the sonic artwork. The work speaks to industrialisation, to landscape and to the commodification of fragile landscapes and ecologies. The final outcome was a series of written works that could be experienced by glimpsing at the works through the trunks of the tropical forest or peering underneath the forest canopy. What does the SVE bring to this body of work, and how is the reading of these works altered by squeezing ones way through the virtual, and peering between the simulated forest walls?

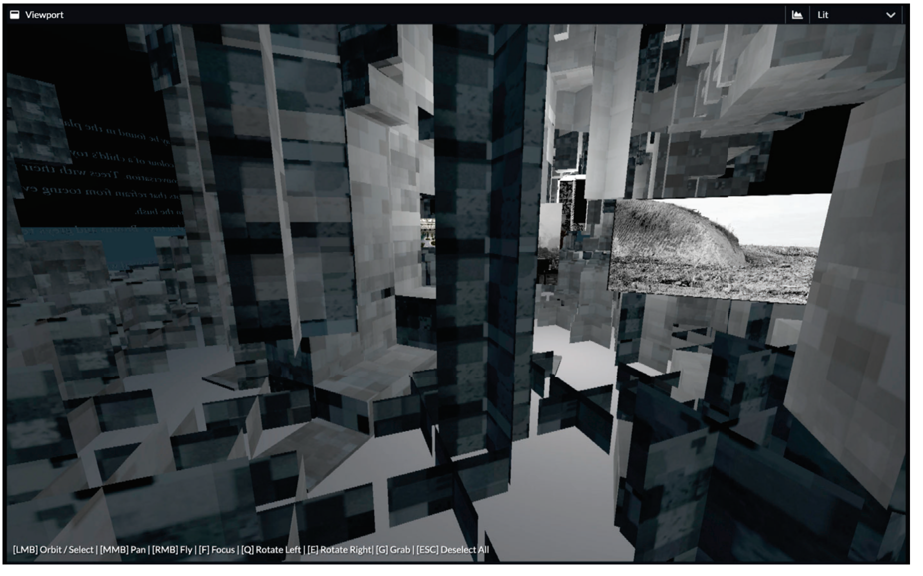


Figure 5. Photographic works by Wayne Barrar enmeshed in the virtual environment.

5. Findings

This project activated an intense period of rich participation and co-generative creation. The tools employed borrow from an interdisciplinary toolkit that touches equally on architecture, virtual reality, simulation, curation and exhibition design. The creative practitioners involved in this project have stated that they wish to undertake a project in this manner again and that they have. Working in visual arts, creative writing or music, the artists often spend considerable periods focused on singularly creating their work. This project and the processes it entailed using SVE's represented a substantial departure from their historical practices. The following section outlines some of the findings from undertaking this process and engaging in a series of conversations on the outcome of the activity.

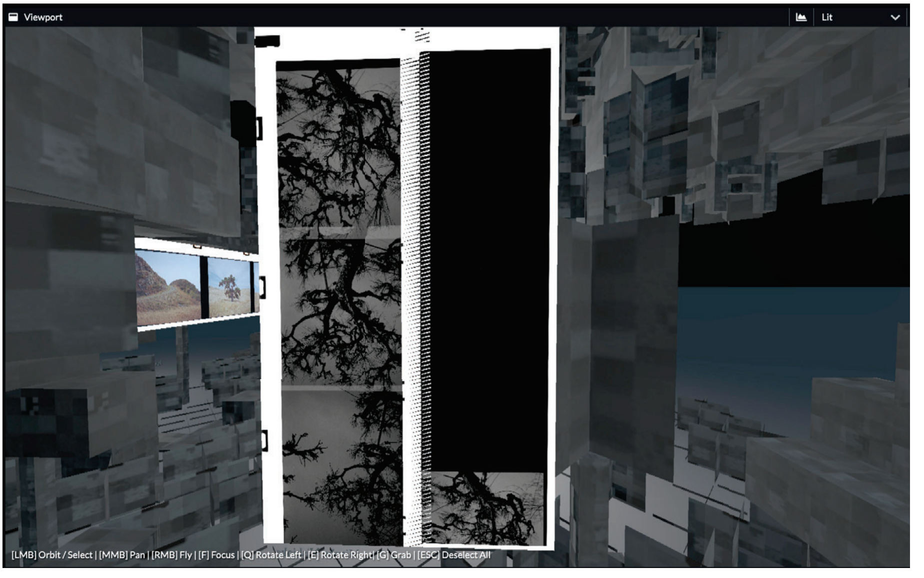


Figure 6. Photographic works by Mizuho Nishioka enmeshed in the virtual environment.

All practitioners report that they would not typically exhibit with such a diverse group. Despite the desire to initially undertake the project, there were some concerns, these were quickly resolved in the proposal to generate an exhibit in an entirely virtual format. One of the larger issues raised was an attempt to achieve artistic integrity for their individual creative practices. There was some concern that one type of work may have an overbearing presence in the overall exhibit. These are however, considerations that were carried over from a career of exhibiting in physical sites. The outcome of working in the SVE was that the overlap or meshing of works was considered a positive attribute of exhibiting in this manner. The unlimited canvas that the SVE provides gives the exhibiting artist an impression of having enough physical to carve a place to position their unique creative activity, and in this constructive place, they also demonstrated a desire to draw in closer, and make the exhibit more compact, more intimate and more layered.

Borrowing the movement controls from game design of WASD and mouse point have proved to be relatively easy to gain mobility within the virtual environment. The ability to move in new ways in the SVE was reported as facilitating a further reading, or experience of the works by the creative practitioners. The ability to navigate freely in the vertical plane, and depart from conventional means of inhabiting space.

A renewed relationship to scale was also put forward. Engaging in viewing the work was altered through being permitted to be too close to the work - an affordance not typically allowed in a conventional gallery setting. Partially due to the porous nature of the exhibition site, 'glimpses' of work were able to be seen across the entire exhibition site. This was reportedly successful in drawing visitors across the site, for them to only capture a glimpse of something again on the other side of the site. In this manner, the SVE does go some way to producing an alternative means to the negotiation of space and relationship to scale.

Figure 7. Text-based works by Kerry Hines peeking through the forest.

There was a notion that the spatialisation of sound was altered in the SVE. The observation was that in the relatively silent areas that the work was experienced (office or home), the subtle shifts in volume in the SVE were more pronounced than if experienced in physical format. This is a striking finding given that most exhibition experiences are held in closely monitored gallery environments. The SVE does, however offer a unique characteristic in that the only material in the SVE is material that the authors wish to be there. There is a considerable difference in inheriting an exhibition site than there is with creating a site to exhibit in from an entirely blank canvas.

The participants noted that portability and sharing with others were also more possible in this format. The work could be shared with anyone, in any place at any time, as long as minimum equipment requirements were met. Sharing of the experience was perhaps overly simplistic. A case of two youths meeting in the space and discussing matters were reported. The SVE, whilst being designed for an exhibition purpose in this case still maintains a heritage as a communicative tool to the core. The SVE was reported as a site that facilitated conversation, prompted unexpected engagements and altered the notions of an exhibition.

The real-time engagement was also noted as an especially valuable characteristic. The feeling of 'being there' and contributing to a live activity was reported as generating a sense of place beyond other online experiences.

6. Conclusion

This paper explores architectural representation and the design of virtual environments against the challenges of curating of artworks in virtual space. It provides an original empirical study on the engagement of artists, curators and virtual environments in the context of CAAD. The project 'In the forest with the trees we made' set about generating a rich and compelling artefact to aid in the understanding of the natural environment and our impacts upon our planet. Inhabitation of this response was made possible by the use of an SVE, which was originally purposed for many different uses. As a tool to aid social interaction and support communication, the SVE excels to such a level that the limitations of the tools seem to be erased. The true benefit and contribution to knowledge this case study makes is in producing a record of engagement and offering a rich description of the research site. This paper postulates that the SVE offers new possibilities when bringing new teams together to work in unfamiliar methods. This case is a single example of how immersive technologies are increasingly being employed in ways not originally intended. This case study documents the projection the SVE can make upon our professional and creative careers.

7. Artefact

The below link will give access to the project In the Forest with the Trees We Made for the duration of 2021. Future attempts to preserve the link beyond this date will be attempted, but cannot be guaranteed. Access point to In the Forest with the Trees We Made: https:hub.link/zL4LT3c

References

De Bono, J.: 2016, Sentimentality and the Digital Expanse, *SIGraDi 2016 [Proceedings of the 20th Conference of the Iberoamerican Society of Digital Graphics*, Argentina, Buenos Aires, 668-676.

Ham, J.: 2008, Developing The a+b/online Virtual Gallery, *[Proceedings of the 13th International Conference on Computer Aided Architectural Design Research in Asia] Chiang Mai (Thailand) 9-12 April*, Chiang Mai, Thailand, 357-363.

Moleta, T.: 2017, Digital Ephemera, *in Virtual Environments in P. Janssen, P. Loh, A. Raonic, M. A. Schnabel (eds.), Protocols, Flows, and Glitches - Proceedings of the 22nd CAADRIA Conference, Xi'an Jiaotong-Liverpool University, Suzhou, China, 5-8 April 2017,*, 13-22.

Schnabel, M.A. and Ham, J.: 2013, A Framework for Social Networked Architectural Education, *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013) / Singapore 15-18 May 2013*, 313-322.

CYCLING VIRTUAL TOUR

A Remote Online Travel System Based On Interactive Technologies And Its User Experience Evaluation

JIE LIU[1], YUECHEN WANG[2] and NING ZHU[3]
[1,2,3]*Tsinghua University*
[1]*ljsusie@sina.com* [2]*756392174@qq.com* [3]*13717742900@163.com*

Abstract. Virtual reality has been widely adopted into various fields of human life. It is entering the world of tourism to remote places. This paper proposes a brand-new interaction design system for remote online virtual tourism based on bicycle riding behavior and projection mapping technologies. Through the user experience evaluation experiments of this system, the research found that this interactive system can effectively improve the realism and sense of the presence of the virtual environment. It can also enhance the delectation and satisfaction of the virtual tour. At the same time, this system can reduce the simulator syndrome which plays as a common problem in the traditional virtual tour experience.

Keywords. Interaction design; immersive environment; virtual tour; user experience.

1. Background

Sightseeing in another place is one of the most enjoyable leisure and entertainment activities for people. However, due to the high cost of traveling, the potential safety hazards of epidemics, and other inevitable problems, people have begun to seek virtual tourism as an alternative to traditional tourism. How to make virtual tourist places present the equivalent experience as real places is a question that designers and engineers have been discussing.

As it is already known that the human experiences towards a particular place rely on the "sense of place"(Ghani, Rahman et al. 2018), which is related to the studies of presence in the context of a virtual environment(Ghani, Rafi et al. 2016). Presence or telepresence is commonly defined as a user's subjective sensation of "being there"(Lessiter, Freeman et al. 2014) and is known to be a fundamental concept for understanding and evaluating the effectiveness of virtual environments(MacIntyre, Bolter et al. 2004). Theoretically, with appropriate software and IT equipment, it is possible to take deliberate, planned, and realistic virtual trips to different scenic spots(Polechoński and Tomik 2019).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 243-252. © 2021 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

2. Related Works

Existing researches discovered that the size of the media display(Lessiter, Freeman et al. 2014), the naturalness of a visual representation(Wijnand, Ijsselsteijn et al. 1998), and the user's interaction with the virtual envrionment(Hendrix and Barfield 1996) are highly correlated with the presence feeling of the visual virtual environment. In this scenario, many cut-edging technologies, especially immersive virtual reality technologies have come into people's sight, aiming to enhance the virtual tourism experience.

2.1. MEDIA DISPLAY SYSTEM

To achieve an immersive media display environment, most researchers choose Head Mounted Display (HMD) or CAVE Automatic Virtual Environment(CAVE) as the visual display device. Rhiu reported using HMD as the media display device to simulate people's driving and walking environment achieved a better user experience than desktop display devices(Rhiu, Kim et al. 2020). Oprean claimed choosing HMD as immersive environment experiences toolkits may help architecture and landscape design students understanding remote site information easily(Oprean, Verniz et al. 2018). Lebiedź tried CAVE as the immersive virtual environment to test virtual tours and architectural visualizations on the application which allowing a virtual walk through the Coal Market in Gdańsk(Lebiedź and Szwoch 2016). After all, although HMD and CAVE could provide an immersive virtual environment, the nausea problem caused by the simulator syndrome, the shadow problem caused by projection light blocked by experiencers in the CAVE severely affect the virtual tourism experience and reduced the level of presence.

2.2. VISUAL REPRESENTATION METHODS

Three hundred sixty-degree (360°) immersive panorama video(Nagy, Stoddart et al. 2018, Kachach, Perez et al. 2020), a high-fidelity 3D digital site model(Kersten, Tschirschwitz et al. 2018), and two mixed(Pizarro Lozano 2016, Rhee, Petikam et al. 2017) are the most popular visual environment construction solutions. Although most 360 videos only provide 2D visual media, they still present a high degree of realism since they are based on real environment information. Besides, the experiencer can freely choose the viewing angle in a panorama video, so it can greatly improve the presence feeling of the virtual environment. The advantages of the 3D digital model lie in the independence of the experiencers to choose the tour route. However, since most of the 3D digital model environments are built based on 3D scanning point cloud information(Wessels, Ruther et al. 2014), it requires high-performance hardware support(Kersten, Tschirschwitz et al. 2018). Globa tried to fuse the panorama video and the digital design model into one visual environment to improve the presence feeling of experiencers(Globa, Wang et al. 2019). It also has been proved compositing 3D virtual objects into the background of the 360-video can increase the realism of the virtual objects(Rhee, Petikam et al. 2017).

2.3. VIRTUAL ENVIRONMENT INTERACTION DESIGN

Interaction with the virtual environment plays a vital role in the immersive environment spatial presence perception(Schubert, Friedmann et al. 1999). Existing research includes automatically adjust travel speed based on viewpoint quality to avoid the information defiency(Freitag, Weyers et al. 2016), adding multiple sensory interaction design such as sound(Globa, Wang et al. 2019) (Johansson 2019)to increase the realism of the scene, attaching descriptive literature to the virtual environment to make it easier for people to understand the spatial location of their environment(Ciolfi and Bannon 2007, Argyriou, Economou et al. 2020), and so on. However, most of the current interaction design research is to study the change of output information during the interaction process to increase the authenticity of the virtual tour. There is very limited research discussing how to improve the information input systems during the virtual tour to increase the perception of reality.

3. Research Hypothesis

In real traveling, tourists hardly use controllers as their tools to help them navigate or recognize the environment, nor would they watch the world with wearing heavy glasses on their heads. This unnatural interactive mode may decrease the authenticity of the virtual tour. Thus, the research wants to explore a new virtual traveling interactive method based on natural travel behavior simulation and test if it will increase the authenticity of the virtual environment.

We chose bicycle as the interactive information input interface since cycling is a relatively common way of traveling and sightseeing, and we decided to use immersive projection mapping(IPM) as the information display system since we want to minimize the physical impact of the display device on the experiencer. A panoramic video has been adopted as visual environment information because it has consistently shown a high degree of realism in previous studies.

4. Cycling Virtual Tour System Design and Technical Implement

The entire remote online travel system consists of four subsystems: 360 dynamic media information formed by a panoramic camera, interactive information processing system formed on Unity3D platform, information input system formed by Arduino, information output system formed by Resolume Arena and projectors (Figure1).

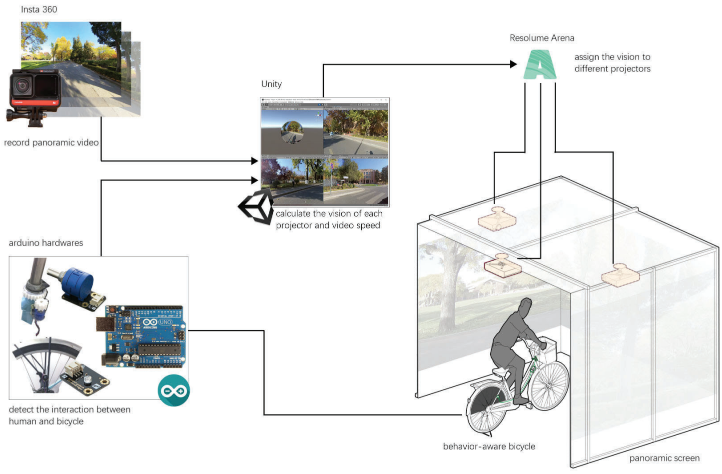


Figure 1. Cycling Virtual Tour System Composition.

4.1. PANORAMIC VIDEO MATERIAL PREPARATION

Recorded by an Insta360 one R, the panoramic video set resolution as 5.7k and 30 frames per second to ensure the clarity and smoothness of basic media information. The panoramic camera was fixed on the handlebar of the bicycle at the same height as the cyclist's eyes instead of wearing on the cyclist's head for ensuring the camera main viewport is always facing the forward direction. A 2.3 kilometers tour route on the University Campus which passed by most of the historical buildings was selected. The video was filmed in the early morning, recorded 10 minutes of the environment digital media. After the video file was initially processed by the Insta360studio software, an mp4 format panoramic video file with a fixed viewing angle was formed, which later played as the background material importing into Unity3D for constructing the virtual tour environment.

4.2. VIDEO PROCESSING IN UNITY3D

Considering the necessity to transform the deformed panoramic video material with the spherical plane into several plane images for projection, the video needs to be intensively processed. In the Unity3D software, we use the panoramic video as video material and map it on the inner surface of a sphere. In this way, a normal angle of view can be obtained by taking views from the center of the sphere to the surface with the "Camera" object. As we were constructing an immersive environment, it is required to ensure that the field of view is filled with virtual images, which means that the horizontal width of the image is 210 degrees and the vertical is 180 degrees. However, after many rounds of tests, we noticed that from the perspective of user experience, there is a limited difference from the vertical viewing angle of 60 degrees to 180 degrees when experiencers riding a bicycle. Therefore, three cameras were adopted in the Unity3D to obtain the video view with 210 degrees horizontally and 60 degrees vertically from the spherical surface.

4.3. INFORMATION INPUT SYSTEM

As an interactive virtual environment, sensors need to be added to the bicycle for collecting user behavior information. In this experiment, we adopted a rotary encoder and a light sensor as information input devices. The rotary encoder was placed on the top tube of the bicycle to detect the direction of the bicycle's handlebar through gears. The light sensor was installed on the seat stay of the bicycle. By placing light barriers on the wheels, the light sensor could easily catch the rotation frequency of the wheel according to the change of light brightness.

The signals of the sensors were converted by Arduino into angle information and speed information and then transmitted to the Unity3D platform as the rotation angle of the cameras' perspective and the playback speed of the panoramic video. In this way, the panoramic video in Unity3D camera view could be changed in real-time according to the bicycle usage status.

4.4. INFORMATION OUTPUT SYSTEM

Projecting each camera display in the Unity3D onto the physical walls to form an immersive interactive environment was the last procedure. We picked Resolume Arena as the video projecting software platform to correct the parallax problem in the projection process. Via utilizing a screen capture plug-in, three "Game" windows in the Unity3D were captured separately into Resolume Arena and respectively assigned to the target projectors for virtual environment establishing.

After all, we achieved a remote online travel system that could change the immersive environment view direction and the traveling speed through cycling behaviors simultaneously.

5. Evaluation

5.1. EXPERIMENT PREPARATION

Since the research attempts to test whether this new system could improve the user experience of the virtual tour, a systematic user experience experiment on the system has been conducted(Figure2). As mentioned before, the virtual traveling system is unique in both the information input method and the information output method, so it contains two variables: the information input method(Controller and Bicycle) and the information output method(HMD and IPM). By successively changing the variables in the experiment, the research attempted to explore the influence coefficient of each variable on the participants' sense of presence and the virtual environment experience satisfaction level. Because when the output information is the same, the effect of shifting the input information is equivalent, the experiment set up three experimental environments: IPM+Bicycle as the target environment, HMD+Controller and HMD+Bicycle as the control environments(Figure3). Every experimental environment provides participants with an interaction design that changes the viewing angle of the tour and the speed of movement(Figure4). All the experimental environments used the same parameters, such as walking route, viewing angle width, acceleration, etc.

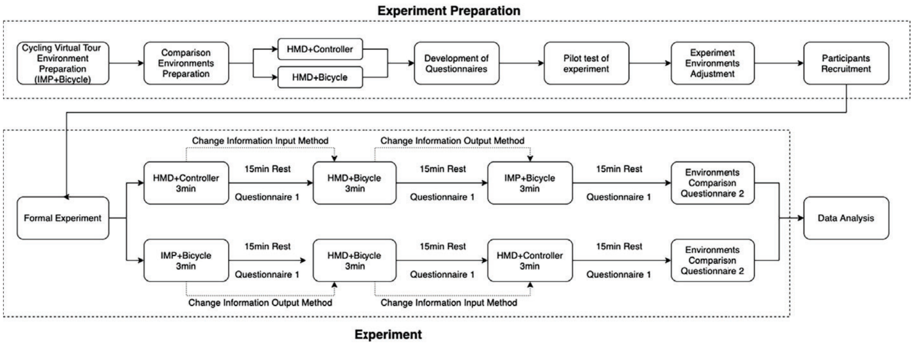


Figure 2. Experiment Design.

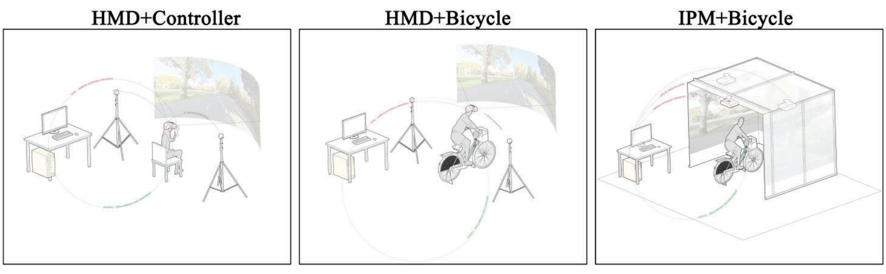


Figure 3. Three Experimental Environment Design.

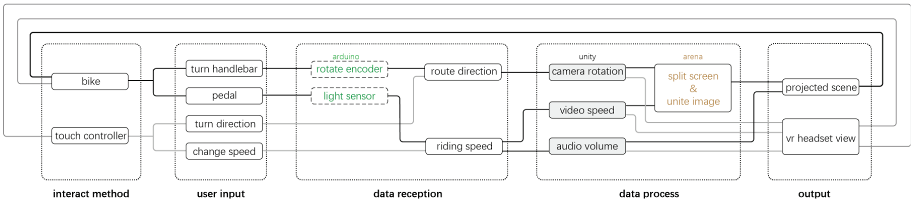


Figure 4. The Interaction Design Logic of Three Experimental Environment.

To verify the experimental hypothesis, the experiment chooses a qualitative research method based on user questionnaires. According to the existing research on spatial presence measurement within immersive environments in the fields of cognitive and computer sciences(Paes, Arantes et al. 2017), presence measured through subjective self-reporting using questionnaires is one of the most common methods of measuring presence(Schuemie, Van Der Straaten et al. 2001). The questionnaire design was based on multiple relevant existing virtual reality space presence evaluation researches(Witmer and Singer 1998, Schubert, Friedmann et al. 1999, Men, Bryan-Kinns et al. 2017, Paes, Arantes et al. 2017). At the same time, the research borrowed parts of Simulator Sickness Questionnaire(SSQ)(Balk, Bertola et al. 2013, Kim, Park et al. 2018) and User

Experience Questionnaire(UEQ) (Laugwitz, Held et al. 2008, Schrepp, Hinderks et al. 2014) to test the user experience of the experiment environments. As a result, the experiment constructed two questionnaires, each contains eight questions. Questionnaire 1 was used to score each experimental environment from 1 to 7, and Questionnaire 2 was used to compare and sort the three experimental environments (each environment option gets 3 to 1 point in order of ranking). By comparing the data between different questionnaires, the stability and reliability of the experimental data can be efficiently increased. Questionnaires are designed as Figure5.

Questionnaire 1	Questionnaire 2
Presence 1. How do you think the similarity between the experimental environment and the real environment? (1-7) 2. Did you feel you are in the environment? (1-7) 3. Did you feel you are moving?(1-7)	**Presence** 1. Please sort the three experiments according to the similarity between the experimental environment and the real environment. 2. Please sort the three experiments according to the involvement of the environment. 3. Please sort the three experiments according to moving speed in the experimental environment.
Attractiveness 4. Did you feel happy during the experimental environment?(1-7) 5. Are you satisfied with the experimental environment? (1-7)	**Attractiveness** 4. Please sort the three experiments according to your pleasure level. 5. Please sort the three experiments according to your satisfaction level.
Efficiency 6.Do you feel this interactive method is easy to learn and master?(1-7)	**Efficiency** 6.Please sort the three experiments according to the difficulty of learning and mastering interactively.
Comfortable 7. Did you feel dizziness during the experiment?(1-7) 8. Did you feel security during the experiment?(1-7)	**Comfortable** 7. Please sort the three experiments according to how much you feel dizzy. 8. Please sort the three experiments according to how much you feel security.

Figure 5. Questionnaires Design.

In order to improve the controllability and operability of the experiment, a pilot experiment with 8 participants was conducted before the formal experiment. Issues such as the duration of a single experiment, the rationality of the placement of the equipment, the speed of information transforming, the angle of lens conversion per unit time, and the safety control measures of the subjects have all been adjusted in the pilot experiment.

The experiment chose to recruit healthy people between 18 and 55 years old as participants. As Faas experimented with 30 participants(Faas, Bao et al. 2014), the sample size in the study of Daniel was also 30 participants (Paes, Arantes et al. 2017), Kim performed the experiments with 24 participants(Kim, Park et al. 2018), Sacks set the sample size as 20 to 25 participants(Sacks, Perlman et al. 2013). Based on those samples, this study set the sample to 32 participants (22 females and 10 males, average age is 24.7).

5.2. EXPERIMENT PROCEDURE

To eliminate the order effect, the order of the study was counterbalanced between subjects. The final sample randomly divided the participants into two groups(each group contains 11 females and 5 males): Group A started with HMD+Controller and sequentially change the information input method and information output method, Group B started with IPM+Bicycle and sequentially change the information output method and information input method. Participants were asked to experience three minutes in each experimental environment(Figure 6), and the experiment allowed to be suspended if the experiencer were suffering from severe dizziness. To minimize the influence of simulator syndrome from the previous test condition on the next test condition, the participants were given a 15-min break between each test condition. During the break, the participants were requested to answer Questionnaire 1. After the participants have experienced all the experimental environments, they were invited to fill in Questionnaire 2 for the three environments comparison.

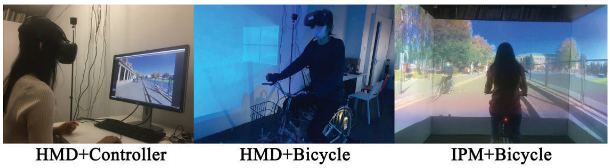


Figure 6. User Experience Experiments.

5.3. DATA ANALYSIS AND RESULTS

By calculating the scores of the two questionnaires and extracting the average of the scores, the data analysis results can be obtained (Figure7), and we achieved the following outcomes.

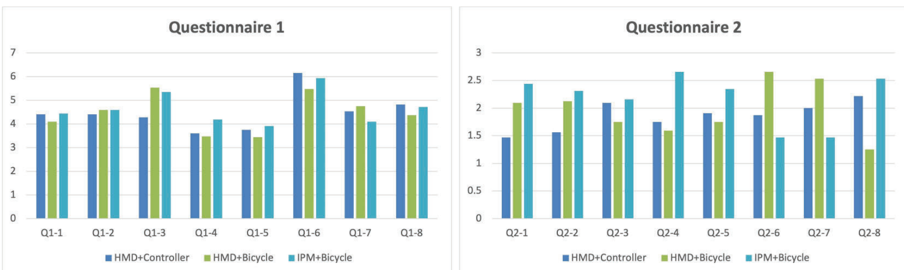


Figure 7. Data Analysis Results.

1. IPM+Bicycle shows superiority in the sense of presence compared to the other two, and the information input system via bicycles contribute more than the projection environment on presence enhancement. Although HMD+Bicycle presented a high sense of presence, the simulator syndrome was too severe for experiencers to enjoy the tour.
2. Participants reported that the user experience of IPM+Bicycle is also more enjoyable, which is reflected both in the pleasure enrichment and satisfaction improvement.
3. IPM+Bicycle is a more natural interactive traveling mode, but it does not show obvious ascendancy on the easement and convenience level of interaction behavior learning and mastering.
4. IPM could effectively decrease the dizziness and increase the security feeling, especially when experiencers were in motion. During the entire experiment,

six participants suspended the experiment nine times in total due to simulator syndrome, accounting for 15.6% of the total number of people and 8.3% of the total number of experiments. 78% of the simulator sickness happened when wearing VR glasses.

6. Conclusion and Contribution

The Cycling Virtual Tour system manifested a better user experience than the traditional virtual tour system with an advanced sense of presence and realism, higher satisfaction degree, and fewer reports of simulator sickness. This research discovered how information input system alteration may influence the virtual tour user experience and providing a design strategy reference for the interactive design of virtual tourism environment in the future.

Additionally, this system can be applied to a variety of spatial environments, such as museums, fitness centers, and family entertainment rooms. Since the projection environment requires a darker light environment, this research providing a new possible direction for the functional design of dark rooms in architecture design.

References

Argyriou, L., Economou, D. and Bouki, V.: 2020, Design methodology for 360° immersive video applications: the case study of a cultural heritage virtual tour, *Personal and Ubiquitous Computing*, **24**(6), 843-859.

Balk, S.A., Bertola, M.A. and Inman, V.W.: 2013, Simulator sickness questionnaire: twenty years later, *the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 257-263.

Ciolfi, L. and Bannon, L.J.: 2007, Designing hybrid places: merging interaction design, ubiquitous technologies and geographies of the museum space, *CoDesign*, **3**(3), 159-180.

Faas, D., Bao, Q., Frey, D.D. and Yang, M.C.: 2014, The influence of immersion and presence in early stage engineering designing and building, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **2**, 139-151.

Freitag, S., Weyers, B. and Kuhlen, T.W.: 2016, Automatic speed adjustment for travel through immersive virtual environments based on viewpoint quality, *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, 67-70.

Ghani, I., Rafi, A. and Woods, P.: 2018, Sense of place in immersive architectural virtual heritage environment, *2016 22nd International Conference on Virtual System & Multimedia (VSMM)*, 25-37.

Ghani, I., Rahman, N.A., Nayan, N.M. and Bahaluddin, A.: 2018, Experiential virtual urban environments: A preliminary investigation, *Planning Malaysia*, **16**(5), 25-37.

Globa, A., Wang, R. and Beza, B.B.: 2019, Sensory Urbanism and Placemaking-Exploring Virtual Reality and the Creation of Place, *Intelligent & Informed - Proceedings of the 24th CAADRIA Conference*, 737-746.

Hendrix, C. and Barfield, W.: 1996, Presence within virtual environments as a function of visual display parameters, *Presence Teleoperators & Virtual Environments*, **5**(3), 274-289.

Ijsselsteijn, W., de Ridder, H., Hamberg, R., Bouwhuis, D. and Freeman, J.: 1998, Perceived depth and the feeling of presence in 3DTV, *Displays*, **18**, 207-214.

Johansson, M.: 2019, VR For Your Ears: Dynamic 3D audio is key to the immersive experience by mathias johansson · illustration by eddie guy, *IEEE Spectrum*, **56**(2), 24-29.

Kachach, R., Perez, P., Villegas, A. and Gonzalez-Sosa, E.: 2020, Virtual Tour: An Immersive Low Cost Telepresence System, *2020 IEEE Conference on Virtual Reality and 3D User*

Interfaces Abstracts and Workshops (VRW), 504-506.

Kersten, T.P., Tschirschwitz, F., Deggim, S. and Lindstaedt, M.: 2018, Virtual Reality for Cultural Heritage Monuments – from 3D Data Recording to Immersive Visualisation, *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*, 74-83.

Kim, H.K., Park, J., Choi, Y. and Choe, M.: 2018, Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment, *Applied Ergonomics*, **69**, 66-73.

Laugwitz, B., Held, T. and Schrepp, M.: 2008, Construction and evaluation of a user experience questionnaire, *Symposium of the Austrian HCI and Usability Engineering Group*, 63-76.

Lebiedź, J. and Szwoch, M.: 2016, Virtual sightseeing in Immersive 3D Visualization Lab, *2016 Federated Conference on Computer Science and Information Systems (FedCSIS)*, 1641-1645.

Lessiter, J., Freeman, J., Keogh, E. and Davidoff, J.: 2014, A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory, *Presence*, **10**(3), 282-297.

Pizarro Lozano, R.: 2016, *It's About Time: The Illusions of Time Perception and Travel in Immersive Virtual Reality*, Ph.D. Thesis, University of Barcelona.

MacIntyre, B., Bolter, J.D. and Gandy, M.: 2004, Presence and the aura of meaningful places, *Presence: Teleoperators and Virtual Environments*, **6**(2), 197-206.

Men, L., Bryan-Kinns, N., Hassard, A.S. and Ma, Z.: 2017, The impact of transitions on user experience in virtual reality, *2017 IEEE Virtual Reality (VR)*, 285-286.

Nagy, D., Stoddart, J., Villaggi, L., Burger, S. and Benjamin, D.: 2018, Digital Dérive. Reconstructing urban environments based on human experience, *ACADIA*, 72-81.

Oprean, D., Verniz, D., Zhao, J., Wallgrün, J.O., Duarte, J.M.P. and Klippel, A.: 2018, Remote studio site experiences: Investigating the potential to develop the immersive site visit, *23rd International Conference on Computer-Aided Architectural Design Research in Asia: Learning, Prototyping and Adapting, CAADRIA 2018*, 421-430.

Paes, D., Arantes, E. and Irizarry, J.: 2017, Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems, *Automation in Construction*, **84**, 292-303.

Polechoński, J. and Tomik, R.: 2019, Can immersive virtual reality travel experience replace real travel?, *Folia Turistica*, **52**, 11-30.

Rhee, T., Petikam, L., Allen, B. and Chalmers, A.: 2017, MR360: Mixed reality rendering for 360° panoramic videos, *IEEE Transactions on Visualization and Computer Graphics*, **23**(4), 1379-1388.

Rhiu, I., Kim, Y.M., Kim, W. and Yun, M.H.: 2020, The evaluation of user experience of a human walking and a driving simulation in the virtual reality, *International Journal of Industrial Ergonomics*, **79**, 103002.

Sacks, R., Perlman, A. and Barak, R.: 2013, Construction safety training using immersive virtual reality, *Construction Management and Economics*, **31**(9), 1005-1017.

Schrepp, M., Hinderks, A. and Thomaschewski, J.: 2014, Applying the user experience questionnaire (UEQ) in different evaluation scenarios, *International Conference of Design, User Experience, and Usability*, 383-392.

Schubert, T., Friedmann, F. and Regenbrecht, H. 1999, Embodied presence in virtual environments, *in* R. Paton and I. Neilson (eds.), *Visual Representations and Interpretations*, Springer, London, 269-278.

Schuemie, M.J., Van Der Straaten, P., Krijn, M. and Van Der Mast, C.A.: 2001, Research on presence in virtual reality: A survey, *CyberPsychology & Behavior*, **4**(2), 183-201.

Wessels, S., Ruther, H., Bhurtha, R. and Schroeder, R.: 2014, Design and creation of a 3D virtual tour of the world heritage site of Petra, Jordan, *Proceedings of AfricaGeo*, 1-3.

Witmer, B.G. and Singer, M.J.: 1998, Measuring presence in virtual environments: A presence questionnaire, *Presence*, **7**(3), 225-240.

AR DIGI-COMPONENT

AR-assisted, real-time, immersive design and robotic fabrication workflow for parametric architectural structures

YANG SONG[1], RICHARD KOECK[2] and SHAN LUO[3]
[1,2]*Department of Architecture, University of Liverpool*
[1,2]*{yang.song|rkoeck}@liverpool.ac.uk*
[3]*Department of Computer Science, University of Liverpool*
[3]*Shan.Luo@liverpool.ac.uk*

Abstract. This research project, entitled AR Digi-Component, tries to digitalize the traditional architectural components and combines Augmented Reality (AR) technologies to explore new possibilities for architectural design and assembly. AR technology and Digitalize components will help to achieve a real-time immersive design and an AR-assisted robotic fabrication process through the augmented environments. As part of the AR Digi-Component project, we created an experimental design prototype in which designers' gestures are being identified in AR real-time immersive design process, and a fabrication prototype in which traditional 2D drawings are being replaced by 3D on-site holographic guidance, followed by an assembly process in which robotic operations are being controlled by humans within an AR simulation to enhance the assembly efficiency and safety. In this paper, we are sharing the preliminary research results of such AR-assisted tests, for which we used a UR10 Robotic arm in combination with Microsoft HoloLens as well as in terms of software Rhino, HAL Robotics, FURobot, PX Simulate, and Fologram plugin in Grasshopper, to demonstrate new kind of applications and workflow of AR technology for real-time, immersive design and robotic fabrication.

Keywords. Augmented Reality; immersive design; holographic assembly instruction; robotic fabrication; real-time interaction.

1. Introduction

Since the introduction of technological innovations such as the internet and mobile computers, including our mobile phones, we have seen substantial changes to how we see and engage with our surroundings in our everyday urban life. Yet, more recent AR technology seems to create new crossroads for which we are just beginning to understand. AR is a relatively new technology field that produces a virtual model and information that can be viewed and interacted with in the real world (Do Carmo, 2007). In other words, AR technology offers a way to bridges the gap between the virtual and the real world, offering all kinds of new interaction

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 253-262.

scenarios in the near future that could be harnessed in the fields of Architecture and Construction. Let's look at some common design workflow models today and see how AR technology has the potential can change it.

1.1. PROBLEM 1 - DESIGN PROCESS

In the current design process, architectural designers and off-site technicians are using 2D plans, 3D models, and renderings to understand the complexity and to make partial modifications to improve their design drafts. These methods are conveyed through paper and screen which provides off-site flattened previews. Designers do not have immersive possibilities which means they can't experience their parametric structure spaces before they were built and they can't modify and preview the draft on-site according to the actual space experience during the traditional design process.

AR offers a new tool in the design process, where designers can show their visual drafts in an on-site space and can use direct hand-based gesture recognition and paddle-based inputs to interact with (Sheldon, 2016). The nature of the AR - easy, user-friendly, little room for errors, and intuitive interactions - can support the design process. AR technology promises to have a series of unique benefits compared to simply working in a non-AR enhanced real environment. We would like to propose creating an immersive design process by combining the above characteristics of AR. Could indeed AR provide designers an immersive adjustment and preview methods during the design process, allowing for an on-site preview and real-time input interactions?

1.2. PROBLEM 2 - ON-SITE ASSEMBLY METHOD

The traditional architectural assembly process requires skilled labors and complex equipments to locate and transform highly detailed 2D drawings to physical on-site construction. It is commonly applied in many areas of architectural construction, but there remain a series of problems. This includes that the current workflow is not particularly time efficient and is open to human error; all of which is caused by translating information from 2D to on-site construction in the assembly process especially for complex structures (Jahn, 2019). As for the construction site, labors working on the assembly of building components have largely relied on 2D construction plans. The more complex the structure, the more time-consuming and error-prone will happen during the construction information translation process.

To reduce the gap between 2D graphic instructions and 3D assembly actions, the use of AR technology applies a method that is based on high precision and detailed AR 3D on-site holographic drawings and instructions in the architectural assembly process (Tsai, 2020). The holographic instruction in scale 1/1 enables the user to walk through the project before the actual construction and teaches unskilled labors step-by-step during the assembly process (Imani, 2017). This potentially opens up a new field of intervention for using AR digital instructions in the assembly process, especially in complex and atypical structures. The research question emerging from here is to find out whether AR technology can replace the traditional 2D detailed drawings in the assembly process?

1.3. PROBLEM 3 - ROBOTIC FABRICATION OPERACTION

Although digital fabrication is widely used in many fields of architectural construction which materials or components are not suitable for manual handiwork, there are still a series of issues that currently exist. The robotic operation process requires specific expert computer science knowledge and skilled programming code workers, which is an expertise that is traditionally not found in the architectural design offices and industries (Schmidt, 2017). Moreover, most robots are controlled by teleoperation and have screen-based simulations before operation. Despite this, it still involves inaccessible, dangerous, or remote locations during the traditional operation process (Olar, 2019).

AR makes robotics operation simpler and safer with intuitive on-site 3D hologram stimulation and provides faster and more intuitive gesture-based robot programming method than conventional techniques (Ong, 2020). We would like to propose that this visualized property could give users intuitive gesture-based input for robotic trajectory plan through AR instead of computer programming requirements, as well as proposing the possibility of on-site virtual robots operation simulation to predict dangerous or error more intuitively before physical operation. The research question is that how will AR technology improve the traditional robotic operation in the assembly process?

2. Research Methodology

This project will elaborate on the workflow of AR-assisted design and assembly for parametric architectural structures. We hope that our research can demonstrate the potential of AR, in the sense that it could be applied at a full architectural scale, such as during façade constructions or other highly labor-intense installation processes. In doing so, we hope to provide some insight into a potentially new workflow model for human-robot collaboration using AR technology (Figure 1).

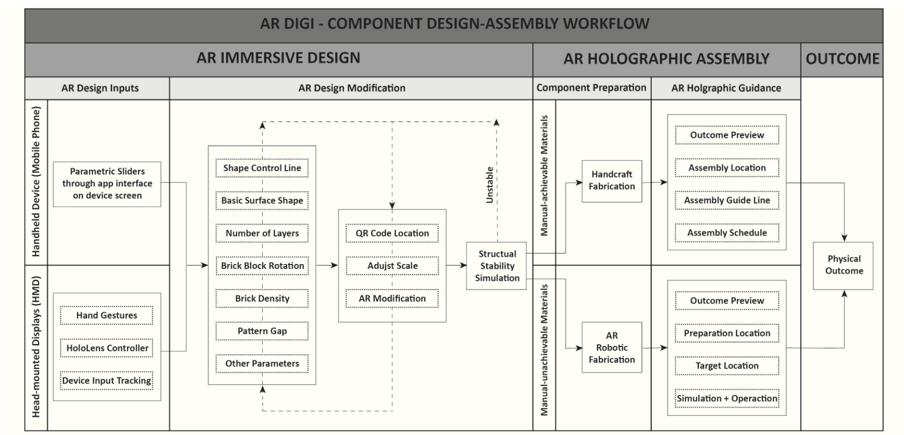


Figure 1. AR Digi-Component design-assembly workflow.

To test such immersive design and robotic fabrication workflow scenarios, we were looking to find a material that relies on manual labor in the current construction process which is easy to be controlled in an AR system and easy to connect with parametric design in a software, such as *Grasshopper*. After several trials, we choose to run our tests using standard UK brick as the main design and assembly material for all the *AR Digi-component*. UK bricks are mated to a standard size of 215 x 120.5 x 65mm, which are easy for AR device to track, recognize, and preview. They also can be re-used and re-design at any state. It innovates how to apply new technology for traditional architectural materials to achieve unique outcomes.

As for our AR device, we choose a commonly available handheld device and a head-mounted display (HMD) from a leading manufacturer, yet not their latest model, Microsoft's *HoloLens 1*. For handheld devices, the ARKit for iPhone allowed us to achieve a screen-based AR experience. For the HMD, Microsoft *HoloLens* gives user a hand-free AR experience and enables the user to engage with digital content and interact with holograms in the real world (Song, 2020).

In terms of software and plug-ins, our *AR Digi-Component* workflow was mainly designed in *Grasshopper* with *Fologram* plug-in and applied to *Fologram App* in both iPhone 11 and *HoloLens 1*. The *Fologram* plug-in provides the possibility to interact with the *Grasshopper* parameters in the AR environment, as well as the *Fologram App* provides the recognition of human gestures, screen taps, device location, and editable interface on mobile phone and *HoloLens*. To integrated the function of *Grasshopper* and the third-party API - *Fologram*, we created a unique AR design and assembly workflow. In our example, we set up different parameter variable inputs that will affect the result of the outcome. These variable inputs are connecting with parameters in *Grasshopper* and shown on the *Fologram App* as parameter sliders for designers to interact with. To complete the whole workflow, we also combine the *Fologram App* with *FURobot* and *HAL robotics* plug-in to fulfill the AR gesture-based operation commands and on-site virtual simulations for robotic fabrication.

In summary, we developed a multi-stage methodology that would allow us to develop, test, and refine the AR-assisted real-time, immersive design and robotic fabrication workflow for parametric structures into the following three tests.

3. AR Digi-Component Tests

3.1. TEST 1 | AUGMENTED REAL-TIME MODIFICATION AND ASSEMBLY

Test 1 is to explore the feasibility of AR real-time modification and assembly process through an augmented environment with virtual information on handheld devices - iPhone 11. It is used to receive the real-time modification input from designers and to illustrate the 3D virtual model for labors in the assembly process.

For the AR real-time modification part, test 1 sets up different parameter variable inputs that will affect the result of the outcome. The adjustable parameter sliders are divided into different parts which cover the entire design process such as basic layer shape, the number of layers, column rotation degree, column deformation control line, and the pattern gap distance. These sliders are connecting with the parameters in *Grasshopper* directly and showing in the *Fologram App* interface on the mobile device's screen in real-time for designers to modify with by using actions on the mobile phone screen such as "on press", "on drag", "on hold", and "on release". The outcome is then shown dynamically on the iPhone 11 according to the real-time inputs after scanning the QR code for on-site location confirmation (Figure 2). This on-site dynamic design method gives designers and participants an intuitive view of outcome preview and a new interactive method of real-time modification. After the shape is designed without further modification, the digital model will be sent to *PX Simulate* plug-in in *Grasshopper*. The designer can preview the on-site structural stable simulation in AR after calculation.

Figure 2. Interactive AR immersive design process through mobile device screen inputs.

For the AR assembly process, test 1 provides a step-by-step virtual guidance assembly instruction. The user can switch the toggle on the *Fologram App* interface from "AR Design" to "AR Assembly". When the assembly interface is activated, the user will first preview the number of bricks to be used and will then be guided to the place of each brick, using the virtual instruction shown on the mobile device. The user can, for example, see the red target lines of the location of the brick in the first layer virtually and place the brick one by one to align them with the red target lines of the first layer. After that, the user can change the sliders through the app to continue the following layers of assembly. The virtual model of the layers that are already finished will be blocked. Only the layer that is in that moment under construction will be highlight and displayed in red target lines, which is relatively intuitive. All the user needs to do is following the on-site red assembly target lines and complete the assembly according to the virtual model shown on their mobile phone device step-by-step (Figure 3).

Test 1 demonstrates that AR real-time modification can give users the possibility of stimulating creativity and an intuitive method to modify on-site design drafts. Although we have not tested the time needed for the assembly, it seems obvious to suggest that the guided AR virtual assembly has the potential of reducing the time normally spent when translating 2D documents to 3D real projects and as such improve the efficiency of the entire construction process. This AR assembly guidance no longer requires skilled construction workers, it creates a new method that the designer and the worker can be one and the same person in this design-assembly system. The communication speed between *Grasshopper* and mobile device in real-time is 2.863 Mb/s, which is fast enough for the real-time modification of simple brick columns.

Although the result of this test 1 is quite successful, it is considerably limited by the fact that the designers can only import parameters by adjusting limited sliders. Mobile AR experience is in parts also impractical and relatively non-immersive, and as such is currently not ideal for an immersive design experience at a full scale. This is of course the case because the preview of the virtual on-site models and all interactive inputs are happening on the device itself, meaning that interacting with a small screen will naturally lack a more integrated experience. Furthermore, the human virtual recognition of the hologram that is displayed on the small mobile screen will cause accuracy errors when the image is overlayed on location on the site. Due to the insufficient accuracy of the space environment perception by mobile devices, errors always occur between digital models and physical outcomes, which are between 1 to 2 cm. Besides, the construction workers would need to use one hand to hold the device and the other hand to carry out the assembly process, which would bring safety hazards and operational inconvenience during construction. Therefore, it seemed that the natural next step would be to try to find a more integrated AR method, which would offer instructions for the assembly through a holographic headset instead of with a handheld device.

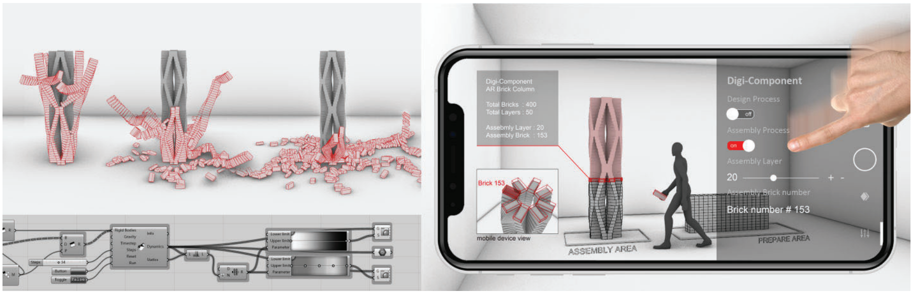


Figure 3. Structural stable simulation in Grasshopper and AR (left), and AR visual assembly guidance on iPhone and the mobile view during assemble (right).

3.2. TEST 2 | AUGMENTED IMMERSIVE DESIGN AND ASSEMBLY

Test 2 explores the possibility of an AR immersive design and assembly process with a head-mounted display (HMD) that is capable of projecting digital information and 3D objects, such as holograms, directly in the workers' field of vision. To do this experiment, we decided to use Microsoft *HoloLens 1*, which uses a sensor-based technology that seemed suitable for our work.

We have used hand tracking, gesture identification, and device location recognition methods to give designers more possibilities and the experience of a more realistic, unobstructed, and more intuitive AR immersive design experience. To begin with, the designer can scan the QR code for on-site location confirmation by *HoloLens*. After that, the designer can "draw" the virtual control baseline of the brick wall on-site in AR environment by "tap and hold" hand gestures. As in the previous scenario, the user can preview the shape of the design, this time however in the form of a 3D hologram that is overlayed directly onto the site, and adjust the control baseline in real-time. Following on from this, the designer can modify the shape by "tap and hold" the virtual control points shown on the surface (Figure 4). After the shape is determined, the designer can preview the brick wall as an on-site holographic model in *HoloLens* and can adjust the numbers of bricks, the angle of bricks, the brick structure density, and the brick pattern arrangement by interacting with the AR sliders through real-time immersive design process.

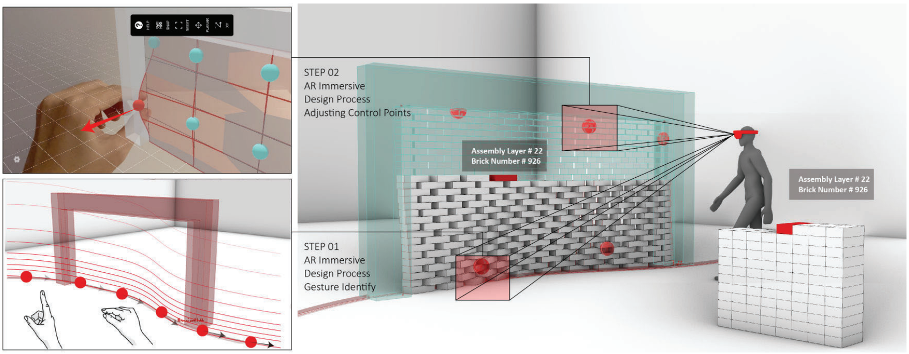


Figure 4. Identify hand gestures inputs and adjust parameter controllers in immersive design.

For the AR holographic assembly part, test 2 provides the users with the same intuitive immersive holographic assembly guidance as test 1. Instead of using iPhone 11, test 2 chooses *HoloLens*, so designers can walk around the on-site holographic model and use hand gestures to operate the assemble process state. The main difference is that test 2 is a hand-free workflow that gives users more flexible manipulation and a more immersive AR surrounding experience.

Test 2 shows that this approach is more immersive and indeed more intuitive. The higher degree of immersion assists the designer who is wearing *HoloLens* to modify and translate an on-site digital model into a physical structure. The input is more intuitive than using handheld devices, since hand gestures and even voice commands are recognized by the HMD.

However, such systems also have technical problems. The sensors in *HoloLens* are affected by the surrounding light condition. If too much or too little UV light is occurring in the natural environment, for instance, the holographic model has sometimes difficulties to lock a model in a specific place. Besides, the communication speed between *Grasshopper* and *HoloLens* in real-time is 4.136 Mb/s. Science this process requires more calculations than Test 1, the holograms have a little lag compared to real-time. The virtual information transformation from *Grasshopper* to *HoloLens* requires an internet with good connection and speed, such as wifi and 4G. If the internet connection is poor, it will cause a delay in hologram and real-time modification. As a consequence, it is sometimes necessary to restart the device and re-scan a QR code for correcting construction location.

Moreover, for the large-scale architectural assembly projects, the material might beyond the range of manual handiwork, such as concrete blocks, large-scale woods, metal blocks, etc,. For large-scale architectural structures, this AR-assisted design-assembly workflow will need the intervention of robotic fabrication.

3.3. TEST 3 | AUGMENTED ROBOTIC FABRICATION

Test 3 chooses the same brick column design as in Test 1, but this time adds robotic fabrication to the workflow of an AR/HMD-assisted design and assembly process. Robotic operations, traditionally, need specific expert computer science and programming knowledge to plan the movement of a robotic arm. For physical operation, robotic errors occur beyond simulation occasionally. This process is not without dangers if we imagine workers being in the same space as the moving robotic arm. AR provides us an interactive virtual robotic control methods and an on-site holographic robotic trajectory simulation to avoid the defect caused by the traditional robotic workflow. To do this experiment, we decided to use Microsoft *HoloLens 1* and a UR10 Robotic arm.

For this AR robotic fabrication experiment, we started with a simple robotic operation - "pick and place". First, the user can preview the brick location in the material preparation area and the target location in the assembly area through *HoloLens*. After preparing a physical brick in the preparation location, the user just needs to "tap" the virtual brick hologram, which is recognized and transformed in AR version through *HoloLens*, "drag" and "release" the virtual brick hologram to the highlighted target location. Next, the command for the robotic arm will be sent from the *HoloLens* sensor to *FURobot* plug-in in *Grasshopper*. The virtual on-site holograph simulation will be sent back to *HoloLens* and be ready for physical operation. Last, the user can preview the whole holographic simulation and switch the toggle to "Operate" to complete the robotic assembly process (Figure 5).

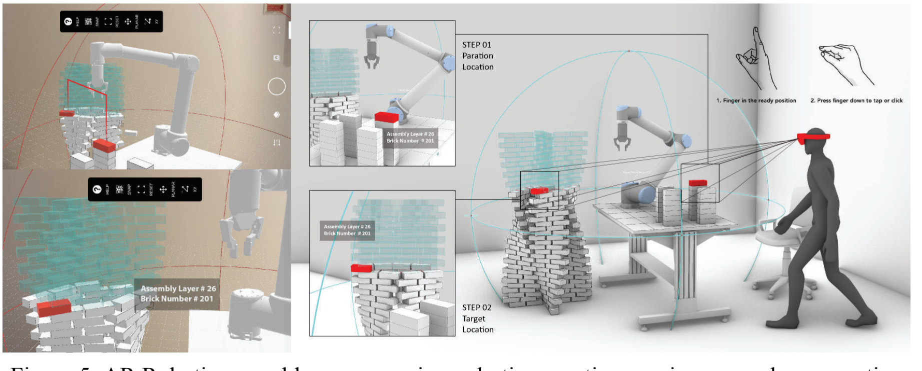


Figure 5. AR Robotic assembly process: view robotic operation maximum reach, preparation area, target area, and robotic operation trajectory.

Test 3 provides that it is a safer and more effective method to operate robotics through AR with on-site gestures command and holographic trajectory simulations. All the computer science programming technics have been pre-coding in *Grasshopper*, the user simply needs to point out the "preparation" and the "target" location. In this way, the robotic fabrication workflow will not require specific computer science knowledge and skilled programming workers.

This last experiment also highlighted certain problems for us. The current functionality of test 3 is very limited. We only use brick-shape as the prototype material for tests, other kinds of materials have not been tested and confirmed that work well with AR/HMD-assisted robotic assembly workflow. But more architectural materials will be testing in future research.

4. Conclusion

The above-described three *AR Digi-Component* tests give an overview of the current state-of-the-art AR technologies, such as AR real-time modification, AR immersive design and holographic assembly, and AR/HMD-assisted robotic operation. Our research leads to three key recommendations in the fields of architecture and construction and in regard to the assembly of building elements at full scale (Figure 6).

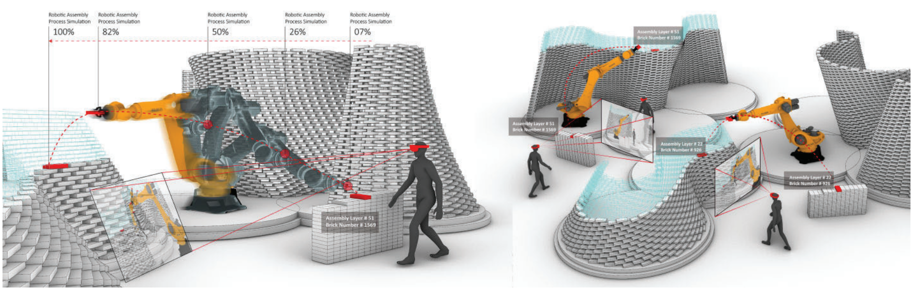


Figure 6. The holographic of robotic trajectory simulation in AR-Robotic assembly workflow for man-machine collaborative fabrication process in large scale architectural application.

In terms of **AR real-time modification and immersive design**, our research has shown that AR technology can translate the designer's gestures into corresponding parameter adjustments in *Grasshopper* to preview the immersive generated design. This method gives users a new way to modify design drifts and preview on-site locations through the AR environment in real-time. We hope that our research shows that, under certain circumstances (e.g. complex and labor-intense designs), a more intuitive and dynamic AR-assisted workflow could assist or replace the more conventional approaches.

For **AR holographic assembly**, it can improve the efficiency and accuracy in the assembly process, especially for unskilled labors to follow the stey-by-stey virtual instruction. This method can arguably also save time that is normally needed when translating 2D information into 3D on-site location design and built. Although there are still tolerances that occurred during transforming the assemble commands by the surrounding environment, devices, and labors, this situation will be improved by adding multiple AR devices for all assembly workers.

For **AR/HMD-assisted robotic fabrication**, it has been shown that modifying robotic movement trajectory plan and operating virtual holographic simulation is safer for human operators compared with the traditional industry robotic operation method. It offers the designers, who do not have special computer science or programming knowledge, a convenient way to operate the robotics for the construction of manual-unachievable materials directly through AR.

In conclusion, the *AR Digi-Component* project bridges the gap between digital design and physical outcome by designing a workflow that includes AR immersive design, AR holographic assembly, and AR robotic fabrication. Using this workflow, the AR device can detect and identify the designers' thinking and idea at any time; transform their gestures and reactions into digital outcomes calculated by parametric rules in *Grasshopper*; preview the hologram overlapping on the real world in real-time through AR device; and get the physical outcomes either in AR holographic assembly method or AR robotic fabrication method depends on the material behaviors. It brings the possibility to interact with AR and get the enormous advantage of feedback through AR to designers in real-time.

The further work will take in premeditation the additional development of involving multiple AR participants in the whole workflow to reduce the tolerance due to the command transformation. More sensors will be used to catch complicated human gestures in the immersive design part. Multiple robotic arms and operations will be developed for the man-machine collaborative fabrication part through an AR-assist real-time environment. Develop and complete the whole AR-assist design and assembly process as a *Grasshopper* plugin with the physical simulation of material properties for crash and collapse detection. The final goal is to make the whole AR design and assemble workflow simplified and modified for architectural scale elements and applications.

References

Do Carmo, R.M.C., Meiguins, B.S., Meiguins, A.S.C., Pinheiro, S.C.V., Almeida, L.H. and Godinho, P.I.A.: 2007, Coordinated and multiple views in augmented reality environment., *11th International Conference Information Visualization*, Zurich, 156–162.

Imani, A.: 2017, Reality or Unreality, Prediction of Architecture Dreams., *3rd International Conference on New Trends in Architecture and Interior Design*, Helsinki.

Jahn, G., Wit, A. and Samara, J.P.: 2019, BENT: Holographic handcraft in large-scale steam-bent timber structures, *ACADIA 2019*, Austin, Texas.

Olar, M.L., Risteiu, M., Panaite, A.F., Rebrisoreanu, M. and Musetoiu, O.: 2019, Controlling a robotic arm with Augmented reality, *MATEC Web of Conferences.*.

Ong, S.K., Yew, A.W.W., Thanigaivel, N.K. and Nee, A.Y.C.: 2020, Augmented reality-assisted robot programming system for industrial applications., *Robotics and Computer Integrated Manufacturing*, **61**, 101820.

Schmidt, B., Borrison, R., Cohen, A., Dix, A., Gärtler, M., Hollender, M., Klöpper, B., Maczey, S. and Siddharthan, S.: 2018, Industrial Virtual Assistants: Challenges and Opportunities, *ACM International Joint Conference*, Singapore, 794-801.

Sheldon, A., Dobbs, T., Fabbri, A., Gardner, N., Haeusler, M.H., Ramos, C. and Zavoleas, Y.: 2016, Putting The AR in (AR)chitecture: Integrating voice recognition and gesture control for Augmented Reality interaction to enhance design practice., *CAADRIA 2016*.

Song, Y.: 2020, BloomShell: Augmented Reality for the assembly and realtime modification of complex curved structure, *eCAADe 2020*, 345-354.

Tsai, C.Y., Liu, T.Y., Lu, Y.H. and Nisar, H.: 2020, A novel interactive assembly teaching aid using multi-template augmented reality, *Springer Science+Business Media*, **7**, 1-28.

A STUDY ON CHAIR DESIGN BY INTERACTIVE THREE-DIMENSIONAL MODELING USING SKETCHING INTERFACE

MASASHI NARUSE[1], ULEMJJARGAL BILEGUUTEE[2] and AKIHIRO MIZUTANI[3]
[1,2,3]*Toyohashi University of Technology*
[1,2,3]*{naruse.masashi.tb|ulemjjargal.bileguutee.vq|mizutani.akihiro.ar}@tut.jp*

Abstract. This paper discusses the potential derived by developing a sketching interface to achieve an intuition-oriented design process for beginners, focusing on fabrication. Using experiments and a questionnaire, we evaluate both the method developed and the change in the consciousness of participation in full-scale 3D (Three Dimensional) design. A specific feature of the developed sketching interface is that it is not fully packaged; it means designers can modify and customize a tool to their needs. However, there was no difference between the sketching interface and ordinary 3D CAD (Computer-Aided Design) in increasing the motivation to use computers to fabricate; including a customizable feature (not fully packaged) could open up the possibilities of increasing motivation for the subjects to participate in the fabrication. The experiment results demonstrated that the sketching interface input system has equivalent reproducibility to existing 3D CAD, and even beginners can intuitively and immediately realize fabrication.

Keywords. 3D CAD; sketching interface; fabrication support; digital fabrication.

1. Background

Fab Lab, which began as an outreach activity for research conducted at the Center for Bits and Atoms of the Massachusetts Institute of Technology Media Lab, has rapidly expanded its network worldwide (Gershenfeld 2005). Participation in fabrication using computers is becoming more comfortable and familiar for people year by year due to the spread of related educational opportunities and teaching materials. High-usability input devices, such as the computer mouse, have been developed with the widespread use of computers. In recent years, LCD (Liquid Crystal Display) pen tablets and touchscreen tablets have become popular because they allow users to input data via simple operations. Moreover, around 2000, the research and development of sketching interfaces began flourishing. As in this research, software development that enables modeling chairs from sketches is being carried out. For these reasons, the hurdle to participation is lower than ever before. However, although facilities that can perform digital fabrication, such

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 263-272.

as Fab Lab, are becoming more common and a personal fabrication revolution is taking place, such fabrication remains far from easy for those not associated with it. In the general participation process of (1) training to use software such as CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) and (2) designing and processing one's work, the education conducted for skill acquisition is by no means "fun." Information on design input using LCD pen tablets and touchscreens has not been fully clarified yet. Moreover, currently, the use of digital tools to reach a user's sound design is not well understood.

2. Research objectives

This study aims to confirm whether the following two objectives could be achieved: (1) developing a straightforward design input method to aid beginners who do not possess specialized knowledge and skills to easily operate, design, process, and fabricate by their intuition and (2) opening up fabrication to society using digital carving technology by eliminating the requirement to learn three-dimensional (3D) CAD, which is a prerequisite for participation and is influencing the field of architecture and furniture design. First, we developed a method that enables beginners' participation in fabrication using digital design and digital processing technology without having to learn 3D CAD. Specifically, we created a system that allows beginners to design chairs. We focused on the following operations from 3D CAD in ordinary digital fabrication: (1) make design input/editing possible as if sketching with paper and pen, (2) automate detail generation for component mounting, and (3) semiautomate data generation required to operate the processing machine.

3. Introduction of interactive 3D modeling by sketching interface

3.1. RELATED WORK

In a previous study (Mizutani et al. 2019) that focused on CNC (Computer Numerical Control) chair fabrication, the authors devised a system that enabled people unfamiliar with CAD operations to design. However, research on design input methods, specifically device studies, had not yet been conducted. An interactive tool called SILK (Sketching Interfaces Like Krazy) (Landay and Myers 2001) is one of the pioneering technologies classified as sketching interfaces; its system replaces designing through traditional CAD graphical user interfaces with just sketching. Research on two-dimensional (2D) graphics, such as screen and website design, as well as on sketching interfaces for 3D graphics has been conducted in the same manner. As the first example of incorporating interactivity, SKETCH (Zeleznik et al. 2006) was remarked upon as being different from the earlier batch-processing approach of outputting the line drawing input to the computer as a 3D shape. These studies clarified that even beginners and children with no experience in 3D graphics can easily create 3D models using a sketching interface. Research on and development of such methods have been actively conducted since around 2000, and a review of those studies was conducted by Igarashi (2006).

The most similar study to our research was on SketchChair (Greg Saul et al.

2011), a system that allows users to design a chair by merely inputting a side view (2D) of the chair from the user interface. The system's primary feature is that it allows a human being to sit on the generated chair model within a physics engine, which then performs a stability analysis. The chair's stability and the person's sitting posture when sitting can be visually confirmed, enabling users to envision the size, scale, and sitting comfort with ease. In other words, the system is equipped with functions that support novices who do not possess such a skill set or knowledge to design original chairs. In ordinary furniture design, 3D CAD is used not only to design shapes but also to create design drawings and processing data. One of the features of such a system that can be considered as both an advantage and disadvantage is that the design drawings for processing chair parts are automatically generated by the software. At about the same time as the release of SketchChair, Kostas Terzidis pointed out in his book (2006) that, currently, designers cannot demonstrate their creativity because toolmakers such as software vendors have prepared essential parts of the design process in advance so that the designers are mere "tool users" who tweak the form within a range of prearranged operability. So it cannot be said that SketchChair is out of the category of "tool maker" and "tool user" defined by Kostas Terzidis and that users cannot be more creative than they are supposed to. Additionally, it cannot be said that we should expect to see an effect of increasing the willingness to participate in full-scale 3D design and encouraging opportunities for participation beyond that. Nearly a decade has passed since the release of SketchChair, but to date, the input and design methods of other sketching interfaces have not been generalized. The reasons for this are (1) the emergence of easy-to-learn software such as SketchUp, which has made 3D design itself more effortless, and (2) the emergence of visual programming interfaces, which make it possible for designers to write their own algorithms and develop original tools.

3.2. SYSTEM OVERVIEW

In this research, we mainly aim to get users actively involved in full-scale 3D design after making chairs using the developed system. Therefore, the design process was conducted by leaving a *yohaku* (i.e., a design mechanism with flexibility to adapt to the user's skill level) in the support system so that the designers could modify and customize the tools to their needs. The base system for development was powered by Rhinoceros and Grasshopper (Robert McNeel & Associates; developed by the Rhinoceros plug-in graphical algorithm editor), which are design platforms providing user-friendly programming environments and compatibility with open-source plugins. The specific system configurations were (1) creating a web application-based sketching interface, (2) enabling the user to customize, on Rhinoceros and Grasshopper, dimensions of chair part and details of joints for assembling. This system is intended for people who have no experience with 3D CAD that includes up to inexperienced architects in 3D from people who are not professional. How to use the system differs depending on the user's skill level in 3D design. Although some design restrictions are set as the initial stage, it is assumed that the tools will be modified later according to the user's wishes. This statement is the true meaning of *yohaku*.

3.3. SUPPORT SYSTEM FEATURES

To realize the paper-and-pen operation, the sketching interface was developed via JavaScript as a web application that could be used with a stylus from a tablet device such as an iPad (Fig. 1-1). When operating the pen tool, the stylus trajectory was drawn as a dot group, and when operating the eraser tool, the points were erased. By making the design input method similar to the experience of using a pen and paper, we assumed that even those who had never used 3D CAD could easily participate in this computer-based design.

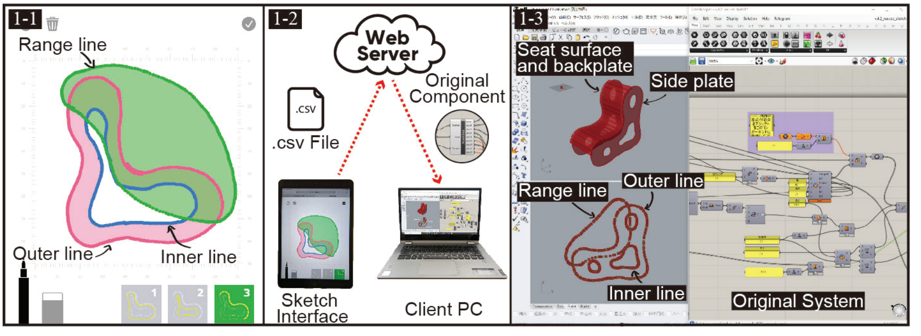


Figure 1. System overview. 1-1: Sketching interface UI screen. 1-2: Data transfer from iPad to PC. 1-3: Process up to 3D model generation by Rhinoceros + Grasshopper.

As shown in Figure 1-3, the chair to be designed comprised two side plates and a plate connecting them in a ladder shape: the seat surface and the backplate. To design the chair, the user had to input a side view of the chair through the sketching interface in Figure 1-1. To design this side view, the information required the (1) outer line, (2) inner line, and (3) range line where the seat and backplate were attached. While switching the information to be input from the icon on the web application, each shape had to be input from (1) to (3). When the user pressed the save confirmation button after the shape was satisfactory, the contour coordinate data of each point cloud (1)-(3) drawn on the sketching interface and acquired by the concave hull was saved as a CSV (Comma-Separated Values) file on the server. Then, the contour coordinate data of the point group in the CSV were downloaded to a web server connected to a local PC (Personal Computer) for processing as shown in Figure 1-2. This PC, on which Rhinoceros and Grasshopper were installed, ran components developed on Grasshopper, as shown in Figure 1-3. A point cloud was generated on Grasshopper from the contour coordinate data, generating a spline. When shapes (1)-(3) input in the sketching interface were splined by the components in Figure 1-3, a 3D model of a chair was automatically generated. The member dimensions of the seat surface and backplate, e.g., the distance between the seat surface and backplate, could be altered and input by the user as parameters from the system shown in Figure 1-3. In some cases, the algorithm could be partially rewritten, and the user could customize the chair configuration method, e.g., for assembling the members and shape for the generated details.

This process summarized above was repeated until the user was satisfied. When the user reached their ideal chair design, the operation data for the digital processing machine, such as a CNC router, were generated. Since the system shown in Figure 1-3 could automatically output the spline data required for generating the operation data, easily performing the series of CAD operations required for generating the G-code was possible. Thus, via the above procedure, we built a mechanism that allows users to participate in computer-based design immediately and without learning 3D CAD.

4. Method

In this study, we experimented with 20 undergraduate and graduate students who had no experience with 3D CAD to discover the effects of using the support system developed in this study and determine possible improvements. The participants were divided into Group A (G-A), which used the developed sketching interface input system (iPad + stylus), and Group B (G-B), which used a ready-made 3D CAD interface (PC + mouse). The experiment was conducted according to the following procedure (Figure 2):

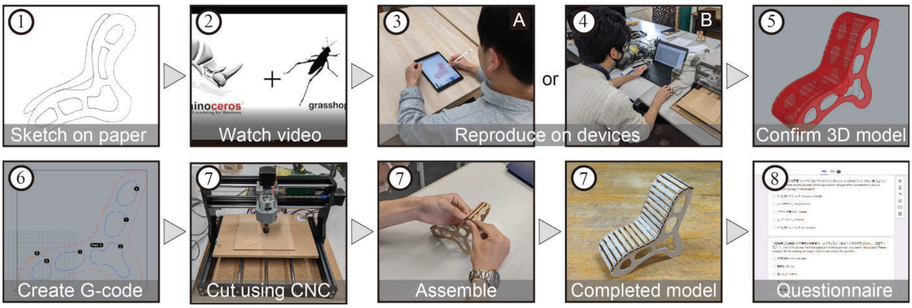


Figure 2. Experimental method: On procedure 3, we measured the input time. The experimenter performed the operations up to experimental steps 4–7.

1. Each subject created a side view of the chair from a sketch using paper and a pen.
2. Each subject received an explanation of the operation method via a video (about 1 minute 30 seconds) about the input operation to be performed by each group.
3. To reproduce the side view drawn in the first step, the subjects in G-A used the stylus to input from the sketching interface, while the subjects in G-B used the mouse to input from the ready-made 3D CAD interface.
4. After confirming the 3D shape of the chair that was three-dimensionalized from the side view by the developed support system, the subjects corrected the shape until they thought that the shape from the first step had been reproduced.
5. The subjects generated a side view of a model (1/5 scale) on the Rhinoceros model space from the developed support system.
6. The subjects generated G-code to process the side plate members using LinCAM3, a CAM software that can be plugged into Rhinoceros.
7. The subjects cut out the side plates for the model from the G-code generated in previous procedure 6 using a desktop CNC router and assembled the model using

the precut seat surface and backplate parts.

8. The subjects responded to a questionnaire survey on the system's use as developed for the participants and their own changes in consciousness regarding fabrication using computers.

5. Results from user experiment and Discussion

5.1. QUESTIONNAIRE RESULT AND DISCUSSION

The questionnaire was answered by all people in each group. Q1-Q7 referred to the system's usability, and Q8-Q11 asked if the participants had gained an interest in fabrication after using the system. Table 1 shows the results of Q1-Q7, Table 2 shows the results of Q8-Q10, and Q11 (multiple choice question).

Table 1. Questionnaire results for questions Q1 to Q7.

Question 1 How was the usability of the input screen (user interface design such as icons) used this time?					
Experimant Group	1.Very easy to handle	2.Easy to handle	3.Neither	4.Difficult to handle	5. Very difficult to handle
A（iPad+stylus）n=10	50.0%	40.0%	10.0%	0.0%	0.0%
B（PC＋mouse）n=10	30.0%	50.0%	0.0%	20.0%	0.0%
Question 2 How difficult was the input operation of the device used this time? Please compare the work with paper and pen and answer.					
Experimant Group	1.Very easy	2.Easy	3.Same	4.Difficult	5.Very difficult
A（iPad+stylus）n=10	40.0%	60.0%	0.0%	0.0%	0.0%
B（PC＋mouse）n=10	10.0%	50.0%	10.0%	30.0%	0.0%
Question 3 Did you get the shape you envisioned? Please compare the work with paper and pen and answer.					
Experimant Group	1.Agree	2.Agree a little	3.Same	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	80.0%	20.0%	0.0%	0.0%	0.0%
B（PC＋mouse）n=10	50.0%	40.0%	0.0%	10.0%	0.0%
Question 4 How was the shape adjustment / correction work? Please compare the work with paper and pen and answer.					
Experimant Group	1.Very easy	2.Easy	3.Same	4.Difficult	5.Very difficult
A（iPad+stylus）n=10	50.0%	20.0%	20.0%	10.0%	0.0%
B（PC＋mouse）n=10	30.0%	50.0%	0.0%	20.0%	0.0%
Question 5 How many shape corrections did you make compared with working with paper and pen?					
Experimant Group	1.Significantly more	2.More	3.Same	4.Less	5.Significantly less
A（iPad+stylus）n=10	10.0%	40.0%	40.0%	10.0%	0.0%
B（PC＋mouse）n=10	10.0%	50.0%	20.0%	20.0%	0.0%
Question 6 Do you think you were able to design the chair you wanted this time?					
Experimant Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	80.0%	20.0%	0.0%	0.0%	0.0%
B（PC＋mouse）n=10	60.0%	40.0%	0.0%	0.0%	0.0%
Question 7 How did you feel about the difficulty of this series of work including model making?					
Experimant Group	1.Very easy	2.Easy	3.Neither	4.Difficult	5.Very difficult
A（iPad+stylus）n=10	80.0%	20.0%	0.0%	0.0%	0.0%
B（PC＋mouse）n=10	30.0%	60.0%	10.0%	0.0%	0.0%

Regarding Q1 from Table 1, over 80% of the subjects answered that the input screen was "Very easy to handle" or "Easy to handle," and there was no significant difference in the overall average. However, the number of subjects who answered "Difficult to handle" was 0% in G-A but 20% in G-B, suggesting that G-A was more comfortable with operating the device. Q2-Q5 compared each device's input operation to paper and pen. Regarding Q2 and Q3, we can say that the design input operation was remarkably simple and the shape was highly reproducible because 100% of the answers were selected from among "Very easy," "Easy," "Agree," and "Agree a little" in G-A. Regarding Q4 (on the shape adjustment work), 70% of the answers in both G-A and G-B were "Very easy" or "Easy." In particular, 50% of G-A answered "Very easy," and it was found that many subjects felt that the device's input operation was more manageable than designing with paper and pen. In response to Q5 (regarding the number of shape corrections), 50% of the subjects in G-A answered "Significantly more" and "More," and 60% of the subjects in G-B answered "Significantly more" and "More". Although the points with high response rates of "Significantly more" and "More" were nearly the same in both G-A and B, it can be inferred that the factors are different. Considering the answers of the subjects in G-A to Q2, Q3, and Q4, this might have been related to the device's straightforwardness compared with using paper and pen, suggesting that corrections were easily repeatable. However, G-B used a ready-made software wherein the spline's control points could be controlled by free mouse operation. More slight adjustments could be made than with paper and pen, which was cited as a factor that increased the number of corrections. Besides regarding Q5, even 40% of subjects in G-A answered "Same," it can be inferred the developed sketch input system is closer to the operation of pen and paper. Regarding Q6 and Q7, 100% of the respondents in both groups answered "Agree" or "Agree a little." For Q7 (concerning the difficulty of the work), 80% of the subjects in G-A answered "Very easy." Therefore, it was found that the developed sketching interface achieved immediate and highly satisfying design input.

Table 2. Questionnaire results for questions Q8 to Q10 and Q11.

Question 8 Do you want to make a chair that you designed yourself in this experiment in full size?					
Experiment Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	40.0%	40.0%	10.0%	10.0%	0.0%
B（PC＋mouse）n=10	30.0%	40.0%	20.0%	10.0%	0.0%
Question 9 Do you want to try manufacturing like this again?					
Experiment Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	70.0%	30.0%	0.0%	0.0%	0.0%
B（PC＋mouse）n=10	90.0%	10.0%	0.0%	0.0%	0.0%
Question 10 Do you want to learn more advanced 3D design (design using a computer) in the future?					
Experiment Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	50.0%	20.0%	20.0%	10.0%	0.0%
B（PC＋mouse）n=10	50.0%	50.0%	0.0%	0.0%	0.0%
Question 11 What do you want to learn in the future to learn 3D design? (Multiple selections are possible)					
Experiment Group	Operation of 2DCAD	Operation of 3DCAD	Operation of CAM	Operation a digital processing machine	Programming
A（iPad+stylus）n=10	0	4	1	2	5
B（PC＋mouse）n=10	7	7	5	4	4

Regarding Q8 (on the subjects' desire to create a full-size chair), there was no large difference between the groups, and over 70% of the subjects were enthusiastic about making a real product. For Q9, regarding whether they wanted to try this fabrication again, all subjects responded "Agree" or "Agree a little" and were highly motivated to participate in future fabrication. Although it seemed as if there was no significant difference, G-B seemed to have more motivation for future fabrication, which was suggested when 90% of the subjects answered "Agree" to Q10 and 100% chose "Agree" or "Agree a little." Regarding the consciousness toward technology as answered in Q11, the subjects of G-B were more positive toward improving their motivation to participate in 3D design. This unexpected result was thought to be because the only difference between the operation processes of G-A and G-B was the input method, as the implementation of *yohaku* to involve the users in the modification of the developed support system, i.e., its operation and processing, was the same. This is because it was predicted that G-B would spend more time in contact with the support system than G-A and have a higher understanding of *yohaku*. G-B performed design input on a local PC, wherein the developed support system's processing results were drawn. The experiment in this study was not appropriate as a method for analyzing the hypothesis that implementing *yohaku* would lead to subsequent participation in full-scale 3D design and improvement in learning motivation. However, both groups showed a high level of motivation to participate in fabrication in the future, indicating the usefulness of a design system that leaves in a mechanism that is not fully packaged.

5.2. ANALYSIS AND CONSIDERATION OF THE MATCH RATE OF FIGURES

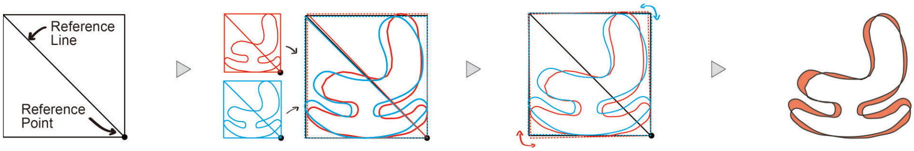


Figure 3. Determination of the difference area.

Next, the chair's side view designed by the subjects in the experiment was analyzed and discussed. The area match rates of the figures drawn on paper and each device were calculated and compared. The method (Figure 3) was as follows: (1) The reference point and reference line were determined to adjust the scale. The diagonal line of a 900 × 900(mm) square was used as the reference line according to the CNC router's acceptable plywood size when determining the actual size. The reference point was set on a corner point of the bounding box, which is the bottom of the chair's backplate. (2) The diagonal from the bounding box of the shape drawn on paper and each device was obtained, then we matched the scale's reference (3) To correct the figure's inclination, the angle of the reference line was matched with the reference point as the axis and the diagonal angle obtained from the bounding box of the figures drawn on paper and each device. (4) The total difference area of the two figures was calculated. The difference area here was the total area of both the inside (minus) and outside (plus) deviations. The different surface areas obtained for each design were divided by the sum of the surface area of the figure used for calculating the different surface areas (the figure drawn on paper and the figures drawn via the input method for each group), and the rate of change was calculated and compared. When using sketches on nonscale paper as a comparison standard, a way to unify each design for the multiple inner diameter lines entered at the discretion of the subjects was not found, so we excluded them from the analysis. It was found that, to obtain the coincidence rate of the figures, including the inner diameter lines, unifying the scale standard and the number of inner diameter lines was necessary. Table 3 shows the area match rate of the outer lines and input time in each input device and Figure 4-1 shows mean match rate of outer line figures (G-; A and G-B) with standard deviation (SD) error bars.

From Table 3, the average value of the match rate was 79.2% in G-A, 77.7% in G-B, suggesting the match rate was slightly higher in G-A. As an analysis of the match rate, Figure 4-1 shows the data with mean value and SD. In comparing the mean values of each group, the null hypothesis H0 was assumed that there is no significant difference between G-A and G-B; where the alternative hypothesis H1 was assumed that there may be a significant difference. After confirming the presence or absence of homoscedasticity by the F-test, the significance level was set to 5% and an unpaired t-test was performed. As a result, the null hypothesis was accepted because the p-value was greater than the significance level of 5%, and no significant difference could be confirmed [$t(18) = 0.36$, $p = 0.7233$]. Since no significant difference could be confirmed and the difference in the matching rate of each group was small, it can be said that each input device has the same degree of graphic reproducibility. Next, the analysis was performed against the input time. From Table 3, the average input time was 469 (s) for G-A, and 873 (s) for G-B which was shorter for G-A. Figure 4-2 shows the data with mean value and SD. In comparing the mean values of each group, the null hypothesis H0 was assumed that there is no significant difference between groups; where the alternative hypothesis H1 was assumed that there may be a significant difference. After confirming the presence or absence of homoscedasticity by F-test, the significance level was set to 5% and an unpaired t-test was performed. As a result, it was found that the null hypothesis was rejected because the p value was smaller than the significance level of 5%, and there was a significant difference[$t(14) = 3.33$, $p = 0.0049$]. Since a significant difference was confirmed, the confidence interval (CI) was calculated and found to be 95%, CI = (358, 580) in G-A; 95%, CI = (663, 1084) in G-B.

Table 3. Match rate of outer line figures. The terms represented in the table are Paper Input Area (PIA), Device Input Area (DIA), Difference Area (DA). Match Rate is calculated by subtracting the differential rate (DA/PIA + DIA) from 100%. .

Group A (iPad+stylus)						Group B (PC+mouse)					
Subjects	PIA (mm²)	DIA (mm²)	DA (mm²)	DA/PIA+DIA	Match Rate	Subjects	PIA (mm²)	DIA (mm²)	DA (mm²)	DA/PIA+DIA	Match Rate
A	429,859	382,226	88,481	10.9%	89.1%	K	345,495	283,895	167,961	26.7%	73.3%
B	383,013	372,662	123,378	16.3%	83.7%	L	270,320	283,754	184,463	33.3%	66.7%
C	293,564	291,932	248,232	42.4%	57.6%	M	421,523	424,973	129,550	15.3%	84.7%
D	273,593	228,355	117,959	23.5%	76.5%	N	342,686	373,085	144,563	20.2%	79.8%
E	343,646	318,877	87,505	13.2%	86.8%	O	318,470	331,081	102,578	15.8%	84.2%
F	269,124	310,140	131,260	22.7%	77.3%	P	248,212	252,002	205,883	41.2%	58.8%
G	285,884	339,816	213,525	34.1%	65.9%	Q	363,055	392,942	99,971	13.2%	86.8%
H	390,529	364,414	112,710	14.9%	85.1%	R	225,386	283,148	109,252	21.5%	78.5%
I	334,782	344,714	86,949	12.8%	87.2%	S	347,406	330,189	166,190	24.5%	75.5%
J	317,320	362,472	114,147	16.8%	83.2%	T	453,717	433,309	104,292	11.8%	88.2%
			Average	20.8%	**79.2%**				Average	22.3%	**77.7%**

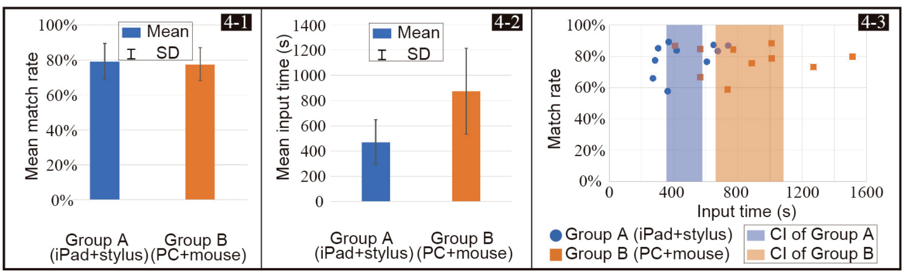


Figure 4. 4-1: Mean match rate of outer line figures (G-A and G-B) with SD error bars. 4-2: Mean input time with SD error bars. 4-3: Relationship between input time to each device and figure match rate and CI of input time. .

From the above, Figure 4-3 shows the relationship between the figure match rate and the input time for each device, and the result of the CI of the input time. From Figure 4-3, it can be said that the input time of G-A is significantly shorter than that of G-B due to the CI in the input times of G-A and G-B do not overlap. From this, it can be considered that since G-A can input intuitively, the variance of the input time by the subject is small and the figure can be reproduced in a shorter time than G-B. By contrast, in G-B, it can be considered that the variance of the input time among the subjects became large due to the skill level of the subject's PC operation. From the above, it can be said that the developed sketch input system has immediate reproducibility equivalent to that of existing 3D CAD, and even people without specialized knowledge can intuitively realize fabrication using a computer.

6. Conclusion and Future Work

Using the developed sketching interface, even beginners without specialized knowledge could reproduce designs as if sketching with paper and pen. Moreover, it was found that design input could be performed more easily and immediately than with ordinary 3D CAD. Herein, analyzing and considering the effect of improving people's motivation to participate in fabrication using computers solely by comparing the differences in design input methods were impossible. However, it has been shown that *yohaku* in a design system may increase people's willingness to participate, although comparing our developed system with other fully packaged systems to determine whether this is accurate is necessary. In future research, if a method to confirm the effect of implementing *yohaku* is developed, studies on how to construct such a system should be conducted. This could include researching how to determine the right amount of *yohaku* and developing a system that could further open up fabrication using computers to society. By achieving this, the developed tool will become more flexible to accommodate the user's proficiency in 3D design, and will contribute to raising the level of understanding of 3D design in the architecture industry in the future.

Acknowledgments

The research team would like to thank Michael Makoto Martinsen for assistance with proofreading, Naoto Muramatsu for assistance with methodology, and the individuals who participated in the experiments. This work was supported by JSPS KAKENHI Grant Number JP19K15169.

References

Gershenfeld, N.A.: 2005, *FAB":The Coming Revolution on Your Desktop-From Personal Computers to Personal Fabrication*, Basic Books.

Igarashi, T.: 2006, Recent Trends in Sketching Interfaces, *Computer Software*, **23**, 3-13.

Kostas, T.: 2006, *Algorithmic Architecture*, Architectural Press.

J.A. Landay and B.A. Myers (eds.): 2001, *Sketching Interfaces: Toward More Human Interface Design*, IEEE.

Mizutani, A., Karashima, K., Egami, F. and Muramatsu, N.: 2019, REPORT ON THE UTILIZED OF A PUBLIC Fab FACILITY THROUGH CRAFTING WORKSHOP, *AIJ J. Technol. Des*, **25**(59), 309-314.

Saul, G., Lau, M., Mitani, J. and Igarashi, T.: 2011, SketchChair: An All-in-one Chair Design System for Endusers, *The fifth International conference on Tangible, Embedded and Embodied Interaction*, Funchal, Portugal, 73-80.

Zeleznik, R.C., Herndon, K.P. and Hughes, J.F.: 2006, SKETCH: an interface for sketching 3D scenes, *ACM SIGGRAPH 2006*, Boston, MA, USA, 9.

A USER-CENTRED FOCUS ON AUGMENTED REALITY AND VIRTUAL REALITY IN AEC: OPPORTUNITIES AND BARRIERS IDENTIFIED BY INDUSTRY PROFESSIONALS

OPPORTUNITIES AND BARRIERS IDENTIFIED BY INDUSTRY PROFESSIONALS

MUGE BELEK FIALHO TEIXEIRA[1], KIEU PHAM[2],
GLENDA CALDWELL[3], JENNIFER SEEVINCK[4], LEVI SWANN[5],
MARKUS RITTENBRUCH[6], NICK KELLY[7], YASUHIRO SANTO[8],
VERONICA GARCIA-HANSEN[9] and KIRSTY VOLTZ[10]
[1,2,3,4,5,6,7,8,9,10]*QUT*
[1,2,3,4,5,6,7,8,9,10]*{muge.teixeira|kieu.pham|g.caldwell|jennifer.seevinck|levi.swann|m.rittenbruch|nick.kelly|y.santo|v.garciahansen|kirsty.volz}@qut.edu.au*

Abstract. This paper presents insights into the opportunities and barriers for using augmented reality (AR) and virtual reality (VR) in the architecture, engineering and construction (AEC) industry by contextualising how their adoption is leveraged in practices. Based on a review of literature, a qualitative study using semi-structured interviews was conducted with thirteen participants from AEC industries between five and thirty years of experience. Interviews were conducted face-to-face and virtually using questions focusing on participants' experiences, perceptions of, and opinions about the use of AR/VR in AEC practice. Qualitative dissemination of key insights highlighted immediate and future possibilities for AR/VR, with current limitations that require future investigation from a user-centred perspective. Suggesting a XR-PACT framework, this paper frames key directions for future research to address current limitations and explore new opportunities that positively impact architecture and other professions, communities of building users.

Keywords. Augmented Reality; Virtual Reality; AEC; User Experience; Technology Adoption.

1. Introduction

Augmented reality (AR) and virtual reality (VR) are well-recognised as key digital disruptors to the Architecture, Engineering and Construction sector (AEC) (Delgado et al., 2020; Li et al., 2018). AR and VR technologies can improve design and decision-making practices in the key areas of visualization, information retrieval and collaboration (Rankohi and Waugh 2013). Yet despite their potential to improve the efficiency and accuracy of building projects, there is a risk that industry may become a passive and reluctant recipient rather than a protagonist of the use of these technologies, especially past its pilot stages. A similar problem occurred with Building Information Modelling (BIM), where the stagnation of its adoption was attributed to the issues of human factors (user experiences, expectations, and intentions), rather than the technology itself (Gu & London, 2010). It is important to understand AR and VR's usability in terms of context, requirements, and effectiveness, in parallel with technological developments to support adoption readiness. The aim of this paper is to bring into focus the opportunities and barriers in AR/VR adoption from the user perspectives of AEC industry professionals, and propose a holistic, user-centred approach to extend future research agendas that are responsive to the critical and developing needs of the industry.

2. The use of AR and VR in AEC Industries

The improvements to software development kits (SDKs) in recent years has afforded a diverse range of AR and VR applications in AEC projects (e.g., Pratama & Dossick, 2019). However, much of their development has been on their technical utility in activities such as client engagement, design support and reviews, or in construction planning, management, and training (Alizadehsalehi et al., 2020; Li et al., 2018).

Semi-immersive and fully immersive experiences affect a user's ability to navigate and comprehend virtual assets and, depending on different cognitive tasks, they may require added functionalities such as head tracking and haptic devices to track and record annotations and mark-ups (Castronovo et al. 2013). Where reviews with end-users involve rapid changes, data servers connected to multiple desk. This approach is seen in semi and fully immersive VR technologies where heuristic methods are used to add functionalities such as head tracking haptics and VR enabled projections (e.g. CAVES), to track and record mark-ups (Castronovo et al, 2013; Bullinger et al, 2010). When non-co-located users need to collaborate in real time, data servers and multiple VR interfaces are programmed in the system's architecture for synchronous or asynchronous exchanges (Bassanino et al., 2010). In cases of interoperability with project software such as BIM, a framework is used to preserve and pre-process geometric, spatial, and material data for accurate representations and renders in the VR environment (Andújar Gran et al., 2018; Gul, 2014, Du et al., 2018). For AR enabled solutions, interactive projection mapping to overlay site information onto physical models, allow consultants to annotate design changes with connected mobile tablets (Calixte & Leclercq, 2017; Hensel, 2015). Including, using point-cloud technology to augment co-located users (in studio or on-site) to review physical models in mixed-reality spaces (Fukuda et al., 2010). tops are developed to allow consultants to expediate changes without relying on physical mock-ups (Bassanino et al. 2010). In cases of interoperability with project software, a framework to operate seamlessly with BIM workflow is essential (Du et al. 2018), and correct conversion of spatial and material data and geometric pre-processing to project accurate renders in VR environments are critical for reviewing spatial and material quality of proposed space (Gül 2014).

Whilst there is a growth in integrating AR and VR technologies into decision-driven activities, there is limited focus on understanding user-centred barriers that would be impediments to successful adoption beyond pilot testing. Yet, the future agendas are focused on advancing technology accuracy at engineering-graded standards, efficiency for workflow and data management, and innovation for economic growth (Delgado et al. 2020). Further, there is a need to identify where AEC industries see the practical opportunities in AR and VR adoption, to target real need and value for future developments. To this end, the paper presents preliminary findings from interviews with industry experts to address a research question of what are the opportunities and barriers for AR and VR in the AEC industry from a user-centred perspective? The following sections describes the methods, findings and the proposed new framework of XR-PACT for future agendas to support a user-centred focus, reflective of the perceptions, experiences, and expectations of AEC practitioners.

3. Methods

Drawing on the insights from literature, a qualitative study using semi-structured interviews with AEC professionals was conducted between July 2020 until October 2020. For the rest of the paper, we refer to AR and VR synonymously as extended reality (XR), unless when the discussion refers to a distinctive usage or development of AR or VR technology. The proceeding sections describe sample selection, methods, and analysis of the semi-structured interviews for understanding the positioning of XR in AEC, and for pursuing its innovation in the future.

3.1. SAMPLE AND PROTOCOL

Thirteen AEC professionals from Tier-1 and Tier-2 companies in and complementary to the AEC industry in Australia were recruited using purposive sampling through email invitation (58.33% success rate). The objective being to produce a sample of participants with relevant experience that logically represented the population (Lavrakas, 2008). Summarised in Table 1, the participant cohort had working experience ranging from 5-30 years in the AEC industry with varied roles. Some participants were solely responsible for technology adoption, future readiness, and managing XR and visualisations teams.

Table 1. Summary of the total AEC participants interviewed including their job title and interview format. .

Participant ID	AEC background	Role	Interview format
1	Engineering	Senior Engineer	Face-to-face
2	Architecture	Creative Director	Virtual
3	Construction and digital assets	Chief commercial Office	Virtual
4	Architecture	Technology lead	Virtual
5	Architecture	Innovation Lead	Virtual
6	Architecture	Computational representative	Virtual
7	AEC consultants in manufacturing, design development and management	General manager	Face-to-face
8	AEC consultants in manufacturing, design development and management	Design Visualiser	Face-to-face
9	Architecture	Visualisation lead	Virtual
10	Architecture	Parametric designer	Virtual
11	Engineering	Director of visualisation	Virtual
12	Engineering	Lead of visualisation	Virtual
13	Design and digital consultancy	Associate Director	Virtual

The semi-structured interview was developed based on the review of literature of 48 journal and conference articles, with open-ended questions that aimed to understand the opportunities, barriers, current use of XR technology, context of use and future projections or aspirations. Interviews were conducted via zoom and in person with audio and video recordings, which were transcribed for analysis. At least two interviewers were present for each interview; with one leading the interview with the set of questions, the other taking notes and raising prompts to elaborate or clarify responses.

3.2. ANALYSIS

A thematic analysis was used to analyse the transcripts and to identify themes relating to the opportunities and barriers of XR adoption in the AEC industry (Figure 1). An initial review with a subset of three transcripts was conducted for familiarisation and proceeded with open coding to establish the initial set of codes in tabular format. Identified codes emerged inductively and were recorded as descriptive concepts relating common perceptions and use of XR.

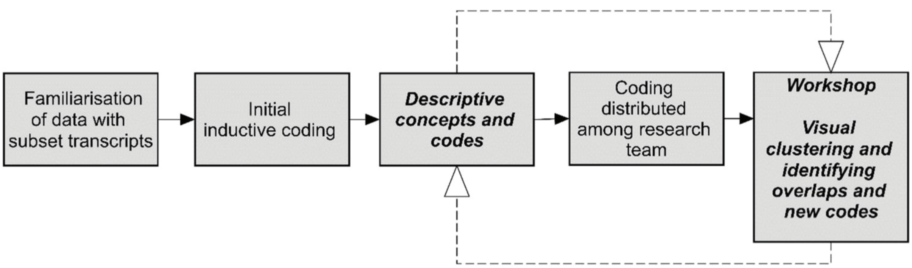


Figure 1. Flow diagram of coding procedure using multiple coders and visual clustering.

The set of codes was distributed amongst a team of five researchers in architecture, interaction design, and industrial design; to code all other nine transcripts and to recode the initial three. The diverse background of the research team resulted in complementary interpretations of the data, drawing on their multidisciplinary lenses. A coding workshop was used to visually cluster coded concepts, memos, insights and overlapping or new codes by transferring all codes (initial and additional) from Nvivo software to post-it notes (Holtzblatt et al., 2004). Through the process depicted in Figure 1, the opportunities and barriers emerged across four key themes: (1) Building in new ways, (2) Transformation of traditional approaches to innovative solutions, (3) XR adoption and (4) Disconnected Technologies and in-house investments.

The following reflective section frames the findings through a qualitative approach by referring to the participants' quotes to feature key themes.

4. Results: Opportunities and Barriers of Using XR in AEC Industry

Participants (P...) shared a similar high-level concept of what XR is, describing it as technology facilitating a relationship between virtual and physical worlds. The specific nature of this relationship was operationalised using different terminology such as "overlaying data into the real world" (P7), "Mimic[king] how the world [is]" as a "virtual world" (P4), "going to a different place from the real world or augmenting something of use over the real world" (P2), "creating a reality that is a mix of virtual and reality" (P13). These definitions of XR also revealed the aspirations of use to highlight the importance of fluidity of experience in transitioning between real and virtual spaces.

4.1. BUILDING IN NEW WAYS - DESIGN THAT IS ITERATIVE, EMOTIVE, AND EXPERIENTIAL

Several participants expressed XR's potential to profoundly affect how buildings are constructed and experienced in the design process. The AEC industry is characterised by standard processes that do not afford "the opportunity to beta test" (P1) or "prototype without investing a lot of resources" (P13). P1 stated: "what we build has to be... buildable... functional... safe... Structures... can be quite expensive and [you] can't just put-up test models" (P1). The opportunity exists for XR to bypass some of these barriers and provide a rich platform that moves past previous 2D and 3D modes of experiencing the design of buildings. P5 stated: "There are potentially all these new opportunities for how we can view or understand design now with this kind of extended reality space, which can... give us a great opportunity to interrogate not just virtual spaces, but also real spaces" (P5). This aspect was elaborated by P13, who identified VR as an opportunity of putting people in virtual spaces to iteratively explore emotion and behaviour, which is seen in other design disciplines (e.g. product design) but has traditionally been difficult to achieve in AEC disciplines. "Being able to elicit the true emotion that people will experience that's really important... Virtual reality has been heralded for being able to elicit that emotion" (P13). Bringing a new medium to building design creates new possibilities beyond the final visualised product of a virtual environment. P5 posed an important question about this potential: "what the changing medium can bring to... design cognition and understanding the impact of our design actions and our design thinking action" (P5).

User-centred testing, a method integral to design of User Experiences within Interaction Design, was also identified as an opportunity across interviews. User-centred testing is beneficial not only as it facilitates the experience of virtual models as a prototype, but also in terms of increased opportunity for quality control insights. One participant shared an instance where the evaluation of the virtual model during a wayfinding check by the client led to an immediate cost saving. A handrail (glass structure) was found to be inadequate, and they were able to halt manufacture and ensure quality approval: "[A client] was walking through the virtual airport and he noticed the balustrade wasn't - like it was a glass balustrade was quite low and he actually took his headset off and he rang the fabricator and he said, like, stop cutting the glass, we need to make higher... It's quite a small thing, but it's a lot of money being spent on glass and our model was quite cheap. It offset the cost of that model, like, immediately" (P12).

4.2. TRANSFORMATION OF TRADITIONAL APPROACHES TO INNOVATIVE SOLUTIONS

The interviews provided insights into how different companies are adapting their traditional work practice with novel approaches in XR. Approaches would vary on a case-by-case basis determined by project need, the interest, and capabilities of individual in-house employees on XR, or the input from established spin-off VR production companies. We found that traditional design processes were enhanced and expanded upon by the uptake of XR. XR did provide many opportunities to increase design capabilities such as reducing the time and cost of physical prototyping and increasing engagement with users for testing space. Simulated environment in VR allowed for different users to fully interact with the virtual space for marketing purposes, "...there's just so much demand for the virtual tours, whether it's in headset or on a sort of a large touchscreen interface. Still, that idea of being able to do virtual tours of spaces before they're built is very appealing right now" (P2). Another participant also saw the growing benefit of visualisation for experiencing the space: "I see those lines (digital vs physical space) breaking down a little bit more, and that our process of image making will be a much more real, physical experience" (P11). The value of AR was however, not as strongly perceived as that of VR due to some technical limitations, such as small viewing planes (field of view) in AR headsets like the HoloLens. Nevertheless, many of the participants remained hopeful about its evolution and furthering opportunities in visualising in real space. Examples for the use of AR included seeing building designs on site, reviewing building models collaboratively with multiple users, for tracking energy use, and navigation. "We'll be able to see...a glowing red area on the building to show that it's poorly insulated or something...useful in a very real way out in space" (P11).

4.3. XR ADOPTION

The interviews showed XR technologies to be piloted and used across diverse groups. Architecture firms reported the most versatile use of XR technology. VR setups, often in combination with a large screen that mirrored the VR view, were commonly used for client walkthroughs and design reviews. Engineering firms reported the use of similar setups for client walkthrough and XR user testing of space, e.g., "we've got these VR setups in all our offices... So yes, we're definitely using VR for that customer testing and we did do a really good project for [regional city] Airport... where people could walk through the airport, they could move the wayfinding and there was some really good sort of outcomes out of that" (P12).

While adoption appears increasingly widespread, barriers to adoption still exist and multiple interviewees reported that some of their colleagues see XR as a "gimmick", or do not understand the need to integrate XR early into a project's lifecycle "With VR, and often, like with all this visualization stuff that we do, you have those people who resist it, don't understand it... you need them to be taking a sort of a leap of faith in - when they're starting a project, they don't foresee any problems, because project's new, it's all planned out to schedule, then who's working on it, they got a great budget that's healthy, so they don't need visualization. But it's when it gets to midway or later in the project when the budget's getting tight and there's all these problems that they've found, and the use of the model would be helpful at that point and it's too late because the budget's blown and they got no time. That's when we get the call, we get the call on Friday afternoon saying, 'Can you do some fly through or VR model? We need it by Tuesday, and we've got two hours budget.' It doesn't work" (P12).

Of the reported benefits of XR, the main one found to increase adoption is the reliance on and integration of XR into the digital pipeline. P12 contrasts the digital approach with previous analogue client walkthroughs: "For... user testing, we were never involved in that sort of like old school prototyping... but I understand that they would make a physical space and they would sit in these foam chairs and move around these spaces, which seems a bit archaic and kind of bizarre considering how accessible VR is and considering the information that we're being fed now, by the design team. Like because they are modelling in 3D more and more, there's already this great starting point that's accurate, it's really detailed and... but in the past, there was often just 2D drawings. So, there was a lot of time being spent to sort of make something 3D and fleshing it out from a 2D drawing, whereas now that's, you know, we are being given these really great... files that we can just drop into a virtual environment and create things really quickly" (P12).

The flipside to increasing adoption and integration are increased expectations, as opined here: "That's probably a bit of a challenge for us now, it's kind of eating into our budget almost because it's becoming quicker and easier to produce these things" (P12). P5 further elaborated on the point of increased expectations of fidelity across different digital media: "It's every single medium, whether it's VR - whatever - has always had this problem. We saw this happen as well when we had fantastic visualization - static images started to emerge and it became easier to do that work. The expectation became that you would have a level of detail and a level of resolution to design often far earlier than you had time to get to...Every medium requires us as professionals within this industry to figure out how best to manage it or how best to utilize it."

4.4. DISCONNECTED TECHNOLOGIES & IN-HOUSE INVESTMENTS

Various BIM and XR technologies involved in creating, transferring, visualising, and presenting digital models were found not to align and be disconnected. For example, where BIM is used in design construction, the models and data are not easily translatable into another part of the industry's digital pipeline, which might use Oracle, because these platforms are competing: “If they don’t talk and they don’t connect, then you’re going to use it as a gimmick through construction, but I can’t use it for ongoing operation. And it’s a real problem with the industry, ‘THE’ big problem” (P3). This also reflects the diversity of industries involved in any AEC implementation: “the problem is that you’ve got a design and construction industry, which uses all these technologies, and then it’s disconnected from the operational and maintenance phase of technology usage...” (P3). This issue of interoperability is a barrier that affects uptake, as the indecision that surrounds knowing which platform to embrace leads to stalling.

The lifecycle of the XR technology is attributable to the hesitation to invest in XR - where the technology and platforms can be quickly outdated by newer versions or bought out by competing ‘tech’ companies. Only two participants described how their company found solutions to this by diversifying their skills to include programming in XR development. These participants were from more digital and technology-oriented industries, and their solution to these technology problems could be related to their ancillary roles to AEC. That is, in one case the design and fabrication studio (which creates facades, etc.) has undertaken a ‘turnkey’ approach, reflecting a diverse range of skills: “We’ve always had quite a broad diversity of skill within the business because we kind of have this turnkey service approach and so we have everything from curators through to engineers and manufacturers” (P7). Another studio developed new tools in-house to automate the production of aspects for virtual reality. “So, we’ve set up this thing, Site Lab, which is kind of just Unity, but there’s a skin that’s sitting on top, but we’ve built all these tools behind that, that automate the production, so that it’s easier for people to produce models” (P12).

5. Discussion and Conclusion

By revealing the opportunities and the barriers of XR adoption in the AEC industry, analysis of interview data raises important questions on how XR technologies can be better directed to service the AEC industry in the future, and how the themes found in this study can inform opportunities and priorities for XR technology developments specific to the users‘ needs of the AEC industry. Whilst there are still ongoing issues (e.g., field of view and interoperability) that require technical improvements, challenges were present in the research participant’s attitudes and perceptions to embrace XR technology. Participants often referred to XR technologies as a ’gimmick‘ rather than as a needed innovation in AEC practices. There were also concerns of the technology being quickly outdated because of new development turnarounds, which affected companies’ confidence to invest beyond piloting their utility - even though participants saw many promises in XR’s potential to phase out outdated practices. Some participants have recognised that these barriers can be overcome by training practitioners to be adaptable to the technology and its changes, to support future readiness or acquire subsidiary companies to expand adoption with specialist support.

The results also highlight XR’s potential to train the next generation of practitioners to design complex building information quickly and intuitively. This outcome was apparent when participants described the increasing pressure to improve visualisation methods and the user experience to remain competitive (in terms of innovation) and to mitigate fragmented practices in collaboration. Further, participants have reported the need for more user-centred approaches to better understand user interaction and behaviour, whether that be for clients or practitioners. However, the ability to do more user-centred approaches is severely limited by the AEC service model to make room for beta testing - reminiscent to the issues of BIM. This factor underlines a need for research to support ongoing development, especially with the limited affordances to extend XR's maturity in practice. Yet, the responses also show the willingness of the AEC industry to navigate these challenges and to find those small opportunities even if it is through brute force testing.

Based on these reflections, we advocate for a user-centred focus to support future XR developments that considers human factors and not just XR's technical utility. Using Benyon (2010)'s People-Activity-Context-Technology (PACT) analysis, we extend Delgado et al. (2010)'s research agenda to consider user experiences for using XR technologies to sustain its maturity in AEC practices. PACT analysis relates to activity and context being intertwined and sharing a bidirectional relationship to technology. Within this relationship activity and context sets requirements for technology, and technology creates opportunity to activity and context. In the findings of interviews, we are seeing both these directions - people having the technology and figuring out how to use it (activity and context) and in other cases activity and context setting what requirements the technology needs to have and new ways of using it.

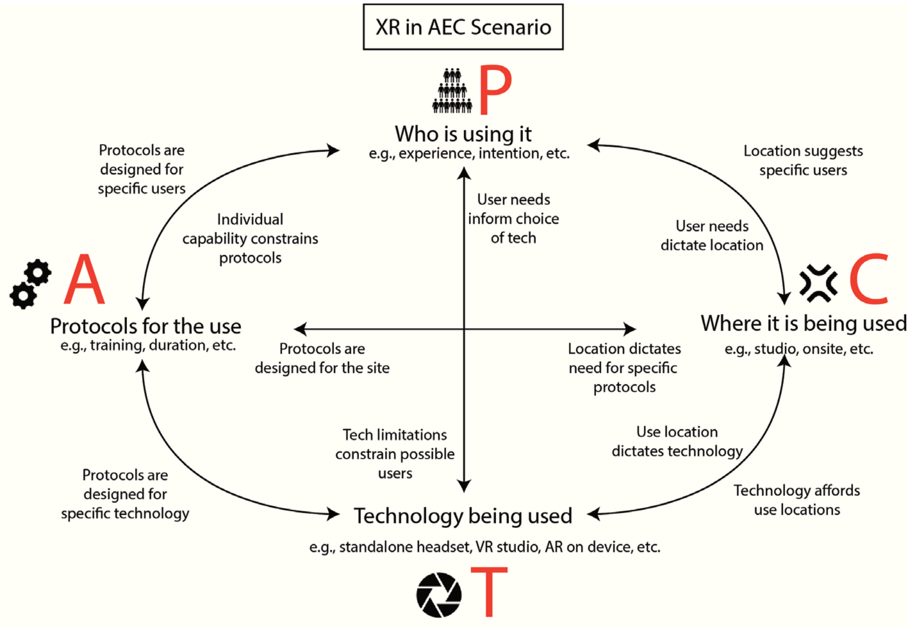


Figure 2. Our proposed user-centred framework to consider the user-experience. This diagram draws upon Benyon (2010)'s PACT approach. .

Looking at Delgado et al (2020)'s suggested research agendas with the perspective of the PACT analysis, we see a clear gap in the People category. Figure 2 is a preliminary XR-PACT framework, to address this gap; showing how dimensions of people, activity, context, and technology can converge to develop XR technology that is reflective of the needs, contexts, and requirements of users in the AEC industry. The interview findings support this XR-PACT framework by highlighting user experiences, expectations and intentions on the use of XR technologies in various contexts and durations, as participants reflect on their use of XR technologies based on their lived experiences.

Our future work will focus on creating user case scenarios that further explore the proposed XR-PACT framework to improve ongoing developments that are reflective of the practical needs and expectations of the AEC industry.

Acknowledgements

We would like to thank our participants from across the ACE industry for their contribution. This study was conducted in accordance with Queensland University of Technology Ethics Approval 1900001016. We acknowledge support from QUT's Creative Industries Faculty and the QUT Design Lab.

References

Alizadehsalehi, S., Hadavi, A. and Huang, J.C.: 2020, From BIM to extended reality in AEC industry, *Automation in Construction*, **116**, 103254.

Bassanino, M., Wu, K.C., Yao, J., Khosrowshahi, F., Fernando, T. and Skjaerbaek, J.: 2010, *The Impact of Immersive Virtual Reality on Visualisation for a Design Review in Construction*, IEEE Computer Society.

Benyon, D.: 2014, *Designing interactive systems: a comprehensive guide to HCI, UX and interaction design*, Pearson, Boston.

Calixte, X. and Leclercq, P.: 2017, The Interactive Projection Mapping as a Spatial Augmented Reality to Help Collaborative Design: Case Study in Architectural Design, *Cooperative Design, Visualization, and Engineering*, 143-152.

Castronovo, F., Nikolic, D., Liu, Y. and Messner, J.: 2013, An evaluation of immersive virtual reality systems for design reviews, *Proceedings of the 13th international conference on construction applications of virtual reality*, **London**, 8.

Davila Delgado, J.M., Oyedele, L., Demian, P. and Beach, T.: 2020, A research agenda for augmented and virtual reality in architecture, engineering and construction, *Advanced Engineering Informatics*, **45**, 101122.

Du, J., Zou, Z., Shi, Y. and Zhao, D.: 2018, Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making, *Automation in Construction*, **85**, 51-64.

Fukuda, T., Zhu, Y. and Yabuki, N.: 2018, Point Cloud Stream on Spatial Mixed Reality, *Proceedings of eCAADe 2018*, Poland, 727-734.

Gül, L.F.: 2014, The impact of digital design representations on synchronous collaborative behaviour, *Journal of Information Technology in Construction*, **19**, 47-71.

Hensel, M.: 2015, Auxiliary Architectures: Augmenting Existing Architectures with Performative Capacities, *Architectural Design*, **85**(2), 116-119.

Holtzblatt, K., Wendell, J.B. and Wood, S.: 2004, *Rapid Contextual Design: A How-To Guide to Key Techniques for User-Centered Design*, Elsevier Science \& Technology, San Francisco, UNITED STATES.

Lavrakas, P.J.: 2008, *Encyclopedia of Survey Research Methods*, SAGE Publications, Thousand Oaks, UNITED STATES.

Li, X., Yi, W., Chi, H.L., Wang, X. and Chan, A.P.C.: 2018, A critical review of virtual and augmented reality (VR/AR) applications in construction safety, *Automation in Construction*, **86**, 150-162.

Pratama, L.A. and Dossick, C.S.: 2019, Workflow in Virtual Reality Tool Development for AEC Industry, *Advances in Informatics and Computing in Civil and Construction Engineering*, Cham, 297-306.

Rankohi, S. and Waugh, L.: 2013, Review and analysis of augmented reality literature for construction industry, *Vis. in Eng.*, **1**(1), 9.

VALIDATING GAME ENGINES AS A QUANTITATIVE DAYLIGHTING SIMULATION TOOL

MUHAMMAD HEGAZY[1], KENSUKE YASUFUKU[2] and HIROKAZU ABE[3]
[1]*Graduate School of Engineering, Osaka University*
[1]*hegazy_muhammad@arch.eng.osaka-u.ac.jp*
[2,3]*Cybermedia Center, Osaka University*
[2,3]*{yasufuku|abe}@cmc.osaka-u.ac.jp*

Abstract. This study aims to investigate the accuracy of representing daylit spaces using game engine-based rendering techniques, compared to validated benchmark renderers and real-life measurements. Two daylit case studies- reflecting different complexity levels and spatiotemporal settings- were rendered in a game engine using a traditional rendering technique and real-time raytracing. Illuminance levels at selected points were measured in Unreal Engine and were compared to those calculated in a validated light simulation tool and an illuminance meter for the simplified and complicated case studies, respectively. In both cases, traditional technique cited a high variance in illuminance levels compared to the references. In the simplified model, real-time ray tracing showed the lowest average error compared to the validated simulation results. In the complicated model, the average error of such technique was close to that of the validated simulation, compared to the actual illuminance measurements. This study illustrates the added benefits of using real-time ray tracing in game engines over traditional ray tracers to offer an immersive and interactive experience of virtual daylit spaces, without sacrificing the quantitative accuracy of the simulated luminous environments.

Keywords. Daylight simulation; game engine; ray tracing; immersive virtual environments.

1. Introduction

As the post-pandemic reality has substantially boosted the fact that people spent around 90% of their time indoors (Schweizer et al. 2007), it became a necessity to revisit the suitability of indoor environments to occupants' satisfaction. Daylighting design can play an immense role in defining a wide variety of buildings' performance qualities. On one hand, reliable daylighting strategies can partially mitigate the need for artificial lighting, and thus can considerably decrease building's annual energy consumption (Chi, Moreno, and Navarro 2018). On the other hand, daylighting availability has shown definitive positive effects on building occupants' wellbeing (Boubekri et al. 2014). However, excessive

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 285-294.

daylighting can cause visual and thermal discomfort (Nabil and Mardaljevic 2006), which may motivate occupants to rely on artificial lighting systems instead. Therefore, achieving a daylight strategy that considers quantitative and subjective preferences requires utilizing simulation tools at an early stage of design.

Due to its dynamic nature, the evaluation of daylighting in virtual settings requires high levels of accuracy in calculating the luminous environment. Physically-based light simulation tools, namely Radiance (Ward 1994), have been widely used as a benchmark in daylighting research, as they generate validated results against real-life scenarios and integrate spatiotemporal sky data. However, those tools require a time-consuming process to render a single lighting scenario, and often lack a user-friendly interface to interactively explore the simulated environment (Jones and Reinhart 2019). On the other hand, game engines can render highly realistic daylit environments in real-time where users can freely explore, evaluate, and customize different daylighting scenarios. However, the lack of validation studies on the luminous accuracy of game engine renderings can act as a barrier against a wider adoption of their advantages in daylight simulation studies.

This paper aims to investigate the luminous accuracy of game engine renderings against validated renderers as well as actual sensor measurements. Illuminance values of two case studies with different spatiotemporal and sky settings were compared across Radiance and Unreal Engine 4 with different render settings. The findings of this study push towards a wider validation of game engines as a simulation tool to represent accurate luminous qualities of daylit environments in a more immersive and interactive virtual setting.

2. Literature Review

Game engines can be defined as a set of tools for rendering, scripting, simulating Physics, and embedding artificial intelligence systems intended to create video games (Anderson et al. 2008). Game engines are based on real-time rendering to allow seamless communication between players and the game environment. Therefore, game engines use several techniques to optimize an adequate representation of lighting environments without sacrificing performance. One of those techniques is "baking" light maps, where light rays are traced, and the resultant effects of light and shade are projected over surfaces as textures (Geig 2013). While this technique can generate visually appealing results, it is limited when the light source is movable in real-time. In recent years, advancements in graphics hardware have enabled more accurate techniques to simulate lighting in game engines, mainly Real-Time Ray Tracing (RT), where physically correct renderings can be computed dynamically for a variety of global lighting effects, including reflections, refractions, and shadows (Gersthofer 2020). As RT basically simulates the behavior of light rays bouncing from the light source to different surfaces, a higher number of calculated bounces can improve the quality of the final output but can heavily affect system performance.

In daylight perception, game engines are often coupled with Virtual Reality (VR) hardware to offer an enhanced feeling of immersion and interactivity, which are two essential principles needed for a convincing virtual experience (Alshaer, Regenbrecht, and O'Hare 2017). In one study to measure perceptual impressions of daylit spaces in VR (Chamilothori et al. 2019), physically-based renders of an office space were projected in Unity 3D Game Engine as a textured cube map. In another study, a hybrid system that synergizes features of game engines with a validated raytracer was developed (Subramaniam et al. 2020). The developed tool offered an immersive virtual medium to assess visual comfort of indoor spaces. In a third study, an immersive light visualization tool was developed by integrating light simulation data from DIALux software with the Unity Engine (Wong et al. 2019).

In the discussed studies, game engines were only used as a supplementary tool to the physically-based images produced in validated renderers. While this shows the importance of accurate luminous effects daylighting in VR, it also highlights the limitations this approach brings to user experience. For example, using static images rather than walkable 3D meshes, limiting locomotion to head movement or teleport, and predefining the evaluated lighting scenarios. In this context, the limitations of Radiance software have been addressed by Jones and Reinhart (Jones and Reinhart 2019). Similarly, a few studies have employed game engines to improve the interactivity and immersiveness of user experience. Recently, Hegazy et al. (Hegazy, Yasufuku, and Abe 2020) employed Unreal Engine 4 (UE4) to develop an interactive system to visualize and assess daylit environments, where users can freely explore the environment in VR, change temporal settings, and report their perception of brightness using snapshotting tools. In a further application to a large-scale environment, daylight perceptions in the developed system were compared to those in the real environment, where consistency could be found between perceived brightness across reality and VR (Hegazy, Ichiriyama, et al. 2020). However, as daylighting performance metrics are often based on accurate calculation of illuminance levels, it is essential to conduct further validation to the accuracy of different game engine simulation techniques to adopt them in daylighting research and make use of their advantages.

3. Methodology

A wide variety of game engines have been used to simulate architectural and urban environments. However, the investigated game engine in this study was UE4 version 25.3, which was selected due to two reasons: 1) being the most widely used engine in architectural visualization (Jeff Mottle 2020) 2) possessing an advanced integration to real-time RT in terms of global illumination. Three rendering techniques in UE4 were examined for two case studies. The first technique is the traditional baked light map, in which the engine calculates lighting in non-real-time and projects the effects of light and shade on static surfaces. The second and third techniques were represented in real-time ray tracing with the number of bounces calculated varied between 3 and 7, to reflect different scenarios of balancing accuracy against performance.

3.1. SIMPLIFIED SHOEBOX MODEL

In daylight simulation, numerous parameters can affect the accuracy of the final results. This includes the surface properties, model complexity, and daylight portals. A simplified shoebox model was selected as an initial case study to eliminate the interference of these parameters and to focus on the accuracy of game engine rendering in a basic scenario. The simplified model is a 6x7x4 meters box with one rectangular opening (3x2 meters) oriented towards the South, with no glass window or furniture. As the selected model was generic, illuminance measurements in Radiance were adopted as the reference values compared to the outputs in UE4.

The model was created in Rhino 3D, lighting analysis was conducted on the model using DIVA for Rhino tool, which includes a fully-featured version of Radiance for physically accurate renderings. The spatial settings of the model were set based on the weather file for Osaka (JPN_OS_Osaka.Intl.AP) with a CIE clear sky. Temporal settings were set to September 21st at 9:00 am. One generic material (GenericInteriorWall_50) was applied on all surfaces of the model. As measurements were based on horizontal illuminance, an analysis grid of 0.6 meter spacing and 0.8-meter height above the floor was created using DIVA, generating 110 analysis nodes. However, to avoid redundant measurements, data included in the comparison was limited to 24 distinctive, uniformly distributed nodes (Figure 1 left). In UE4, the model was imported in FBX format. A spatiotemporal scenario for daylighting was realized using the SunSky system equipped with the Engine, which can be considered the equivalent of weather files in Radiance. This system can automatically adjust sun brightness and position, and sky conditions based on real spatiotemporal settings. In that aspect, geographical coordinates were set to 135 and 34 (Osaka, Japan), with identical temporal settings as in Radiance. Furthermore, a physically-based material matching diffuse color and reflectivity of Radiance material was created in UE4 and applied to the model. In UE4, materials are defined based on the physical properties of Base color, Specularity, Roughness, and Refraction. In this context, the generic Radiance material was translated to UE4 as (Base color=R 0.93 G 0.92 B 0.86, Specularity=0, Roughness=0.53). Illuminance levels at selected nodes were measured in UE4 using the HDR Histogram tool, which is integrated to the engine and can show absolute illuminance and luminance levels at any given point on the viewport, in a similar manner to the "Falsecolor viewer" tool in Radiance (Figure 1 middle and right).

In UE4, the output illuminance at selected nodes was measured under three rendering scenarios. In the case of the traditional baked lightmap technique, indirect lighting multiplier was set to 2, the reflection type was "screen space", and the simulation quality was set to "Highest". In the second and third scenarios, real-time ray tracing (RT) was used to calculate Global Illumination (GI), ambient lighting, reflections, and refractions. For GI, RT was set to "Brute Force", which is more GPU intensive but generates more accurate results. In RT, the number of bounces calculated can lead to a more realistic rendering while sacrificing performance. However, it can also affect illuminance levels measured due to more lighting being reflected to different surfaces. Therefore, a variation of 3 and 7 bounces was investigated as separate scenarios. (Figure 2) shows a rendering of the simplified model at the selected spatiotemporal settings, in Radiance and the three UE4 scenarios.

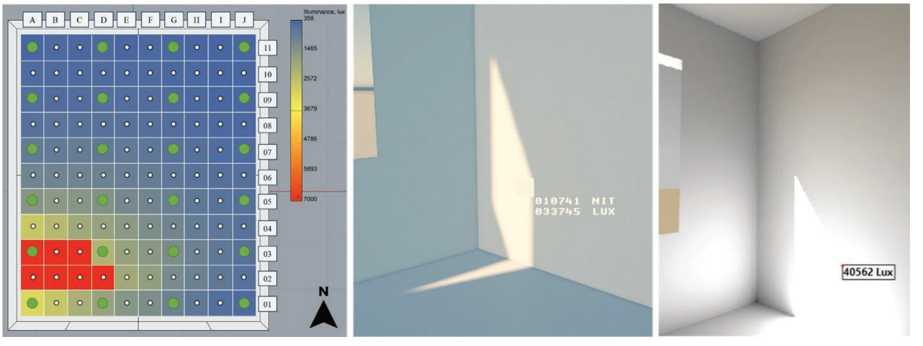


Figure 1. (Left) Measurement grid for horizontal illuminance generated in DIVA, nodes in green are included in the comparison. (Middle) measuring illuminance levels in UE4 using the integrated lighting analysis tool (HDR Histogram). (Right) Measuring illuminance at a given point for a Radiance output HDR image.

Figure 2. A point-in-time rendering for the simplified model; (a) Radiance, (b) UE4 with no RT, (c) UE4 RT 3 bounces, (d) UE4 RT 7 bounces.

3.2. COMPLICATED OFFICE MODEL

When it comes to daylighting simulation, one of the major advancements of game engines over traditional ray tracers is their ability to offer rich interactivity and immersion capabilities to the virtual environments explored. This can be represented in first person walkthroughs in real-time, collision physics, and dynamic sky system (full day cycle). However, these potentials cannot be highly illustrated in simplified models like the previously discussed case study, because they are too small to explore and have no objects to interact with. Therefore, game engines can show more potential for simulating daylighting in large, explorable spaces. Hence, the selection of the second case study was prone to the following criteria: first, to include a large-scale space. Second, both direct and indirect daylight effects should be available throughout the day. Third, to host a variety of related functions (i.e. meeting, studying, dining, computer-based work). Fourth, to be accessible by the authors for a prolonged period with the ability to control lighting conditions. An office building within a university campus was selected as it fulfilled the stated criteria (Figure 3 left). The test environment was limited to a common hall area on the 1st floor, which is daylit by a courtyard of 7.0m x7.0m dimensions. The investigated space hosts various study areas, meeting rooms with glass walls, a kitchenette corner, and an open conference hall (Figure 3 middle).

In this case study, illuminance levels measured in the real environment were taken as a reference to compare to Radiance and UE4. A set of 11 analysis points were selected within the central area of the space, reflecting a variety of directly and indirectly daylit, horizontal and vertical surfaces (Figure 3 right). Illuminance levels at these points were collected on March 18th, using a Konica Minolta T-10A luxmeter at 11:00 am (clear sky) and 2:00 pm (overcast sky), where all artificial lights were switched off and blinds were fully opened to ensure the space is only daylit. A digital twin of the test environment was modelled in 3DS Max software using the original floor plan drawings of the building as well as reference images of the current situation. Furthermore, surface textures (e.g. carpets, furniture) in reality were scanned and overlaid over respective surfaces in the 3D model. For lighting analysis in Radiance, the model was imported to Rhino 3D in FBX format. Due to the limitations of Radiance with complex scenes, polygon count of furniture was optimized, and surface textures were abstracted to average diffuse colors and applied as Radiance materials, with the consideration of the physical properties of different materials. In DIVA, the same weather file was used for the simplified model, and the 11 measurement points were created as analysis nodes in the same locations as reality. Simulations were run twice to reflect the two temporal and sky condition settings. On the other hand, the model was imported from 3DS Max to UE4 using Datasmith plugin, which ensures seamless conversion of meshes and textures between the two tools. In UE4, Base color was replaced by the scanned texture map of each surface, with accurate scaling. Other properties, such as specularity and glass transmittance were provided by the building's architect. As UE4 can handle large polygon counts, the original fully detailed objects were maintained without optimization. Lighting analysis and illuminance measurements in UE4 followed the same methodology and render settings discussed in (Section 3.1), generating three sets of scenarios reflecting different rendering techniques in UE4 (Figure 4).

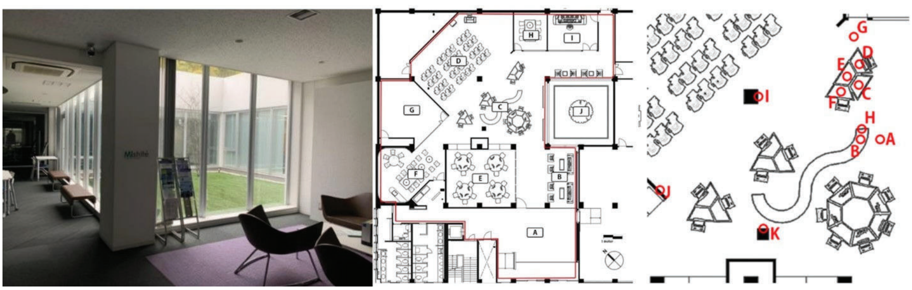


Figure 3. (left) the lounge area in the selected case study. (middle) different functional areas within the selected case study, the measurement points included in the study are in areas C and D, J represents the courtyard. (Right) Sensor points selected for comparison, points H, I, J, and K are on vertical surfaces.

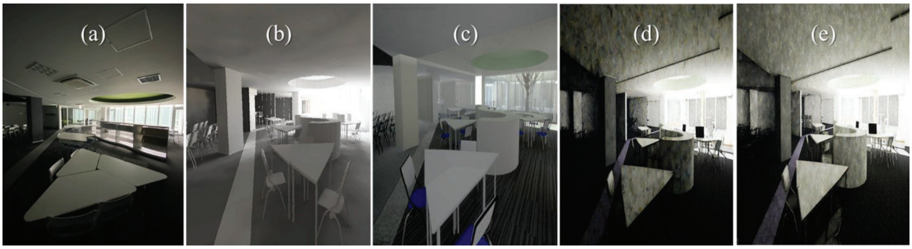


Figure 4. A point-in-time view at 11:00 am for the test environment, and its corresponding simulation outputs in different techniques. (a) real space, (b) Radiance, (c) UE4 with no RT, (d) UE4 RT 3 bounces, (e) UE4 RT 7 bounces.

4. Results and Discussion

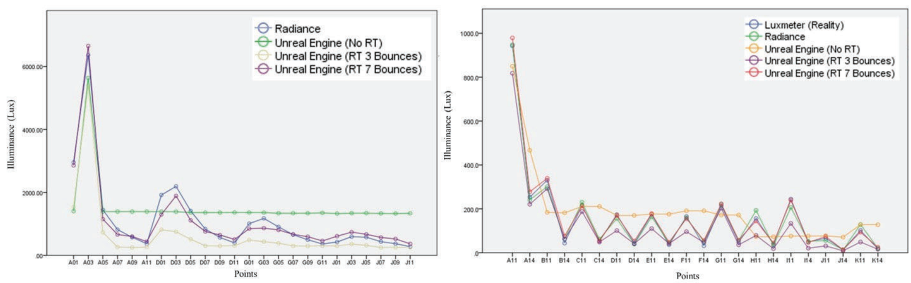


Figure 5. (left) illuminance measurements in the simplified model using different rendering tools. (Right) luxmeter measurements for the real office space, and respective illuminance measurements of its virtual replica in different rendering tools, point number reflect the time during which was measured (e.g., A14 is Point A at 2:00 pm).

In both case studies, the rendered images in UE4 showed its ability to generate results that are visually close to those produced in Radiance. Unlike Radiance, which needed about 2 minutes on a high-end workstation to produce one image, UE4 could generate the images in real-time allowing more freedom to explore virtually infinite views and lighting scenarios. However, this freedom imposes challenges in UE4 to balance between quality and performance. In other words, using RT with 3 bounce count led to highly noticeable artifacts (noise) within the produced scene, but it could be navigated smoothly at 60 frames per second (FPS). While rising bounces to 7 partially eliminated noise and increased the overall quality of the scene, it noticeably decreased the performance down to 24 FPS. This finding was more obvious in the complicated model, specifically in areas far from direct sunlight.

For the simplified model, illuminance levels at the selected points were compared between Radiance as a reference, and the three UE4 rendering scenarios (Figure 5 left). In all the four scenarios, illuminance values ranged between 200 and 7000 lux, with most measurements below the 2000 lux threshold. Through observational analysis, it was found that outputs of UE4 with baked lightmap technique (no RT) were the most varied from those in Radiance. Moreover, it was shown that this technique failed to distinguish between illuminance levels below 2000 lux, where redundant measurements of (1200-1300 lux) were found for most points with indirect daylighting. In contrast, outputs of RT renderings followed a similar pattern of values to that of Radiance. In the case of RT with 3 bounces, measurements were found to be consistently underestimated across all points, compared to Radiance. Increasing the bounces to 7 noticeably improved the results, specifically for points close to direct sunlight, while slightly overestimating the illuminance of the farther points (e.g., points J01-J11). In the complicated model, all illuminance levels were found to be below 1000 lux. Thanks to the availability of real-life measurements in this case, it was possible to compare the accuracy of UE4 renderings compared to a validated simulation tool like Radiance, taking luxmeter data as reference for both (Figure 5 right). As expected, Radiance results were very close to those of reality. As for the simplified model, renderings in UE4 no RT obviously varied from reality, with redundant values across points B-H in the two-day times tested. In the case of RT with 3 bounces, measurements showed a fewer variation from reality and followed the same pattern of high and low values. Moreover, RT with 7 bounces performed noticeably better, with a few values closer to reality than Radiance (points I11 and K11). Furthermore, the discrepancies between illuminance outputs of reference benchmarks and UE4 were quantified by calculating the relative error of each measurement compared to the reference, as well as the average error for all points (Table 1) using the following formula:

$$\frac{|InvestigatedValue - ReferenceValue|}{ReferenceValue} \times 100 \tag{1}$$

In the simplified model, the lowest and the highest errors in UE4 baked lightmap calculations were 3.7 and 381%, thus a very high average error of 126% was found for all points measured. This illustrated that on average, this rendering technique estimated illuminance levels as low as half or as high as double of the reference values. notably lower error ranges were found in the case of RT with 3 bounces, ranging between 8 and 67% and an average error of 44% for all points. In line with the observations, RT with 7 bounces showed the lowest average error (19.8%), with the lowest error of 1.5 and the highest of 40%. It is worth noticing that the deduced errors were referenced to Radiance and thus they reflect how close the measurements are to Radiance calculations rather than absolute values in real life. In the complicated model, error percentages were referenced to the luxmeter data. As expected, Radiance showed the lowest average error (15%) across all points, with the lowest and the highest errors as 0.5 and 60% respectively. UE4 baked light map showed an average error even higher than that in the simplified model (162%), illustrating a high discrepancy in estimating illuminance levels in the complicated, textured environment. However, RT with 3 bounces showed better results, with an average error of 30%, 5%, and 56% as the lowest and the highest errors respectively. Furthermore, results of RT with 7 bounces showed almost similar average error (15.8%) as that in Radiance. Following the recommendations by Fisher (Fisher 1992), an acceptable error range between measurements and simulation should be 10% for average illuminance calculations and 20% for each measurement point. While the average error for UE4 RT renderings slightly exceeded this threshold, it is also worth noticing that it was the case for Radiance, meaning that in this specific study, UE4 RT could quantitatively output results that match the accuracy of a validated ray tracer. Moreover, as discussed by Reinhart and Anderson (Reinhart and Andersen 2006), it is worth noticing that the ultimate sensor that perceive and assess the appearance and brightness of daylit spaces is the human eye, and thus the difference between 400 lux and 500 lux (20% error) might not be humanly noticeable in the first place. As shown in Figure 3 and Figure 5, UE4 could generate images that are more visually similar to Radiance in the case of the simplified model. On the contrary, the quantitative accuracy of the measured points was higher in the case of the complicated model. The reasons for this drop in accuracy for the simplified model renderings despite the lack of interfering parameters are not clear, thus it is important to investigate such aspects on a wider range of cases and spatiotemporal settings.

Table 1. Average relative errors for all the measured points compared to references.

Case	Reference	Number of points	Average error of all points (%)			
			Radiance	UE4 No RT	UE4 RT3	UE4 RT7
Shoebox	Radiance	24	-	126.1	44.2	19.8
Office	Reality	22	15.0	162.7	30.6	15.8

5. Conclusions

This study investigated the luminous accuracy of Unreal Engine based on point-in-time illuminance values. Two daylit case studies were selected to reflect different spatial complexity levels, and three rendering techniques were used to generate the scenes. For the simplified case study, ray tracing with 7 bounces showed the least varied results from Radiance, while renders from baked lightmap performed the worst. In the complicated case studies, results from Radiance and Unreal Engine were compared to luxmeter data in reality. Likewise, raytracing with 7 bounces showed an average error that is very close to that in Radiance. To the authors' knowledge, this study is one of the very first to address the adequacy of game engine-based renderings in daylighting research, specifically in application to real-time ray tracing techniques. While the findings of this study are not conclusive, they clearly illustrate the potential of the newly introduced techniques in calculating illuminance levels with an accuracy that is comparable to benchmark tools, with the added benefits of instant feedback and interaction. With the advancement of hardware, real-time ray tracing is witnessing rapid development, and more game engines are implementing their own ray tracing techniques (e.g., CryEngine and Unity). A future direction of this study is to compare the accuracy of other game engines against Unreal. As the interactivity and immersion offered by game engines pose a useful application in human perception studies of daylit spaces, the authors would conduct a further study to investigate the accuracy of game engines in luminance measurements, as they closely relate to what the human eye perceives. Also, more complicated daylighting scenarios (e.g. reflectors, Venetian blinds) and climate regions would be included in future case studies.

References

Alshaer, A., Regenbrecht, H. and O'Hare, D.: 2017, Immersion factors affecting perception and behaviour in a virtual reality power wheelchair simulator, *Applied ergonomics*, **58**, 1-12.

Anderson, E.F., Engel, S., McLoughlin, L. and Comninos, P.: 2008, The case for research in game engine architecture., *Proceedings of the 2008 Conference on Future Play*, **1**, 228–231.

Boubekri, M., Cheung, I.N., Reid, K.J., Wang, C.H. and Zee, P.C.: 2014, Impact of Windows and Daylight Exposure on Overall Health and Sleep Quality of Office Workers: A Case-Control Pilot Study, *J. of Clinical Sleep Medicine*, **10(6)**, 603–611.

Chamilothori, K., Wienold, J. and Andersen, M.: 2016, Adequacy of Immersive Virtual Reality for the Perception of Daylit Spaces: Comparison of Real and Virtual Environments, *J. of the Illuminating Engineering Society*, **15**(203-226), 15:2-3.

Chi, D.A., Moreno, D. and Navarro, J.: 2018, Correlating daylight availability metric with lighting, heating and cooling energy consumptions, *Building and Environment*, **132**, 170-180.

Fisher, A.: 1992, Tolerances in lighting design, *Proceedings of the CIE Seminar on Computer Programs for light and lighting*, Vienna, Austria.

Hegazy, M., Ichiriyama, K., Yasufuku, K. and Abe, H.: 2020, Visualizing user perception of daylighting: a comparison between VR and reality, *Proceedings of BuildSIM-Nordic 2020.*, Oslo, Norway.

Hegazy, M., Yasufuku, K. and Abe, H.: 2020, Evaluating and visualizing perceptual impressions of daylighting in immersive virtual environments, *J. of Asian Architecture and Building Engineering*, **0**(0), 1-17.

Jones, N.L. and Reinhart, C.F.: 2019, Effects of real-time simulation feedback on design for visual comfort, *J.of Building Performance Simulation*, **12**(3), 343-361.

Nabil, A. and Mardaljevic, J.: 2006, Useful Daylight Illuminances: A Replacement for Daylight Factors, *Energy and Buildings*, **38(7)**, 905-913.

Reinhart, C.F. and Andersen, M.: 2006, Development and validation of a Radiance model for a translucent panel, *Energy and Buildings*, **38**(7), 890-904.

Schweizer, C., Edwards, R.D., Bayer-Oglesby, L., Gauderman, W.J., Ilacqua, V., Jantunen, M.J., Lai, H.K., Nieuwenhuijsen, M. and Künzli, N.: 2007, Indoor time–microenvironment–activity patterns in seven regions of Europe, *J. of exposure science & environmental epidemiology*, **17**(2), 170-181.

Subramaniam, S., Reis, G. and Hoffmann, S.: 2020, A Tool for Assessing Visual Comfort Through an Immersive Environment, *Proceedings of PLEA 2020*, A Coruña, Spain, 7.

Ward, G.J.: 1994, The RADIANCE lighting simulation and rendering system, *Proceedings of SIGGRAPH '94*, Orlando, FL, USA, 459-472.

Wong, M.O., Du, J., Zhang, Z.Q., Liu, Y.Q., Chen, S.M. and Lee, S.H.: 2019, An experience-based interactive lighting design approach using BIM and VR: a case study, *IOP Conference Series: Earth and Environmental Science*, **238**(1), 012006.

PARTICIPATORY AR

A Parametric Design Instrument

DAVID SILCOCK[1], MARC AUREL SCHNABEL[2],
TANE MOLETA[3] and ANDRE BROWN[4]
[1,2,3,4]*Victoria University of Wellington*
[1]*david.t.silcock@gmail.com* [2,3,4]*{MarcAurel.Schnabel|Tane.Moleta|Andre.Brown}@vuw.ac.nz*

Abstract. CAAD research has frequently investigated the realm of public participation in large scale urban design re-development. Yet, the recurring problem lies with the lay-person often not being able to read 2d and 3d graphic information effectively, and hence be able to participate in the process of design development proactively. To date, much-existing research focuses on developing designs for urban settings using contemporary interaction devices such as the /Hololens/; such devices, with custom interfaces, require a significant level of expertise, or an experienced 'guide', to help navigate or create within these environments. Our paper presents a novel alternative based on real-time-virtual-engines, XR, and a parametric back-end system. The paper discusses the advantages that the resulting tangible user interface (TUI) can play in the lay-person's engagement in the design process. In the paper, we describe how the integration of interaction design (IxD) and augmented reality (AR) offer new opportunities due to the increasing availability of barrier-free technologies that can better include lay-persons as active participants in the design development process.

Keywords. Augmented Reality (AR / XR); Participatory Design; Urban Design; Tangible User Interface (TUI); Parametric.

1. Introduction

Within the realm of urban design, and design and architecture in general, both client and architect should strive to strengthen their shared relationship, and develop a common core language. With a strong foundation such as this, communication between the layperson and the expert becomes less confusing and ambiguous and is therefore holistic, and common ground is found (Brown and Berridge, 2001). It has been reported for many years that there exists an apparent disconnect between the public/client (layperson), and the designer/architect (expert) (Healey, 1997). Urban design poses many of these disconnects, emphasising and focusing on clearly communicating design options while understanding that the layperson has not undergone the same

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 295-304.

rigorous training a designer who has developed strong spatial organisation and relationships skills. Some of these disconnects within urban design include the sun's effect on the orientation of buildings; appropriate positioning of a building on a section ("Location and orientation for passive heating and cooling" 2019); understanding of spatial arrangements (Seichter and Schnabel 2005) and understanding the translation from 2D to 3D representation (Hornyanszky-Dalholm and Rydberg-Mitchel, 1992). These issues have typically led to the designer taking control of these issues whilst failing to effectively interpret the layperson's intentions (Norouzi et al., 2015). The disconnect lies here.

There are some exceptions, such as 'Benchworks' by Seichter (2004), Schnabel and Chen's 'Multi-touch Table' (2011), and 'Laypeople's Collaborative Immersive Virtual Reality Design Discourse in Neighborhood Design' by Chowdhury and Schnabel (2019). Their research reports how design interaction instruments need to be increasingly accessible and have to be explicitly designed for the lay-person to provide a fair and equitable opportunity for participation and communication.

To address the defined problems above, this research's scope focuses on the preliminary design stage of the architectural design process. However, this focus is not on the design itself, but on the participatory methods developed to reach a design outcome.

1.1. FOUR FIELDS

We have found the project to sit at the intersection of four primary areas of design. These four fields are augmented reality (AR), urban design, serious games and interaction design (IxD). The first two fields that will be discussed being AR and serious games have modern connotations seen as a result of their gained traction over recent years. We believe that the advancement of technology in these fields offer insight into the direction they will lead in the future. Thus, the solutions being developed in modern-day AR and serious games, whether it be ARToolKit or similar products, show great potential when addressing the problems outlined at the beginning of the project (Kato et al., 2000, Seichter, 2004). Within the context of the project, the degree of availability and social applicability of AR allows for effective communication of the solutions with the layperson, and, consequently, provide an opportunity for them to be key stakeholders in the design process. Serious games, being games created for a primary purpose other than entertainment, provide a method of engaging laypeople in the design process. Researchers like Ben Sawyer pathing the way for better education through serious gaming (Sawyer, 2003). Through this method, new and more user-friendly systems have emerged to facilitate engagement in areas that may otherwise not interest the general user. It encourages youth engagement in these systems, promoting early education in ways that aim to entertain and educate the user simultaneously.

Although having its roots deep within all cultures of the world, the field of urban design is still not seen as an individual profession. Instead, it is seen as an activity involving the disciplines of architecture, landscape architecture, and planning (Schurch, 1999). Its disjointed history and adoption as a field give insight into its ever-developing and shifting nature. With the simultaneous advancement of modern technology, a natural progression forward in urban design is to adopt these technologies and begin developing novel methods of practising urban design.

Interaction design, one of the project's fundamental drivers, is described by Preece et al. (2003) as developing interactive products that are easy, effective, and pleasurable to use - from the user' perspective. With this in mind, a designer must pay very close attention to the user's needs, limitations and context, and allow for a customisable output to suit precise demands in that specific context. Interaction design is one aspect that makes up the realm of UX design (Cooper et al., 2007). Ben Schneiderman's eight golden rules of interface design (1987) provide a potentially crucial set of criteria for assessing and critiquing an interactive, participatory tool. With the adoption of these into the design process, the development of the necessary interface will have a robust backing in the literature that has been adopted by many of the world's leading interface designers.

2. System of Analysis

The analysis system looks to establish a set of criteria against which a participatory, low-tech AR environment can be evaluated (Figure 1). It divides the tool into two critical phases which focus is individually placed. First, we have the interaction design (IxD) phase, where Ben Schneiderman's (1987) and Jakob Nielson's (2012) established criteria provide a robust base for evaluating the effectiveness of a user interface. Secondly, a set of criteria for assessing the participatory function of the tool is established. The complete set of criteria emphasises communication, co-design, intuitive use and facilitation of design. After each design phase, these criteria are used to assess the interactive AR environment's effectiveness. Through the assessment method, an outcome can be found as to whether the tool is effective as a user interface and a participatory design environment.

With the adoption of a low-tech tangible user interfaces (TUI) AR method, particular criteria relevant in high-tech AR, become irrelevant. The culling resulted from personal analysis of criteria that either would not function in a TUI user interface or would have such minimal input that it would become impractical to place focus on it. Seen in the table above, relevant criteria have been marked with the letter Y, while irrelevant criteria have been marked with the letter N.

	Phase	Criteria found	Relevance in TUI
1	IxD	Strive for consistency in aspects such as terminology, icons, colours and menu hierarchy be identical throughout the whole interface	Y
2	IxD	Enable frequent users to use shortcuts to reduce the number of interactions and to increase the pace of interaction.	N
3	IxD	For every operator action, offer informative feedback.	Y
4	IxD	Offer simple design dialogue to yield closure at the completion of a group of actions	Y
5	IxD	Offer simple error handling if an aspect of the system cannot be designed to prevent serious errors from occurring.	N
6	IxD	Permit easy reversal of actions so that the user knows that errors can be undone, encouraging exploration of unfamiliar options.	Y
7	IxD	Give the operator the sense that they are in charge of the system and that the system responds to their actions.	Y
8	IxD	Reduce short-term memory load in the system.	Y
9	Participatory	Communication is enabled among design participants (layperson - layperson)	Y
10	Participatory	Emphasize co-research and co-design among designers and users (layperson - designer)	Y
11	Participatory	Allow for intuitive layperson interaction with the environment	Y
12	Participatory	*Facilitate* design rather than *dictate* design	Y

Figure 1. Defined system of analysis with outlining of relevant criteria.

3. Technology

The technology adopted in the project was the *Vuforia Augmented Reality SDK*. Vuforia is an AR software development kit for mobile devices that uses computer vision technology to recognise and track images and 3D objects in real-time. When utilised in collaboration with *Unity3D*, the user can design trackers and import them into the Vuforia target manager. The Vuforia target manager assesses the quality of the target, as well as finding tracking point locations. The user is then able to download their trackers and import them for use in a Unity3D project.

The current workflow for Vuforia requires only a base level of knowledge in augmented reality and 3D modelling. The process begins with the digital modelling of the object in any programme with the functionality to export as an OBJ file type. While these objects are modelled, image trackers must also be designed and imported into the Vuforia Target Manager. As mentioned previously, the target manager is where Vuforia determines the image trackers' quality and collates them into a database that can be used in Unity3D. The target manager requires the designer to set the overall width of the tracker and have requirements for them to be PNG or JPG file format, RGB or grayscale colour space and being under 2MB.

Once imported into Unity3D, the process of making one's desired model and target database appear and function in augmented reality is very intuitive. The designer simply creates an image-based target through the Vuforia Unity plugin and then makes the model a child of the image target. For testing the AR scene within Unity3D, a webcam is the most accessible camera to use. The scene must be built and then imported to the device to see the augmented scene functioning on a smartphone or tablet. The process can be very time-consuming if other designers need to test small changes in the AR scene repeatedly.

The most significant advantage of Vuforia is that it allows multiple different trackers in one scene, allowing the tracking of various building types in one AR environment. The image-based targets are also customisable and can be any high contrast image or drawing that the designer would like to use. One of the setbacks is the buildings' customizability once they are in AR, and the need for the 3D model to be generated externally from Unity3D. Once the buildings have been imported into Unity3D and placed in an AR scene, they are no longer customisable. The workflow that has been developed allows for the arrangement of buildings concerning one another but not the design of the buildings themselves. Despite these setbacks, we have still found Vuforia to be the tool that resonates the best with this research. Although it doesn't allow for complete customisation of individual buildings, it facilitates a very intuitive interface that merges very nicely with Unity3D, allowing for easy testing and building of these AR scenes as an application that can be used on smartphones or tablets.

4. Exploration

4.1. THE HOUSE AND THE MARKET

Before any further exploration was conducted, a pilot study using a base set of designs was developed to test the capabilities of Vuforia further. In the spirit of functionality and ease, tools existing within Vuforia itself were applied to a simple house+market typology. The typology consists of a simple house with a food market out the front, with possible combinations of the two to test the project's parametric aspects. These combinations are based on four functions: expand house up, expand house out, add a small market and add a large market. With these combinations, a total of 12 typologies can be created. A further reason for choosing the house+market typology is its shared characteristics across different regions, allowing for simpler testing of Vuforia's capabilities in a setting that is not constrained by local conditions, vernacular or complex design.

4.2. IMAGE-BASED TARGETS

Image-based targets in Vuforia have specific requirements for them to be effective. According to the Vuforia website, to have the highest chance of tracking effectively, the targets must fulfil the following criteria: i) be rich in detail, ii) have a high amount of contrast, iii) Not have any repetitive patterns. These requirements mean that images with sharp edges work very well as an image-based target, but a hatched grid, for example, does not.

Within Unity3D, the various simple house+market typologies are assigned to image-based targets so that when the camera reads them, the associated buildings are generated. The workflow provides a unique advantage within the realm of urban design. If the designer assigns typologies to different targets, the user can begin to arrange them in any manner that they wish. A significant limitation of these image-based targets is that a unique target must be designed for each building. This means that if a user wants two of the same typology in an urban arrangement, the underlying targets must be different even though they are the same design.

If utilised by a layperson, these image-based targets may pose some issues if not appropriately communicated. It would need to be very clear how each target functions and what building type it is generating. If only utilising the image-based targets, with no additional information, it may be challenging to understand the spatiality and arrangement of individual buildings and the function of that building.

Figure 2. Developing urban arrangements using simple image-based targets.

4.3. VIRTUAL BUTTONS

Virtual buttons in Vuforia provide a method for making image-based targets parametrically interactive. The functionality of virtual buttons relies heavily on the quality of the target with which the virtual button is associated. By covering a certain number of defined tracking points on an image-based target, events are triggered using Vuforia's OnButtonPressed and OnButtonReleased events.

The dependence on the quality of the underlying image-based target means that the virtual button's size and placement must be considered carefully, concerning both the user experience and the function of the image-based target. Several factors must be taken into account when designing virtual buttons for use in augmented reality; these factors are:

- Size: Virtual buttons should take up about 10% of the image target's size. When defining this, the length and width of the button are considered.
- Shape: If the virtual button is too skinny in one dimension it will not track easily. They should also be easily identifiable to stand out from the rest of the image.
- Texture or contrast: Virtual buttons should be defined in high contrast areas of the targets. The underlying target area needs to have sufficient features that

tracking points can be applied to. Choose a button design different in texture from the object that hides the tracking points, causing the button to activate.

- The arrangement on the target: Arrange buttons around the target's borders with enough space from the edge to avoid losing image tracking when the user "presses" a button.

Within the project context, these virtual buttons can change between different typologies parametrically and add additional components to existing buildings. Through testing their capabilities in Unity3D, the virtual buttons can be very effective in this regard. Starting with a simple house component, by covering or 'pressing' the virtual button, a small market place is added to the house's front, transforming it from a simple dwelling into a 'house+market' typology. With this single virtual button, the individual target now has the capabilities of harbouring the two unique typologies: the house and the house+market

Further looking into these virtual buttons' capabilities brought the realisation that by having multiple virtual buttons in a single target, the number of typologies able to be created expands exponentially. With the creation of a new target, four virtual buttons are planted, and with this, twelve unique typologies can be parametrically generated. These additional virtual buttons give an inexperienced user the ability to define what they would like their building to look like, and the freedom to explore options while simultaneously allowing the experienced design to retain a bulk of the design work.

When first visualised in AR, the image-based target centre is a small house (Figure 3 left). The house provides a base point that all of the variations are based off. The designer can then place a virtual button covers over the four buttons to the central target's side to trigger the building of the various typologies (Figure 3 right).

The process behind the events that happen when these virtual buttons are covered relies on a small amount of *C-sharp* scripting using the 'OnButtonPressed' and 'OnButtonReleased' events. The event triggered for OnButtonPressed is a simple animation, causing the associated model to scale from 0 to 1. The scaling happens for all virtual buttons, so, for example, if the 'expand up' virtual button is covered, the second story of the house is scaled from 0 to 1. The OnButtonReleased event causes the opposite of the OnButtonPressed event, simply scaling the model from 1 to 0.

Figure 3. Image-based target, with two virtual buttons on either side of the central tracker. Covering the ‘expand up’ and ‘expand out’ virtual buttons causes a new typology to be created.

4.4. CREATING URBAN ARRAGEMENTS

With the introduction of additional C-sharp scripting, the user can build typologies out to an XYZ-axis through the press of the spacebar. The creation of buildings gives the user the chance to create entire communities of these buildings based on their personal preferences.

By building multiple house types in one scene, the user can see how structures relate to one another at a 3D scale, rather than the standard model of representation with two-dimensional drawings. It also gives the user the chance to see how one building relates to another and how entire streets of buildings can be arranged concerning adjacent streets. A designer could consider problems like adding a market to the front of an existing building earlier in the design process, avoiding the market infringing on the road and being seen as ”bad design. The structure may be built further back from the street to allow for potential later development in early design stages.

4.5. REAL-TIME LIGHTING

The lighting method in the project involved a graphical user interface (GUI) slider in simulating real-time lighting within the AR environment. A slider can be built through a combination of Unity3D’s existing UI functionality and a small amount of C-sharp coding, which angled a directional light as if to follow the sun direction from 6:00 a.m. at the left of the slider, to 6:00 p.m. at the right. The UI lets the user know with certainty what time of the day is correlated with certain sun conditions, and, unlike previously explored methods, gives better insight into the way that real-world sun paths cast shadows on buildings.

The on-screen GUI used in this method requires user engagement with both a GUI and a TUI simultaneously. While these are both forms of user-interface, their interaction is vastly different (Ullmer & Ishii, 2000). In a GUI, we see interaction occurring with a mouse on a screen instead of a TUI where the user interface is a tangible element set in front of the user. For the slider lighting system to work one of two things must occur: i)The user would have to transition between GUI and TUI in a way that they do not lose touch with their initial design goal or ii) the

GUI and TUI would next to be designed as if occurring within one unified user interface.

5. Conclusion

The paper explores the role of an appropriately low-tech AR environment in the engagement of laypeople in urban design. It employed the Vuforia SDK, and exploited the software's capabilities as a method of creating tangible user interfaces to facilitate intuitive interaction within an AR environment. Our novel application is based on real-time-virtual-engines and XR that are connected to a parametric system that allows urban design proposals to be communicated with ease in real-time to laypeople and expert. Thus allowing for a novel and more equitable design interaction.

Within the realm of urban design and architecture, there is a disconnect between the public/client (layperson) and the designer/architect (expert). The disconnect is often found in the communication of design options and implications. In the past, these issues have been addressed by the designer commanding control of them and failing to communicate design options with the client effectively. The project sought to explore AR's role, and specifically, illustrates an effective system developed to show how appropriate tangible user interfaces can play a significant role in bridging this divide.The ease of gaining familiarity with the system is one essential ingredient; easily interpreted instant system feedback is the other.

The project outcomes are an intuitive solution for layperson engagement in urban design and a system of analysis for such a tool grounded in the existing literature. A low-tech TUI was an effective design tool, as it allows for a shallow learning curve due to the tangible aspect being something that the layperson is more familiar with. Facilitation of design was also found to occur at multiple scales. The small was the individual configurator and the large being building configurations out to the XYZ axis and developing an urban arrangement. These contributions offer a significant step into an area of research that does not focus primarily on experienced users and high-tech methods of interactions, hence being more democratic. Future research within this field could greatly expand upon the developed interactions, providing even more opportunity for layperson engagement in the process of urban design.

References

"Location and orientation for passive heating and cooling" : 2019. Available from <http://www.level.org.nz/passive-design/location-orientation-and-layout/> (accessed 15th May 2020).

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

Broschart, D., Zeile, P. and Streich, B.: 2013, Augmented Reality as a Communication Tool in Urban Design Processes, *Proceedings of RealCORP 2013*, Rome, 119-126.

Brown, A. and Berridge, P. 2001, Games One:Two:Three: A triangle of virtual game scenarios for architectural collaboration, *in* M. Stellingwerff and J. Verbeke (eds.), *Accolade - Architecture, Collaboration, Design*, Delft University Press, 95-120.

Chowdhury, S. and Schnabel, M.A.: 2019, Laypeople's Collaborative Immersive Virtual Reality Design Discourse in Neighborhood Design, *Frontiers In Robotics And AI*, **6**, 97.

Cooper, A., Reimann, R. and Cronin, D.: 2007, *About Face 3:The Essentials of Interaction Design*, Wiley.
Healey, P.: 1997, *Collaborative Planning: Shaping Places in Fragmented Societies*, UBC Press.
Hornyanszky-Dalholm, E. and Rydberg-Mitchel, B.: 1992, Communicating with Laypeople, *Proceedings of European Full-Scale Modelling Conference 1992*, Lausanne, 25-32.
Kato, H., Billinghurst, M., Poupyrev, I. and Imamoto, I.: 2000, Virtual object manipulation on a table-top AR environment, *Proceedings of IEEE and ACM International Symposium on Augmented Reality 2000*, Munich.
Lo, T.T., Schnabel, M.A. and Moleta, T.: 2018, Social Media Design: Using VR to Empower Homebuyers to Design their Living Space Collaboratively, *Virtual + Actual: Process and Product of Design, Design Communication Associations (DCA) Conference*, Ithaca, 138-146.
Nielson, J.: 2012, "Usability 101: Introduction to Usability" . Available from <https://www.nngroup.com/articles/usability-101-introduction-to-usability/> (accessed 13th May 2020).
Nourizi, N., Shabak, M., Embi, M. and Khan, T.: 2015, A New Insight into Design Approach with Focus to Architect-Client Relationship, *Asian Social Science*, **11**, 108-120.
Preece, J., Rogers, Y. and Sharp, H.: 2002, *Interaction design: Beyond Human-Computer Interaction*, Wiley.
Sawyer, B.: 2002, *Serious Games: Improving Public Policy Through Game-Based Learning and Simulation*, Woodrow Wilson International Center for Scholars.
Schnabel, M.A. and Chen, R.I. 2011, Design Interaction via Multi-touch, *in* Y. Luo (ed.), *Cooperative Design Visualisation & Engineering, CDVE, Lecture Notes in Computer Science*, Springer, Berlin, Vol 6874, 14-21.
Schneiderman, B.: 1987, *Designing the User Interface: Strategies for Effective Human-Computer Interaction*, Pearson.
Schurch, T.: 1999, Reconsidering urban design: Thoughts about its definition and status as a field or profession, *Journal of Urban Design*, **4**, 5-28.
Seichter, H.: 2004, Benchworks - Augmented Reality Urban Design, *Ninth Computer Aided Architectural Design Research in Asia (CAADRIA)*, Seoul, 937-946.
Seichter, H. and Schnabel, M.A.: 2005, Digital and Tangible Sensation: An Augmented Reality Urban Design Studio, *Tenth International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA)*, New Delhi, 193-202.
Spinuzzi, C.: 2005, The Methodology of Participatory Design, *Technical Communication*, **52**, 163-174.

BIG DATA BUGS

Investigating the design of Augmented Reality applications for museum exhibitions

ANASTASIA GLOBA[1], CALLUM PARKER[2], JUDE PHILP[3] and JOHN ANTONIOS[4]
[1,2,3,4]*University of Sydney*
[1]*{anastasia.globa}@sydney.edu.au* [4]*antonios.john@gmail.com*

Abstract. This paper presents a reflection on the co-design approach taken for designing a web-based and smartphone-augmented reality (AR) application (app) for a local museum exhibit on geo-located data for entomology specimens. The AR app allows visitors to spatially visualise insect specimens in-situ and view more detailed information through their own devices. The design of the app was guided by continuous input from curators of the museum to ensure it met their requirements. The contribution of this paper is two-fold: (1) design recommendations for AR apps created for museum exhibitions, which are derived from a focus group session with museum curators; and (2) considerations for co-designing AR apps in museum contexts, based on a reflection of the design process. This paper details the iterative co-design process that was adopted for the 'Big Data Bugs' project and presents a short summary of results deriving from a focus group testing with museum curators.

Keywords. Augmented reality; data visualization; human computer interactions; museum exhibitions; co-design.

1. INTRODUCTION

Natural history museums worldwide cope with dual audiences through a division of services: exhibitions largely do the work of 'edutainment'; while dedicated research is carried out behind the scenes by an international network of area specialists. Interactive exhibits within museums of natural history are thus predominantly products for edutainment, aimed at a specific learning outcome gleaned through participation (Addis 2005). Museum exhibitions are traditionally physical in nature. Most simply, an exhibit includes a specimen, a label that identifies it, and some kind of graphic element to guide the visitor. Increasingly exhibitions include an interactive aspect - such as Quick Response (QR) codes for visitors to access more detailed information on their own devices (Paddon 2016). Interactives predominantly work alongside the greatest assets of any museum, the collections, to support learning outcomes through active audience

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 305-314.

participation (Yoon et al. 2017). For instance, large interactive computer screens are used at Museum Victoria ‘Wild’ exhibition to allow the audience members to select information and at the Chau Chak Wing Museum’s ‘Mummy Room’ to show spectroscopic and x-ray images for the audience to explore the insides of bodies and pigments of coffins. These kinds of interactives exploit the connections between curiosity and learning to engage with visitors (Cho et al. 2019), and explicitly use a strategy of exploring a single object on display, so to not completely divert the visitor’s attention away from the exhibits. These screens demand space, power and maintenance (Davies et al. 2017) to support the significantly large data files for images and animations. With the world-wide pandemic of 2020 alternatives for touchscreens need to be found due to the risk of spreading germs while using the screen. Despite the disadvantages, younger audiences familiarity with digital technologies alongside the potential for including a wide range of data types and outcomes within an interactive make these technologies essential within the University museum context.

Used in conjunction with physical displays, augmented reality (AR) is being increasingly used to show historical-geographical contexts (Kim et al. 2017) and scientific investigation (Moro et al. 2017). Its effectiveness lies in its ability to provide the user with an augmented view of real world information, displaying virtual content in-situ to make museum exhibitions more engaging (Hansberger et al. 2017) and enhance the in- formation already physically provided (Peddie 2017). AR can also also be useful for museum exhibits that are too fragile to be displayed or handled by visitors (Kalantari & Rauschnabel 2018). In certain cases, viewing an exhibit from multiple perspectives is important to understand the makeup or anatomy of specimens (Sarupuri et al. 2016). Despite a growing body of research, there is little documented around the design process of museum-focused AR applications (apps) and the considerations for integrating them with museum exhibits. Therefore, in this paper we detail the design process of our project which focused on the creation of an AR app, ‘Big Data Bugs’ created for the Natural Selections exhibition in the Chau Chak Wing Museum. Ultimately the aim of our research is to learn more about complex learning outcomes for AR use of museum collections beyond exhibition, and to gain insights into designing interfaces for AR and the best practices for displaying and interacting with data. Although planned second-phase training was inhibited by COVID19 restrictions, the outcomes of the current research led to new knowledge in the form of design recommendations for AR apps in museum contexts, along with considerations for co-designing them, to help inform future work by researchers and industry practitioners.

2. APPROACH

For ‘Big Data Bugs’ an iterative co-design prototyping approach was adopted, following a research-through-design strategy (Zimmerman et al. 2007). The work on the AR application itself was foregrounded by a series of investigations related to the four distinct topics (design phases): (1) effective approaches for visualisation of geo-lacated data; (2) types of UI (User Interface) design styles applicable for AR applications; (3) categorisation of (insect) collection data in such a way that it could be translated into data visualisation variables; and (4) using three dimensional objects such as CNC (Computer Numerically Controlled) routed maps as reliably trackable AR markers (Fig. 1).

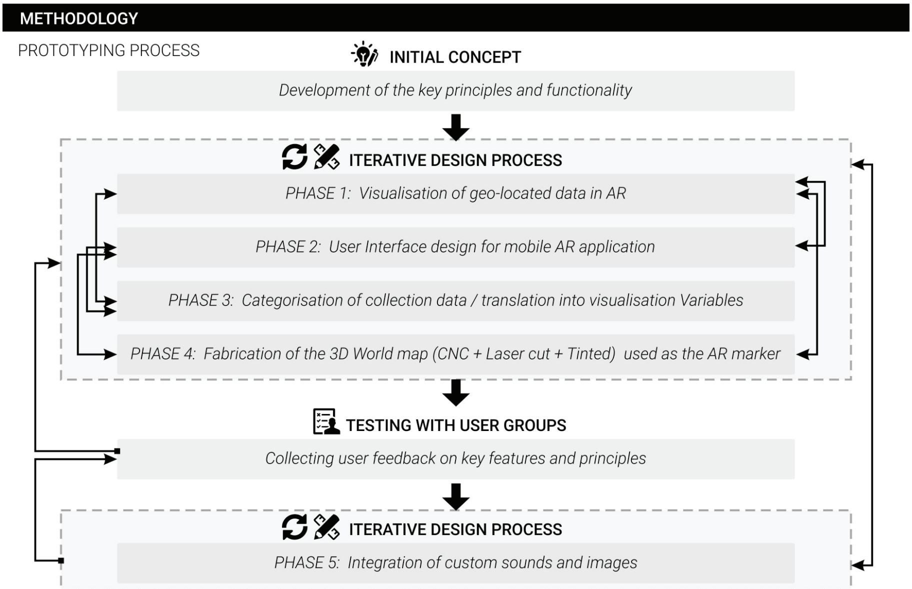


Figure 1. Iterative prototyping methodology.

At the conceptual stage the key principles and functionality ideas were developed before progression to the iterative co-design stage with four initial design phases (mentioned above) that explored: AR data visualisation, UI, data categorisation and 3D AR marker fabrication. To gain broader feedback on the design of our AR app, we facilitated an online focus group with 12 museum specialists. They were asked a series of questions about current museum interactives and our AR app's design. The data was then looped back into the iterative co-design process again for the proposed phase five. In discussion we quickly adopted the suggestion of adding new functionality through sound files to create a sense of familiarity and connection with the specimens and noises made by familiar insects in daily life; and the potential of custom image upload of 'citizen science' viewings.

2.1. VISUALISATION OF GEO-LOCATED DATA IN AR

Several approaches suitable for geo-located data visualisations were examined and prototyped for this study. We looked into the height map or terrain metaphor, where the number of insects collected for each location determined the terrain elevation. Another tested strategy was to use extruded shapes, such as rectangles - similar to the 3D bar chart approach, colour-coding them based on the type of insects found in each location. The third visualisation approach investigated the use of geo-mapped 3D bubbles, merging data domes into curvilinear clusters and congregations. As a result of these data-to-form explorations a hybrid data visualisation approach was developed that used a number of characteristics from the elevation/extrusion and bubble diagram methods. This visualisation method was also strongly informed by the long-standing museum practice of using metal pins to fix and exhibit insects.

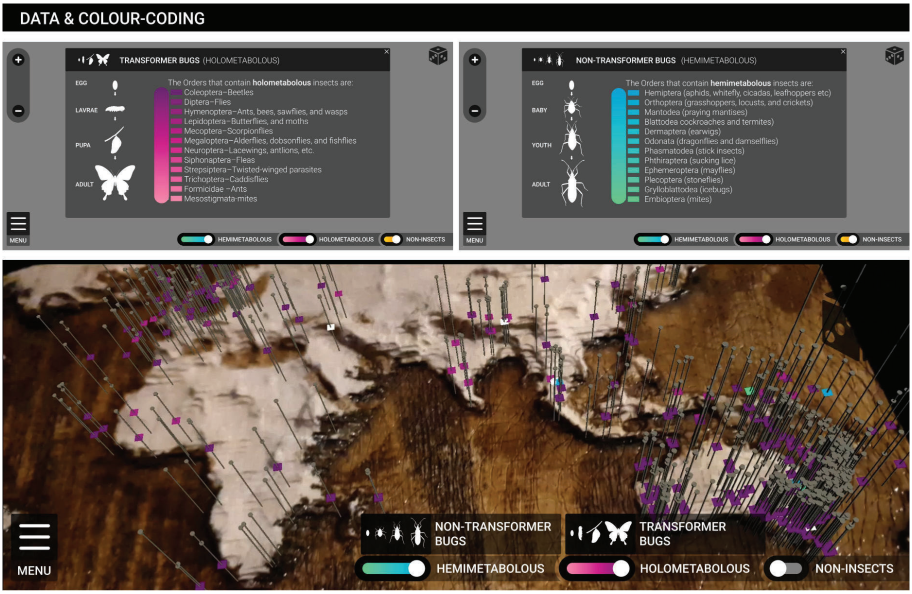


Figure 2. The colour coding used.

From the collection and insect typology perspectives there were no suitable super-order category that would allow users' informed exploration of the AR map, where existing taxonomic groupings needed to be built into the design. However, after a series of co-design discussions a suitable solution that worked both for the app designers and the curator team was identified. Working with the curatorial team, it was decided to separate the non-insect data entries by distinctly coding them with orange to yellow spectrum. Secondly, all orders were split into two main groups based on the way they grew into their final adult form: purple-to-pink identified the Holometabolous or 'transformer' species such as stick insects (Figure 1, top right) and blue-to-green identified the Hemimetabolous or non-transformer groups such as butterflies (Figure 2, top left). This approach allowed users to make sense of the visual information that the colours were communicating and to learn key concepts for entomology. The co-design strategy improved navigation of the AR map whilst keeping focus on information and learning.

This particular colour-coding strategy was a negotiation between a number of challenges and a good example of a co-design approach. The first challenge was to figure out an effective method to assign colours to the museum's highest hierarchical category, the 29 orders represented in the entomology data. Technically, it was possible to come up with an identifiable colour for each order, however in practice it would require users to distinguish between all those colours and constantly refer to the colour legend that would have to be extremely extensive. Even though an average human eye is capable of registering over 100 colours, our cognitive capacity to process, count and compare between different objects is far more limited. This could be related to human ability of subitizing items, where humans can easily identify 3-5 items, but struggle to compute larger quantities (6+) (Piazza et al. 2002, Dehaene & Cohen 1994). Therefore, from the usability and data visualisation stand-points this was not a feasible solution.

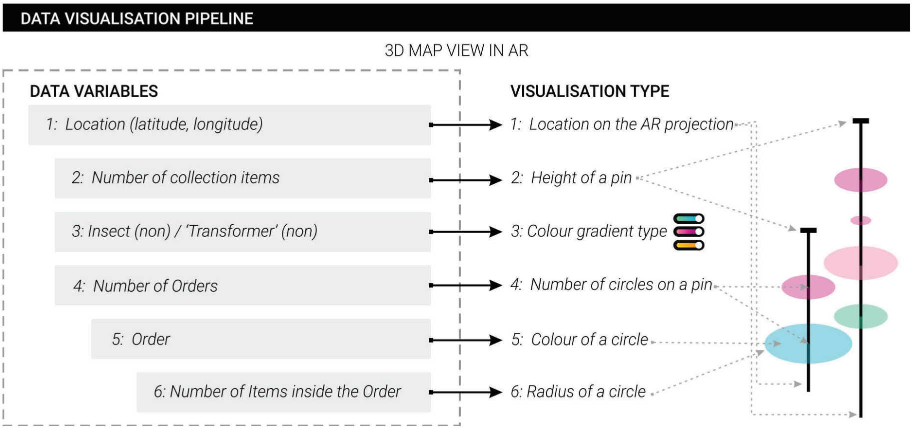


Figure 3. The data visualisation pipeline.

Figure 2 (bottom) illustrates the data-to-form visualisation approach adopted by this study. The height of each pin represents the total number of insects that were collected in each location. Multiple planes with circles on each of those pins represent different insect orders, such as Orthoptera (grasshoppers etc.), Blattodea (cockroaches and termites), Diptera (flies) or Formicidae (ants). Where the radius of each circle represents the number of genera - the lowest, most narrow hierarchical identifiers for each order variable collected for this geo-location tag. The orders themselves were visually communicated using a three-part gradient colour-coding approach.

As well as the 3D data mapping visualisation logic (presented in detail in Figure 3), the application also contained another functionality for communicating in-depth data related to specific selected collection items. The 'explore in detail' function allowed users to 'zoom-in' and take a look into each selected bug in more detail. This detailed view was intentionally separated from the 3D map view and presented additional data variables related to: 1. detailed hierarchical information (order/family/species/genera), 2. adult form characteristics that were presented as an interactive 3D model of a bug and its graphic outline icon, 3. textual description narrative, 4. repeatable attributes such as number of wings for the chosen item and 5. number of artefacts in the collection for each explored data item. At this stage curators requested that four prominent family groups were added to allow further investigation into two orders, coleoptera and lepidoptera, with the largest number of specimens in the collection.

2.2. USER INTERFACE DESIGN

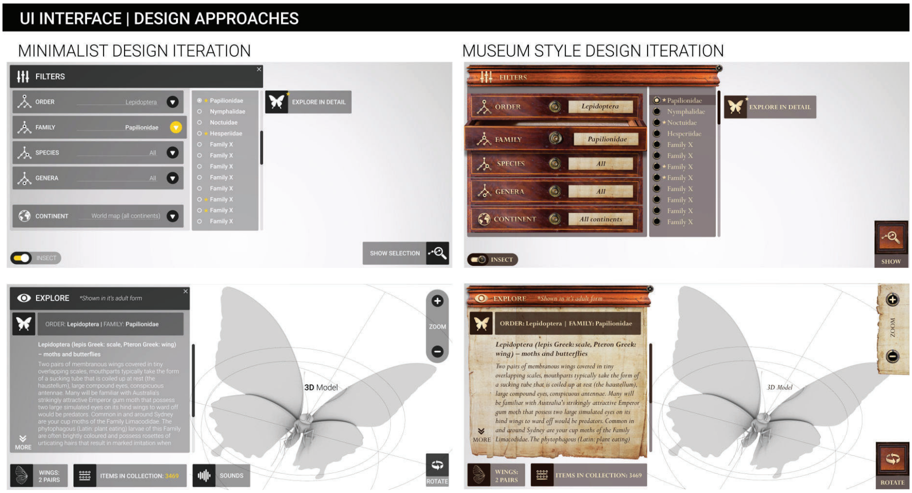


Figure 4. The user interface design approaches.

Prior to development of the interface for the mobile app a two-step investigation study was run to determine the most appropriate and effective UI (User Interface) design approach. Research into existing UI styles commonly used for AR applications revealed a range of prominent approaches that are frequently used in practice, including: cartoon style UIs (colourful and large buttons and icons, similar to 'Pokemon Go'), minimalist UI (clean and clear approach), futuristic UI ('Matrix' style - black back with glowing or transparent buttons and tabs) and realistic UI (realistically portrayed objects and textures). Among these UI design approaches two were determined to be most suitable for this project, namely: minimalist design approach (Figure 4, left) that would allow users to focus on the content rather than the UI; and the realistic UI style that was reminiscent of old museum atmosphere and the red wood with brass furniture that contained the collection items (Figure 4, right).

As a second step of the UI design studies both minimalist and realistic design approaches were implemented in the AR application and were tested as design concepts during the initial user-group study. The Results section includes a detailed report on the findings related to the feedback that was given by the study participants in response to those two proposed UI options. One result from the process was a collective decision to proceed with the cleaner and clearer minimal design approach which was less distracting and re-iterated the importance of the content rather than the interface; and to add further areas for novice audiences to engage with such as sounds and uploads.

2.3. COLLECTION DATA

Creative ways of interpreting complex hierarchical geo-located data-sets is among the main challenges addressed by this research project. Intricate and interconnected nature of data that is being visualised in the proposed AR environment created both challenges and opportunities. To this end, an existing museum collection containing over 300,000 thousand insect and non-insect specimens was recorded as a data set which contained both existing and obsolete geographic and taxonomic data. (Britton & Stanbury 1982). Within the University context, irregularities in museum data was a key message that curators desired to communicate.

Understanding the nature and consistency of existing data was essential when developing both the functionality and available visualisation strategies for the app. We have detailed the data-to visualisation pipeline that was developed for this study in Section 4. Due to the fact that most of the available data entries had the geo-location tag as a variable, the location criterion was chosen to be the common denominator. From there on the choice of mapping our big data bugs based on the world coordinates (attitude and longitude translated as X and Y values in the game world) was a natural preference. A topographic world map was chosen over political map option as the collection was accumulated over three hundreds of years, as countries shifted their borders, emerged or ceased to exist.

2.4. FABRICATION OF THE 3D WORLD MAP FOR AR TRACKING

The map was essential to expand the audiences' visualisation of insects and non-insects in the collection, providing clues to ecological factors of difference. By definition the world topographic map describes the shape and character of the surface of the world. When working with the two dimensional objects topographic world maps are usually graphically described as land masses such as continents or islands with contour-lines projected onto them. 2D pictures are also most commonly used source for image-based AR markers utilised in practice. In this study we aimed to challenge this commonly used approach of creating flat AR markers. The objective was to fabricate a 3D topographic map and investigate an opportunity of using three dimensional digitally fabricated AR models that would be easily trackable with such widely spread and popular technology as Vuforia Engine (PTC 2020).

Even though technically the topographical world map was a three dimensional model that was procedurally generated (Network 2020) from a source height map image, the Z (height) direction of it was extremely negligent com- pared to the length (X) and the width (Y) of a model. This was true even after the height of the terrain was intentionally exaggerated. Thus, the resulting world projection visually read more as a bas-relief map rather than a true 3D object. These design constrains inspired us to investigate an opportunity of using an image tracking technology applied to a 3D object. To this end best practice guidelines for designing and developing image-based targets were used to inform the way our experimental 3D world map iterations were designed and fabricated. The desired attributes were: rich in detail, good contrast and containing no repetitive patterns.

By its very nature the world map shapes are non repetitive and unique. It also helped that we used timber as our fabrication material, as wood fibres created additional unique non-repetitive patterns on the surface of a model. After the first 3D model iteration was CNC routed out of plywood it was apparent that the output was way too organic and smooth to be successfully tracked by the engine. To add extra ‘rich in detail’ qualities to the model multiple contour-lines were laser cut on top of the CNC cut timber. Because the model height was smaller than 50mm, a standard curve laser etching technique was applied to the timber surface as if it was a flat-sheet material . While some lines were burned slightly thinner or thicker than others, where the laser point was less or more focused, the overall approach proved to be very successful. And finally, to improve the AR image-tracker it was decided to tint the ocean or water areas of the map. As a result of this multi-step hybrid fabrication - the 3D world map was photographed and successfully and reliably tracked by Vuforia engine using simple image tracking technology.

3. RESULTS AND DISCUSSION

The following sections are based on reflections of our design process and data collected from our focus group.

Use accessible language Our focus group participants were a group of 12 professionals working in fields related to museums and curating of natural science collections. They could understand the scientific entomological names for the specimens but were concerned that it would not be easily understood by a general audience. Not all species have ‘common names’ which would make an app with different modes, such as advanced and novice, difficult to achieve. Because familiarity with scientific terms was a stated goal for this interactive, we implemented a colour-coding system to the transformer/Holometabolous and non-transformer/Holometabolous categories to assist novice’s in their exploration.

Design for quick experiences Visitors have low attention spans, so it is important to design apps that are quick to use. Designers should create apps that provide key details at a high-level while providing the option for users delve deeper if they have time. To further the quick experience functionality a ‘random bug’ button was introduces to the UI of the application, allowing users to look into a selection of randomly picked orders or families. The feedback from participants also indicated their preference for UIs that included visually descriptive images, such as insect outlines for the icons, and a desired avoidance of extensive text.

Establish a strong link with the exhibit It is important that the AR app contains references to the physical exhibit, the same as the physical space containing references to the app (QR codes). Users would like to see details of where they might find particular specimens along with recommendations on what else they should see. The AR app should serve a dual purpose of guiding users around the physical space while providing additional information about particular objects in the exhibit. Additionally, targeted visits and workshops can be organised to engage with particular user groups, connecting them with the exhibition, application content and its functionality. For example biology student groups can be invited to attend guided tours, or the use of the app can be potentially included in some of the study courses for different educational levels (university, school etc).

From the design workflow perspective an inclusion of professionals had a number of significant advantages. Firstly, each major decision was to be presented and communicated clearly and often in lay terms so that all team members could understand it. This allowed us to have clarity for each design challenge, and the whole process. Secondly, when dealing with design decisions and outputs, the iterative co-design process allowed us to test a number of non-conventional and experimental approaches, that might not have been apparent or intuitive from designer or game-developer perspective, but were suggested by people with very specific (narrow) knowledge and expertise. The need to have a justification or reasoning (to account for non-implied knowledge) led to more informed and often creative design outputs. Finally, the iterative design approach allowed us to test and constantly improve our design variations. In this respect our design process was not linear. By avoiding the A to B tangent of design-specification-to-design-output logic, we constantly spiralled and looped back to inform and improve earlier design outputs.

Three simple guidelines summarise our design considerations: (1) Zoom out - see the core of the problem without insignificant details. This made it easy to communicate the problem to others; (2) Zoom in - exploit the unconventional perspective of unique knowledge holders; (3) Iterate, test and loop back - unlearn, make, test, learn and make again.

4. CONCLUSION AND FUTURE WORK

The iterative co-design approach to designing an interactive AR application for visualising museum insect collection, detailed in this manuscript, proved to be an effective method when dealing with complex design projects such as this. Distinctly different skill-sets and perspectives of our team members lead to creative and often unexpected outcomes. One of the main lessons learned throughout this study is that persistent and systematic inclusion of professionals from distinctly different fields (game design, data visualisation, museum collection, curating etc.) yield comprehensive and original results as all research steps and design decisions were critically accessed and challenged to accommodate for varied view points and knowledge sets.

This is an on-going project and in this manuscript we are reporting our design process together with a brief summary of initial user group testing results. Future work on this project will involve: (1) in depth analysis of data collected from the first user-group study; (2) reporting of the findings in a follow-up journal paper; (3) using the user feedback to inform future iteration of the AR application, such as adding insects sounds and allowing upload of custom images; (4) organising the next series of user testing workshops targeting a wider range of audiences; (5) exploring potential opportunities of engaging with the extended scope of sensory data interpretations, for example allowing visually- impaired people or people with learning disabilities to explore Dig Data Bugs in such way that would make sense for them.

Acknowledgement

We would like to thank the staff of DMaF Lab at The University of Sydney who helped us to produce various iterations of the 3D models used as AR markers.

References

Addis, M.: 2005, New technologies and cultural consumption–edutainment is born!, *European Journal of Marketing*, **V**, p.

Britton, E.B. and Stanbury, P.J.: 1982, Type specimens in the Macleay Museum, University of Sydney. VIII. Insects: beetles (Insecta: Coleoptera), *Proceedings of the Linnean Society of New South Wales*, **105**, 241-293.

Cho, J., Kim, H., Lim, J., Kim, T. and Park, J.: 2019, Interactive Exhibition from Wall Panels in a Museum, *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*, New York, NY, USA, 367-372.

Davies, N., Clinch, S., Mikusz, M., Bates, O., Turner, H. and Friday, A.: 2017, Better off: when should pervasive displays be powered down?, *Proceedings of the 6th ACM International Symposium on Pervasive Displays*, 1-9.

Dehaene, S. and Cohen, L.: 1994, Dissociable mechanisms of subitizing and counting: Neuropsychological evidence from simultanagnosic patients., *Journal of Experimental Psychology: Human Perception and Performance*, **20**(5), 958.

Hansberger, J.T., Peng, C., Mathis, S.L., Shanthakumar, V.A., Meacham, S.C., Cao, L. and Blakely, V.R.: 2017, Dispelling the gorilla arm syndrome: the viability of prolonged gesture interactions, *International Conference on Virtual, Augmented and Mixed Reality*, 505-520.

Kalantari, M. and Rauschnabel, P. 2018, Exploring the early adopters of augmented reality smart glasses: The case of Microsoft HoloLens, *in* . (ed.), *Augmented reality and virtual reality*, Springer, 229-245.

Kim, H., Matuszka, T., Kim, J.I., Kim, J. and Woo, W.: 2017, Ontology-based mobile augmented reality in cultural heritage sites: information modeling and user study, *Multimedia Tools and Applications*, **76**(24), 26001-26029.

Moro, C., Stromberga, Z., Raikos, A. and Stirling, A.: 2017, The effectiveness of virtual and augmented reality in health sciences and medical anatomy, *Anatomical sciences education*, **10**(6), 549-559.

Paddon, H.: 2016, Taxidermy and the Representation of Nature, *Changing Perceptions of Nature*, **V**, 99-106.

Peddie, J.: 2017, *Augmented reality: Where we will all live*, Springer.

Piazza, M., Mechelli, A., Butterworth, B. and Price, C.J.: 2002, Are subitizing and counting implemented as separate or functionally overlapping processes?, *Neuroimage*, **15**(2), 435-446.

Sarupuri, B., Lee, G.A. and Billinghurst, M.: 2016, Using augmented reality to assist forklift operation, *Australian Conference on Computer-Human Interaction*, 16-24.

Yoon, S., Anderson, E., Lin, J. and Elinich, K.: 2017, How augmented reality enables conceptual understanding of challenging science content, *Journal of Educational Technology \& Society*, **20**(1), 156-168.

Zimmerman, J., Forlizzi, J. and Evenson, S.: 2007, Research through design as a method for interaction design research in HCI, *Proceedings of the SIGCHI conference on Human factors in computing systems*, 493-502.

USING VIRTUAL FILTERS TO MEASURE HOW THE ELDERLY PERCEIVE COLOR

MINYOUNG CHUNG[1] and HYUNSOO LEE[2]
[1,2]*Yonsei University, Seoul, Republic of Korea*
[1,2]*{minyoungch|hyunsl}@yonsei.ac.kr*

Abstract. This study was conducted to test the effectiveness of a virtual filter that digitally compensates for age-related changes in color perception. Many elderly people experience declining color perception. Medical studies have been conducted on how elderly people's lenses affect their color perception. However, digital practical method for improving elderly people's color perception need to be developed. Subway map is a good example of many elder's daily experience. To adapt virtual filters to subway maps' colors, standard short-wavelength colors, namely purple and green, were selected for variance independence (VI) because colors with short wavelengths of 400-600 nm on visible light are difficult for elderly people to perceive. Standard color VIs of subway lines and VI transferred to artificial lenses were measured with a spectrophotometer. CIE LAB and RGB; Color value on virtual filter (VD) was analyzed from VI. This virtual filter was developed based on artificial lenses using Dynamo. A visual programming algorithm was developed to adjust the color of a virtual filter through an interface. The results showed that virtual filters can be used to help elderly people detect short-wavelength colors. Therefore, virtual filters should be incorporated into lenses for use by the elderly.

Keywords. Virtual filter; Elderly people's perception; Colors on subway map.

1. Introduction

Color is one of the crucial visual elements of objects that people perceive visually and so is important to mobility. This study was conducted to determine how to change the colors of subway map. Color is defined as the strength of the cognition (Kendel, 2016). The Seoul Metro's subway map is the most widely used public transportation map of transit-oriented development (TOD) in South Korea. Seoul Metro subway map is seen by 7,000,000 passengers every day, 1,000,000 of whom are over 65 years old (Seoul, 2020). The Seoul Metro subway lines are shown in nine colors on its TOD maps with much more complex combinations of colors.

Public transportation such as Seoul metro subway is needed to support perceived color of elders in subway maps. Main color of subway map line 1 dark blue, line 2 green, line 4 blue and line 5 purple is not distinguished on color combination of nine subway lines for elderly people. Green, blue, and purple are

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 325-334.

the colors with the short wavelengths on visible light and are also the colors which people lost the ability to perceive as they age. Thus, for example, blue colors on a black background would appear to be the same color to elderly people. The ability to properly distinguish between colors is a critical part of properly reading maps.

Given the importance of being able to perceive colors in daily life, it is important to understand how aging changes people's abilities to perceive color. However, studies on elderly people's lenses have been largely limited to the medical, architecture, and design fields. Medicals simulated the donors human lens that is similar to artificial lens in some part of visible light. The short part of spectrum through a lens report what elderly people see. Previous studies of lens rarely present on computer. Thus, this study used the Dynamo software to simulate color in an artificial lens. Lens color values were adjusted based on comparative studies of artificial lenses, human eye lenses, and Photoshop filters to simulate the vision of elderly people.

2. Research Question

There have been studies examining how elderly people perceive public interior spaces but not studies with digital application. Artificial lenses are not an effective solution for field application. This study was conducted to determine how elderly people perceive colors by examining how different lenses transmit visible light (Kessel, 2010) into a virtual filter. This study used a virtual filter developed using a visual programming language to manipulate an artificial lens CIE LAB. The validity of how virtual filters represent colors as they are perceived can be confirmed by colorimetry on CIE LAB, RGB and margin of Munsell. The objective of this study was to develop a digitized virtual filter to represent artificial lenses to help elderly people better read maps. The research questions with virtual filter study was conducted to address that affect the way maps colors perceived.

- What is color value transferred artificial lens as VI ?
- What is the color value transferred virtual filters as VD?
- What is differences in color value between artificial lens and virtual filter?

3. Related Information

3.1. MAPS, ACCESSIBILITY AND COLORS

Subway users have a particular need to be able to quickly understand the overall network. Seoul Metro subway map is a representation of public transportation networks on Transit-oriented development (TOD). TOD seeks to create integrated urban spaces that allow more than 20,000,000 people of Korea to easily move between activities, buildings, and public spaces using public transportation.

Distinguishing between lines by portraying them in different colors makes it easier to understand the network layout than if they were portrayed in the same color. Studies have been conducted on the colors used in subway maps. Netzel (2016) found that viewers could locate desired information more quickly using colored maps than greyscale maps (Figure 1 left in color). Lee (2019) found that higher color tones used in Tokyo's subway system's map are more easily perceived by those with visually impaired people than those of Seoul Metro subway map which have lower color tones. Personal mobility is a key determinant of personal independence, the ability to access goods and services, pursuing social and economic opportunities (Capezuti et al., 2014). Therefore, making maps visually accessible to the elderly can help them maintain their independence. Color run through only for normal lens would be more tricky for elderly people to read than normal lens on Netzel's gray map (2016).

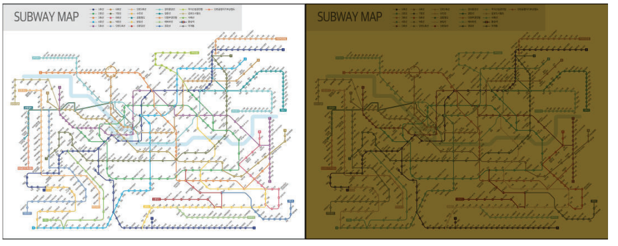


Figure 1. Seoul Metro subway map (left) and when viewed through Y A3 digital lens (Chung,2020).

Visible accessibility of subway map remains a challenge for elderly people. Elderly people might have difficulty identifying destinations on subway lines depicted in yellow. The purpose of this study was to identify the filter that reflects how many elderly people perceive colors to identify a set of colors that would be sufficiently accessible to the elderly and the population at large.

3.2. ELDERLY PEOPLE'S COLOR PERCEPTION ON ARTIFICIAL LENSES

Beginning at around age 50, the internal structure of the lens changes, causing it to harden, which in turn increases the scattering of light. These changes result in a gradual yellowing of vision over time. Various chromatic adaptation mechanisms generally leave people unaware of these gradual changes. Around 20% of people over 80 years old might have marked yellowing of vision (Ishihara, 2001). Nearly 5% of the world's population has cataracts and yellowed vision. This is expected to increase as various populations around the world are aging on average.

Ishihara (2001) studied which colors the elderly confused to simulate their vision. Many elderly people cannot discriminate certain combinations of colors, such as dark blue, green and dark green as above Figure 1. Yoshida (1992) conducted an optical simulation study using YA3 artificial lens (Figure 2), but a yellow filter for this lens is no longer in production. The present study was conducted to create a virtual lens by comparing the results of studies using artificial lenses YA3, Y2 and DG(Yoshida & Hashimoto, 1991; Ishihara, 2001) (e.g. Figure 2).

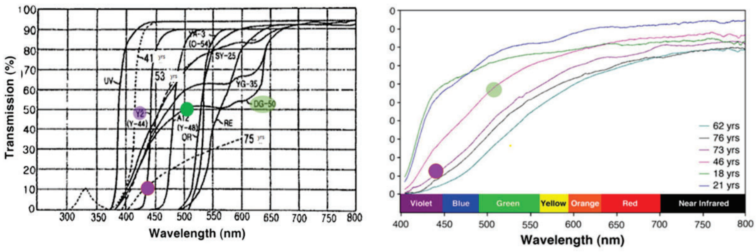


Figure 2. V.I. Reliability on artificial camera lens, (Ishihara, 2001) and on donor's human lens (Kessel, 2010) transmittance of visible spectrum.

3.3. REPRESENTING COLORIMETRY USING VISUAL PROGRAMMING

3.3.1. Colorimetry

Colorimetry is the quantification of how people perceive colors and can be used to predict how an observer will perceive a given color. In 1931, the Commission Internationale de l'Eclairage (CIE) developed a system for measuring color known as the XYZ tristimulus values, which served as the foundation for modern colorimetry. The XYZ values can be used to determine whether two colors match or not. In 1976, the CIELAB color spaces were developed which allowed for uniform CIE values to be used to describe the perceived differences between stimuli under a single set of viewing conditions (CIE, 2020). The L of CIELAB dimension corresponds to perceived lightness, ranging from 0.0 for black to 100.0 for diffuse white. The A of x axis and B of y axis dimensions correlate with the red-green and yellow-blue chroma perceptions, respectively (Figure 3). They can have positive and negative values. Both A and B have values of 0.0 for grayscale stimuli. The L, A, and B dimensions are combined as Cartesian coordinates to form a three-dimensional color space.

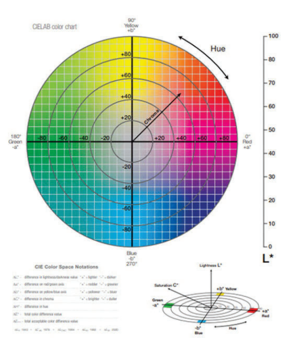


Figure 3. CIE LAB Color space (CIE, 2020).

The color tolerance of similarity for multi-component Munsell and Delta E is a single number representing the distance between two colors. Delta E indicates how color differences are perceived. The term "delta" comes from mathematics, meaning that change in a value. On a typical scale, Delta E will range from 0 to 100. Values of 0-1 indicate differences that are imperceptible by humans while a value of 100 indicates that colors are opposites. It is tempting to determine the Delta E values between red, green, and blue, but the RGB system was developed for convenient use with electronic systems and does not reflect how humans perceive colors. Therefore, Pantone color chips were used because the Seoul Metro subway map's colors are Pantone colors. Subway line's Standard color of CIELAB were measured and their equivalent RGB values were obtained for use with computers.

3.3.2. Programming algorithm using Dynamo

Dynamo is a great application for colors. Colors in Dynamo are created using alpha, red, green and blue inputs where alpha is transparency and red, green, and blue are mixed to generate the whole spectrum of visible color. Dynamo is an open source visual programming platform that was used in this study for adaption on digital field. Data is measurements of variables at various points. When working with abstract data and varying numbers, it can be difficult to determine which factors are causing changes in the data. Therefore, the color of virtual filters can be adjusted.

Coordination and collaboration involves multiple levels of communication where virtual filters are involved in the communication between people regarding values, intents, context, and procedures. The age-related decrease in spectral transmission through the human lens can be modeled by an algorithm that may be useful in designing of intraocular lenses that mimic the characteristics of the human lens and in studies on color vision, psychophysics and melanopsin activation (Kessel, 2010). Although the results of the aforementioned research are often used to predict yellow vision in artificial settings, there have limited on field application investigating how aging affects color perception. Perception of the elderly people is a concern for subways because better visibility would increase elderly people's accessibility.

4. Research methodology

To digitize virtual filters to correct elderly people's perceptions of color, it should be understood how colors are related in artificial lenses (Figure 2), which is possible with spectrophotometers.

4.1. MEASURING THE COLOR VALUES TRANSFERRED ARTIFICIAL LENS

First, the changes in color perceived by elderly people were measured by a spectrophotometer with color from color chips as viewed through an artificial lens DG and Y2 based on Figure 2. DG artificial lens demonstrate 400-550nm and include 500nm that is representative for green. Y2 artificial lens demonstrates a spot of purple 450nm wavelength on visible light.

Pantone color of line 2 is 354C and line 5 is 2583C that are designated by Seoul in 2017. Their colors corresponded to Pantone color chips that were measured by Coloreye-7000a spectrophotometers. Spectrophotometer values were input into an

Excel file where the visual programming algorithm was on run on them (Escalante, 2019). It was possible to get subway map colors RGB on the interface of Dynamo automatically. Spectrophotometer measurements were taken three times on the common application of CIE illuminant D65 using visual field that subtended '2 degrees' standard of central fovea (Fairchild, 2015) and the median value was ultimately input into the Excel file.

Second, Dynamo was used to predict digitized color data to overcome the limitations of filed application using an artificial lens and spectrophotometer. To explore the virtual filter used to perceive the color of subway map, the Seoul Metro subway map was viewed with standard colors based on Pantone color chips that Seoul Metro determined. Seoul Metro subway map colors which were analyzed in this study had the representative short wavelengths of on the map.

4.2. ADJUSTING COLOR VALUES USING A VIRTUAL FILTER

After the color chip values for the Seoul Metro subway map's standard colors were been collected, the virtual filter (VD) was created based on the data transferred by the artificial lens (VI). Color chips transferred by the artificial lens DG and Y2 got the spectrophotometer value. As above transmission of visible light of green through DG lens and dark blue through Y2 lens. Line 2's color chip value of Pantone no. 354C was shown to have a LAB value of (26, -38, 27), an RGB value of (0, 74, 14), and a Munsell value (8.8GY, 2.53, 7.96) when viewed through a DG artificial lens. Line 5's color chip value of 2583C was shown to have a LAB value of (46, 16, 51), an RGB value of (147, 98, 10), and a Munsell H VC value of (9.25YR, 4.43, 8.58) when viewed through a Y2 artificial lens.

The second part of the study examined adaption virtual fitter using visual programming. These values were noted, compared and adapted for the digitization of color change results of the artificial lens to interface with Revit using Dynamo (VI) based on the color range and transparency produced by the algorithm. Code block nodes of red, green and blue were defined by plugging in the appropriate combinations of 0 and 255 (Figure 4) corresponding to color panel on interface (Table 1&2). The lens was set to glazed glass (see bottoms of Figure 5).

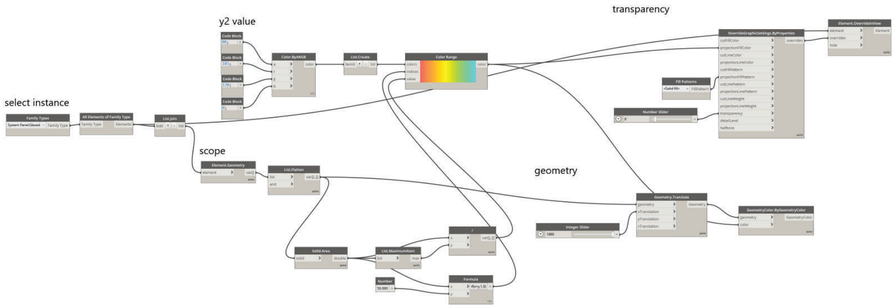


Figure 4. RGB values input into the algorithm of color changing.

The changed value overlaid on the color panel can confirm the color value with an effect similar to the yellowing phenomenon of the lens. Transmitted color matching between artificial lens and virtual lens is the key of finding. This Figure 4 algorithm is explained on below flowchart Figure 5.

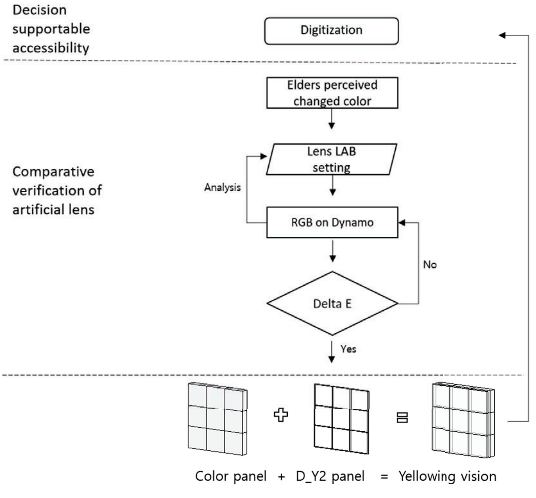


Figure 5. Algorithm flowchart.

The changed value overlaid on the color panel confirmed the color value with an effect similar to the yellowing phenomenon in the human lens. The key finding was that the colors transmitted through the artificial and virtual lenses were the same.

4.3. THE DIFFERENCE COLOR VALUES BETWEEN ARTIFICIAL LENS AND VIRTUAL LENS

To quantify the difference in colors and how elderly people perceived them, the short-wavelength colors on Seoul Metro subway map was examined after being passed through an artificial lens. To digitize the color, color chips were transferred to a virtual filter and Dynamo was used to visualize the colors on the interface where they were then measured using the Adobe Photoshop color sampler. (Table 1) shows the color digitization process.

The result shows the transmitted color on the virtual filter interface, which was measured using color sampler. These results were compared with those produced by the Revit interface which were transmitted through the camera filter. The Delta E 2000 (2020) score was calculated to determine each color chip's position on the two-dimensional CIE LAB map produced by virtual filter applied to the artificial lens. Condition comparison judgment as shown the proposed flowchart Figure 5. The RGB values of colors with Delta E values exceeding 2.0 were adjusted again in Dynamo. Delta E 2.0 over 1.0 is not the same color on human eyes. Virtual lens is limited to adjust exact value for Y2 lens.

Line 2's RGB value was (0, 74, 14) as measured by the artificial lens and (0, 75, 19) as measured by the adjusted virtual lens (e.g. Table 1).

Table 1. Measuring DG virtual filter .

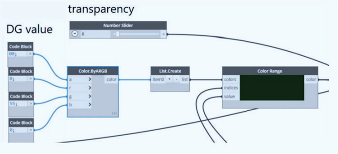
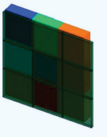
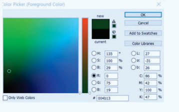
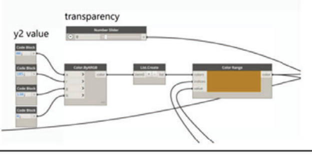
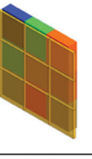
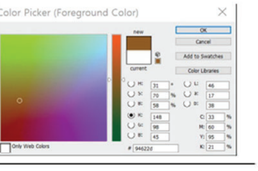
	Spectrophotometers		Visual programming	
■	LAB	RGB	LAB	RGB
354C	61 –72 37	0 175 75		
DG	-	-		
354C+DG	26 –38 27	0 74 14	27 -31 26	0 75 19
Image				
Delta E		1.8937 < 2		
Margin of Munsell H V/C		H±0.3, V±0.04 C±0.09 <1		

Table 2. measuring Y2 virtual filter.

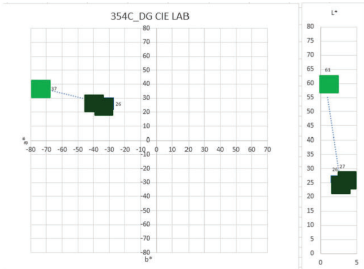
	Spectrophotometers		Visual programming	
▲	LAB	RGB	LAB	RGB
2583C	52 41 -34	170 96 183		
Y2	-	-		185 130 0
2583C+Y2	46 16 51	147 98 10	46 17 38	148 98 45
Image				
Delta E		13.42		
Margin of Munsell H V/C		H±1.81., V±0.04 C±1.65. <2		

4.4. RESULT

The saturation decreased because the variance on color space LAB was reduced (Table 1) when colors are transmitted, getting closer to the central axis on CIE LAB (e.g. Table 3 left). Visible light transmission decrease makes green is near to black. Delta E (Delta E 2000, 2020) of less than 2.0 is perceived same by human eyes.

The purpose of this study was to determine which virtual filter could be used to accurately represent map colors to elderly viewers. The virtual filter identified in this study produced a color for Line 2 with a Delta E 2000 of less than 2. Thus, the virtual filter successfully represented the target color (Tables 1 & 2). The yellowing of the virtual lens accurately simulated how elderly people perceive the colors of subway lines. This virtual lens produced a narrower range of colors than the original colors. Virtual lens based on DG artificial lens (Figure 2 left) can be used for other saturation and tone of purple, blue and green ranges.

Table 3. (V.D.) DG Virtual filter validity on CIE LAB maps.



		R	G	B		L*	a*	b*
02_354C		0	175	75		61	-72	37
DG_02		0	74	14		26	-38	27
D_DG_02		0	75	19		27	-31	26

5. Conclusion

The virtual filter developed in this study accurately represented how elderly people perceive color on maps in day light. The virtual filter was developed in three major steps. First, the virtual filter quantified elderly people's perceptions of colors on subway map as determined by CIE LAB's Delta E measurements. Second, color information discrimination that we can find the same thing with digitized digital color values. Third, the virtual filter simulated the transmission of light through an artificial lens and showed differences in digitization between artificial lens and visual programming interface. Whether the transmission value was valid, the digitally change of the simulated lens and the value of the CIE color space range equal to the human eye colorimetric color were implemented in Line 2. Own RGB value of the virtual filter was different from that of the artificial lens. The RGB value of the simulated lens for Line 5 exceeded the limit of B and so could only be approximately implemented. The simulated Y2 lens was not perfectly valid and the validity of the DG based on reliability was verified.

Therefore, we conclude that colors on digital interface of subway map transfers virtual filter, changed and affects the color perception that are comparable with the artificial lens produced by the short - wavelength transmittance of DG artificial lens. Y2 artificial lens cannot be distinguished by virtual filter for same color transmittance that acquire minus RGB range that is not scope of RGB.

This virtual lens study has boundary in understanding color perception of elderly people. It has limited based on Y2 around 450nm in 10% transmission and DG lens from 400nm to 550 nm in 10 to 50% value of visible light transmittance that is twice clearer view than that of 75years old lens (e.g. figure 2) under D65.

Therefore, the future study will be on Augmented Reality in 360 VR on underground with DG virtual lens.

Interface of this study reflected the reason behind the color change, so it can be used to understand how elderly people perceive colors. Elderly people will not be able to perfectly see every color, but there are other potential combinations that they would be able to perceive more easily.

People should be able to extract information from every color on maps. The appropriate lens to achieve this lies with you even if the color combination is not an easy one. Interface take an open path on what causes the information blindness and what role combinations play in creating distinct colors. It may be that elderly people's reactions to the situation are at the core of the color distinction problem and people cannot control anything other than reacting to being colorblind. Stakeholders must recognize that the perceived unlikeability of many elderly people is the product of social interactions. The results of this study can be used to improve the accessibility of signage in public transportation facilities, such as subways and bus terminals, for all users, including elderly people.

Acknowledgements

This work was supported by the BK21 Plus funded by National Research Foundation of Korea, NRF (2021).

References

Capezuti, E. A.: 2014, *The Encyclopedia of Elder Care: The Comprehensive Resource on Geriatric Health and Social Care*, Springer Publishing Company, New York. N.Y. .

Chung, M. and Lee, H.: 2020, Digital Artificial Lens for Analysis of Age Related Color Perception, *Journal of the Korean Institute of Interior Design*, **29(6)**, 74-81.

Delta E, 2000: 2020, "calculator" . Available from <http://colormine.org/delta-e-calculator> (accessed 1st June 2020).

Escalante, C.: 2019, "Create and Colorize Revit Curtain Wall Panel using Dynamo and Excel" . Available from <http://cyberspaceandtime.com/> (accessed 1st June 2020).

Fairchild, D.M.: 2015, *Color appearance models*, Wiley, New York Chichester, West Sussex.

Ishihara, K.E.A.: 2001, Age related decline in color perception and difficulties with daily activities–measurement, questionnaire, optical and computer graphics simulation studies, *International Journal of Industrial Ergonomics*, **28(3-4)**, 153-163.

Kandel, E.: 2016, *Reductionism in Art and Brain Science*, Columbia University Press, New York Chichester, West Sussex .

Kessel, L.A.: 2010, Age-Related Changes in the Transmission Properties of the Human Lens and Their Relevance to Circadian Entrainment, *Journal of Cataract and Refractive Surgery*, **36(2)**, 308-312.

Commission Internationale de l'Eclairage, C.I.E.: 2020, "CIELAB" . Available from <https://cie.co.at/> (accessed 1st November 2019).

Lee, S.K.: 2015, Analysis on Sign Color Characteristic in Public Subway Station : Focused on a Comparison of a Subway Station on Korea and Japan, *Korea Society of Color Studies*, **29(1)**, 15-23.

Netzel, R.E.A.: 2017, User Performance and Reading Strategies for Metro Maps: An Eye Tracking Study, *Spatial Cognition and Computation 17(1)*.

Seoul, M.: 2020, "Number of passengers of Seoul Metro Subway" . Available from <https://www.data.go.kr/dataset/15003169/fileData.do> (accessed 1st Feb 2020).

TOWARDS A FRAMEWORK FOR EMOTIONAL TACTILE INTERACTION DESIGN

CHOR-KHENG LIM
[1]*Department of Art and Design, YuanZe University*
[1]*kheng@saturn.yzu.edu.tw*

Abstract. This study aims to explore the possibility of maintaining intuitive behavior patterns and the most natural relationship coming from physical touch between "human" and "object" as interaction behaviors in interaction designs. Such an interaction will convey affection while providing brand new applications and innovative experiences offered by digital technology. "Interactive behavior is natural, but the experience of affection is novel" is the core idea of the interaction design in this study. The study aims to use a familiar artifact in daily life as the main carrier and embed technology in them and activate them, enabling them with sensitive sensing ability. With such an ability, the interaction between "human" and "objects" is thus sensed in a pattern of touch, which itself is affective and interactive. Interactions at the proper time can be provided as feedback, allowing users to experience emotional interaction. Through the analysis of the author's six interaction design projects and experiments over 10 years, the design process and framework for emotional tactile interaction design in using a familiar artifact is proposed.

Keywords. Tactile; Interaction design; Intuitive behavior; Familiar artifact.

1. Background and Objective

In addition to verbal communication, humans communicate using nonverbal methods , such as facial expressions, gestures, and touch. Among these methods, "touch" is a significant way of conveying affection, thus playing an essential role in improving mental and physical health (Field, 2010; Morrison, et.al, 2010; App, et.al, 2011). In daily life, physical contact and touch behavior occur frequently both between "human" and "human" and between "human" and "object." According to research, affective touch can regulate physiological reactions, build up relationships, and alleviate disruptive behavior (Van Erp et.al, 2013, 2015; Burleson, 2007). Hector et al. also suggest in their human-computer interaction study that affective touch can function as a regulator with a positive effect, not only between "human" and "human" but also between "human" and "robot," which is mediated through digital computation (Guthier, 2016). Due to recent progress in technology, human-computer interaction interface design is shifting from a graphical user interface (GUI) to a more natural and human-centric

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 335-344.

natural user interface (NUI). NUI focuses more on natural human behaviors, such as touch, body gesture recognition, and language recognition.

The research literature reveals that the focus of interaction design is shifting toward a more intuitive NUI design, and how to turn the behavior patterns obtained from observing user behavior into a more adaptive interaction interface is this study's major focus. Some studies have explored how to understand user behavior through "observation," with user-centered design in mind and have successfully applied it during the design process. They use "observation" as the primary design method in the course of design and propose its value (Kang, 2013). The study by Kang and Suto proposed a theoretical model of ADT design, indicating the close relationship among designers, users, and artifacts. Such a relationship shows that the designer's observation of user behavior must be based on his/her behavior pattern and the physical laws applicable to the artifact he/she contacts. Thus user experience emphasizes his/her behavior of "human" and "object" or physical properties and the inseparable, interactive behavior relationship between the two.

As a result, technologies such as Ubiquitous Computing, Mobile Computing, Sensors and Actuators, Internet of Things, Ambient Intelligence (Aml), and Affective Computing have been adopted to meet the more natural and human-centric needs of interactive design. There are many interactive behaviors and patterns in human events. However, despite these proven technologies, the interaction interface or devices for the current interaction designs are still presented in a way that depends largely on existing input interfaces offered by the digital interactive products, including touch screens, keyboard and mouse, joysticks, and button control devices. Interactive behaviors are still based on the operation behavior patterns provided by such digital devices, which raises the learning threshold for operation. Therefore, this study aims to explore the possibility of maintaining intuitive behavior patterns and the most natural relationship coming from physical touch between "human" and "object" as interaction behaviors in interaction designs. Such an interaction will convey affection while providing novel applications and innovative experience offered by digital technology. "Interactive behavior is natural, but the experience of affection is novel" is the core idea of the interaction design in this study. The study aims to use a familiar artifact in daily life as the main carrier and embed technology in it and activate it, enabling it with sensitive sensing ability. With such an ability, the interaction between "human" and "objects" is thus sensed in a pattern of touch, which itself is affective and interactive. Interactions at the proper time can be provided as feedback, allowing users to experience emotional interaction. Through analysis of the author's six interaction design projects and design experiments spanning ten years, the design process and framework for emotional tactile interaction design in using a familiar artifact is proposed.

2. Research Method and Analysis

Based on the study objective, user behavior is explored through observation, whereas creativity is applied in designing the solution. With the research method called AEIOU, which is often used in user experience studies, the author validated and analyzed six interaction design projects (Lim, 2015, 2016, 2018, 2019) conducted during the period from 2010 to 2020. The six interaction design projects in this study are divided into two categories: interaction design for intergenerational care and interactive space design. The pain points, design solutions, and introductions to the technologies employed for each project are shown in Tables 1 & 2.

Table 1. Interaction design for intergenerational care.

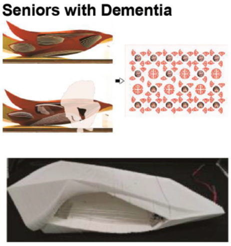
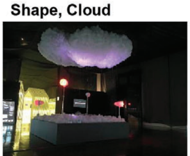
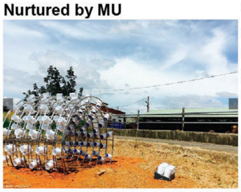
Project Name	Paint Point (P) - Solution(S)	Technology
1. **2019** **Pillow Fight** 	(P). Through observation, the author's mother in the terminal phase of cancer was found to be less and less capable of playing with grandchildren. The experiences that remained most intimate to mother were only holding a pillow sitting on the wheelchair or sitting on the bed side, watching her grandchildren playing tablet games by themselves. How can more interaction be created between these two generations in an intuitive way? (S). By combining the familiar objects dear to them, the pillow and computer games played by the grandchildren, grandparents can enjoy intimate family relationships anytime through intuitive interaction pattern (touching).	•Capacitive touch sensors design (conductive thread, fabric) •PCB design •Bluetooth BLE •App games •Digital fabrication (laser cut, 3D print) •Mass production
2. **2019** **Wonder Corner** 	(P). The living room is the space where family members spend time together most often. Is it possible for the family members to physically interact more intimately with the objects in such a space, instead of playing with a cell phone, with head down? (S). By connecting the sofa, cushions, TV, stereo, lights, and floor in the living room through IoT technology, the author built an interaction pattern that allows family members to enjoy entertainment together. Sitting on a sofa, holding a cushion, and sitting on the floor could be the inputs to the game. Lights, TV, and stereo then can be the audio and video outputs of the game. In the design, the most natural way of contact between body and object can be used to replace an electronic game's joystick or controller. The information of activities happening in the space is collected through the transmission of messages by the objects endowed with the ability to sense.	•Capacitive touch sensors design (conductive thread) •PCB design •Bluetooth BLE •MQTT (IoT) •App games •Parametric design •Digital fabrication (laser cut, 3D print)
3. **2010** **Interactive Space Design for Seniors with Dementia** 	(P). Why are the technology products for seniors only designed with focus on the function, mainly as an assistive device? Shouldn't we care about the psychological needs of the seniors whose only hope is just a little bit more company? How can we enable the children of parents with dementia to pay more attention to their parents, who keep waiting at home most of the time for children's company? (S). We designed an adaptive shoe rack and an adaptive wall in the living room. When the children return home, they can take off the shoes and put them in the adaptive shoe rack. The adaptive wall will then immediately show the pictures that include them and the parents, prompting the shared memory, and play the music that both enjoy. This will not only bring up the children's memory of their parents with dementia but also, through it, reminds them of their need for more caring.	•Arduino (IR sensors, motors, LED) •Digital fabrication (laser cut, 3D print)

Table 2. Interactive space design.

Project Name	Paint Point (P) - Solution(S)	Technology
1. **2015** **HHSS Adaptive Wall** (A soft illuminating wall that detects heartbeat)  	(P). How can we allow the physical space to reflect the heart rates of those in action in the space? How can we enable the space to visualize the physiological information of those who are experiencing such space through dynamic feedback from the structure? How can we allow the space to feel people's heartbeats? (S). We designed a two-meter-long tunnel in which the spatial structure pulses mechanically in a rhythm following the heart rates of the people who act in it. By illuminating a piece of soft cloth, the skin layer of such a spatial structure reacts with feedback to such a rhythmic pulse. Those who experience must put on headphones first when entering the entry and listen to their favorite music. They then enter the tunnel to experience the visualization of their heart rates. The soft illuminating cloth also changes its color and presentation following a change in the rhythmic pulse. The design receives the heart rates of the visitors most naturally with a receiver hidden in the headphone. The heart rate is then transmitted via Bluetooth connection to the control end of the spatial structure, allowing the motor on the structure to operate.	•EL fabric •Arduino (heart sensors, motors, speakers) •Bluetooth •Parametric design •Digital fabrication (laser cut)
2. **2015** **Shape, Cloud**  	(P). How to let visitors interact with, feel, and enjoy the natural elements, namely, cloud, wind, thunder, and rain, through an interactive device. (S). We designed a cloud and a fan for visitors to blow air. "Invisible wind" serves as an input whereas "visible cloud" is an output. When visitors blow air together, thunder will come from a big cloud; a muffled thunder will be heard if blowing continues; louder thunder will be heard with further blowing; and finally, it begins to rain when the maximum value is reached. Children can work with parents and have fun interactively experiencing changes in the natural phenomena.	•Arduino (sound sensors, LEDs, speakers) •Bluetooth •Parametric design •Digital fabrication (laser cut)
3. **2017** **The Mystic Land Nurtured by MU**  	(P). Following a site survey, a cattle farm was found next to the site with a flight path above it. The site was a big, open field without any obstructions; the space was bright and shiny, with distinct light and shadow. We consider how to let the visitors or children coming to feed the cattle in the farm experience simultaneously, on-site, the spatial devices that are related to cattle, hay, milk, and life. (S). The theme of the design, the Mystic Land Nurtured by MU, is conceived from observing the status quo of the site. Nearly 200 milk powder cans that author's son has drunk for five years have been used and made into a milk-bottle castle shaped like a round hay bale. Give it to author's son as a gift and tell him that this is the secret place that nurtures him. On the cap of the can, make transparent stickers with silhouettes showing the growths of the author's son in different stages of life. All the silhouettes appear on the ground under the sun. Milk powder cans and the structure are secured by the parts made with 3D printing. They sway as the wind blows from different angles. Cowbells are hidden in the milk bottles. The cowbells of the whole structure will ring when the wind is strong.	•Parametric design •Digital fabrication (laser cut, 3D print)

2.1. "PROBLEM FINDING" METHOD AND PROCESS IN EARLY PHASE OF THE DESIGN

The AEIOU method emphasizes observations in five dimensions: activity, environment, interaction, object, and user. These observations will serve as analysis factors used to understand user-relevant humans, activities, and objects in each design project. Table 3 shows the AEIOU factor analysis performed by observing pain points in the design project. From the empirical analyses of these design projects, this study concludes the pain points in the early phase of the design or "problem finding" method and process. Based on the emotional orientation, the author observed the pain points in the life event and then found the familiar pattern of interaction from human, activities, and object observed. Finally the author sorted out the familiar life object that creates a relationship with the human in these interactions. The major process is shown in Figure 1. The familiar artifacts sorted out from activities will serve as the main interactive carrier that will subsequently enter into a design solution.

Table 3. AEIOU factor analysis of each design project .

Project Name	**U**ser	**A**ctivity (paint point)	**E**nvironment	**O**bject (familiar artifact)	Interaction
1. **2019 Pillow Fight**	•Grandmother •Grandchild	Grandmother was unable to accompany her grandchild due to illness, so she could only watch her grandchild play by himself.	Living room	•Pillow •Wheelchair •Bed •Tablet	•(touch) Grandmother holding the pillow •(touch, sight) Grandmother sitting on the wheelchair and watching her grandchildren playing tablet games by themselves. •(touch) Grandmother sitting on the bed side •(touch) Grandchild playing tablet on the floor
2. **2019 Wonder Corner**	•Family members	The whole family gathered together but looking at their respective phones/tablets.	Living room	•Mobile phone •Tablet •Pillow/Cushion •Sofa •Floor •TV •Lamp	•(touch, sight) Adults sitting on the sofa and playing their mobile phones •(touch, sight) Adults sitting on the sofa, holding the cushions and all become phubbers. •(touch, sight, hear) Children sitting on the floor and playing tablet games. •(sight, hear) The TV is on and sometimes someone looks up and watches.
3. **2010 Interactive Space Design for Patients with Dementia**	•Seniors •Child	The child who goes home every day no longer cares about the elder with dementia who waits for him to come home every day.	Home	•Shoe rack •Entrance Door	•(touch) Child takes off the shoes and puts into the shoe rack •(touch, sight) Seniors with Dementia sitting and looking at the entrance door, waiting for their children come home.
4. **2015 HHSS Adaptive Wall** (A soft illuminating wall that detects hear beat)	•Visitors (All age groups)	How to make the tunnel respond to the physiological state of people who walk into the space? Can the space feel like people are alive?	Exhibition Hall	•Tunnel wall •Earmuff headphones	•(touch, hear) Wear headphones to listen to music •(touch, sight) Walk through the tunnel, and the wall will give feedback in time.
5. **2015 Shape, Cloud**	•Visitors (All age groups)	How to represent natural phenomena in a fun and interactive way. Natural phenomena related to a cloud: wind, thunder, rain.	Exhibition Hall	•Windmill •Cloud	•(touch) Blow •(hear) Thunder in the distance before the wind was blowing •(hear) The closer the thunder, the louder •(sight, listening) raining
6. **2017 The Mystic Land Nurtured by MU**	•Visitors (All age groups)	How to present the birth of life next to the cattle farm?	Outdoor exhibition	•Milk powder can •Bells	•(hear) The sound of bells in the farm • (hear) The sound of wind blowing •(sight) strong sunlight

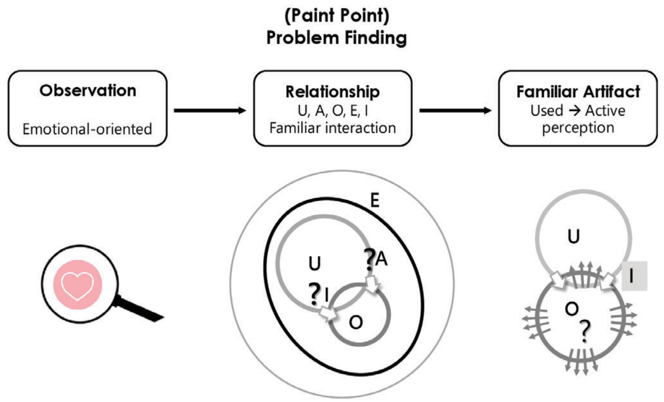


Figure 1. The "problem finding" method and process in the early phase of the design.

2.2. "PROBLEM SOLVING" METHOD AND PROCESS IN THE DESIGN PROCESS

The findings and phenomenon based on the observations from AEIOU in the previous phase will be applied effectively in the design process as operating elements for the creative concept. The relationship between Users and Objects, i.e., Interaction, concluded from the "Problem Finding" stage in the early phase of design will continue to serve as a familiar interaction pattern for the design concept. The identified object, especially the familiar artifact in life, then serves as the author's major design carrier or interaction interface in each design project. These familiar artifacts will be redefined for their roles in the design process. Their roles will change from the original status of passive usage to activated objects with active perceiving ability by using ubiquitous computing or the method of how the sensing technology is hidden.

Figure 2 (a, b, c, d, e, f) shows how to make a familiar object the interaction carrier in each interaction design project and how to maintain the object's familiar interactive behavior and pattern designated by the design concept. Because this phase includes the implementation and modification process from abstract concept to the material object, it is, therefore, one with the major steps and processes in which the manufacturing technology and application are validated in the transformation from concept to tactile object. Most of the design projects in this study are for prototype design and development in the design process. However, "Pillow Fight" has undergone many cycles of V-validation (application validation) and has entered commercialization; it has also been mass-produced in small volumes successfully and finally sold to institutions for seniors. Based on the design process and step analyses for solving all project issues, this study has concluded a framework of method and process for "problem solving" in the design process, as shown in Figure 3.

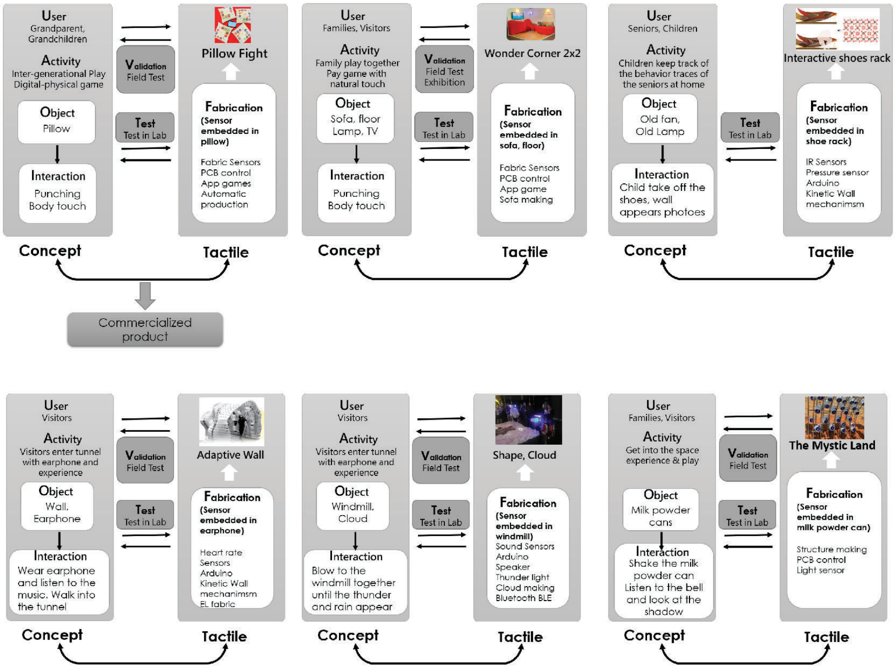


Figure 2. The process making a familiar object the interaction carrier in each interaction design project.

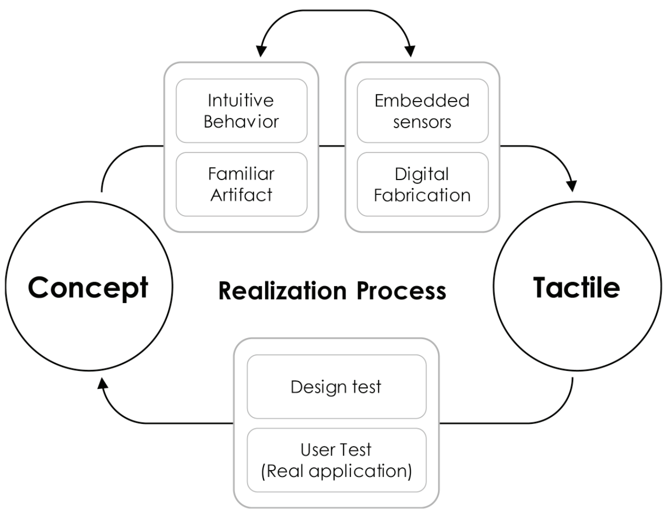


Figure 3. The “problem solving” method and process in the design process.

2.3. "PROBLEM SOLVING" METHOD AND PROCESS IN THE DESIGN RESULT

As a follow-up from the design method and process analysis for the eight design projects conducted by the author over a decade, this section will explore the interaction solving and its interaction characteristics sought for the familiar artifact in each project's design result, as shown in Table 4. There are five analysis factors: Familiar Artifact, Activated, Method, Intuitive behavior and new experience.

Table 4. Interaction solving and its interaction characteristics sought for familiar artifacts.

Project Name	Familiar Artifact	Activated Perception	Method	Intuitive behavior	New experience
1. **2019 Pillow Fight**	•Pillow	Sense by users' punching and touching	Make the original material of the object into sensor cotton + conductive thread (Developed and manufactured sensing element. The sensing layer is hidden in the cotton, then sewn into a pillow core.)	Punch pillow Touch pillow	**Intergenerational care, parent-child entertainment** Play games with mobile App
2. **2019 Wonder Corner**	•Sofa •Floor •Lamp	Sense by users' punching and touching	Make the original material of the object into sensor Original sofa fabric+ conductive fiber (Developed and manufactured sensing element. The sensing layer is hidden in the cotton, then sewn into a sofa cover.)	Touch sofa Touch floor	**Parent-child entertainment** Play games with mobile App
3. **2010 Interactive Space Design for Patients with Dementia**	•Shoes rack	Can sense children coming back home	**Redesigned** shoe rack combined with interactive control. To combine sensing and control, redesigned a new shoe cabinet (made into a sensor element and dynamic mechanism hidden in the shoe cabinet) At the same time, the interactive wall is also designed to present a photo.	Changing shoes when children go back home.	**Intergenerational care** Combined with interactive sensor to remind children to care for their demented elders when they come back home.
4. **2015 HHSS Adaptive Wall** (A soft illuminating wall that detects heartbeat)	•Headphone •Wall	Can sense the heartbeat of visitors who listen to music with headphones in the space	**Redesign** space structure combined with interactive control To combine sensing and control, the tunnel of a free-form wooden structure similar to blood vessels was redesigned. (Sensor and dynamic mechanisms were made to be hidden in space.)	listening to music with headphone while walking through the tunnel.	**Physiological Information Visualization** Combined with dynamic soft wall dynamic changes
5. **2015 Shape, Cloud**	•Wind mill •Cloud	Can sense the volume of the air that visitors blow out	**Reproduce** cloud shape structure and combine with interactive control. To combine the sensing and control, natural phenomenon, thunder, lightning were reproduced by the feedback of LED and sound control.	parents and children work together to blow at the windmill.	**Parent-child entertainment** Natural phenomenon reproduction, combined with natural action entertainment experience
6. **2017 The Mystic Land Nurtured by MU**	•Milk powder cans •Bells	Can sense the touch and shock by visitors or wind	**Redesign** space structure and combined with interactive control. To combine the sensing and control, sensors embedded and hidden in the milk powder cans.	Chidren hiding into the space and playing with the cans by shaking, listen to the bell ring.	**Parent-child entertainment** Natural phenomenon reproduction, combined with natural action entertainment experience

3. RESEARCH RESULTS

Based on the analysis shown in Table 4, this study completes a design process that starts from the observation AEIOU method and focuses on intuitive interaction behavior design by activating familiar objects in daily life to become input sensor devices. Through analysis of the six design projects completed by the author during the last decade, certain characteristics and methods can be identified as follows (Figure 4):

1. "Hidden technology " appears in interactive behavior and persists in maintaining original intuitive behavior patterns.

2. Three methods of how "Perceiving Object" activates original object into one with perceiving functions:

- M1: Use raw material and make a component into one with a sensing function
- M2: Combine original object with interactive controls
- M3: Redesign show rack by combining interactive controls

The comparison of these three methods is shown in Table 5:

Table 5. The comparison of three methods of activated original object to become the sensors.

Method	Fabrication Time	Making Difficulty	Familiar to Users
M1	Long	High	High
M2	Middle	Middle	Middle
M3	Short	Middle	Low

3. The feedback mechanism is based on visual and auditory senses. Feedback mechanism and actuation object for the intergenerational caring design process: APP provided to the younger generation, dynamic (original object changing from passive dynamic to active variation). The feedback mechanism of the interactive space design project is based on visual and auditory senses.

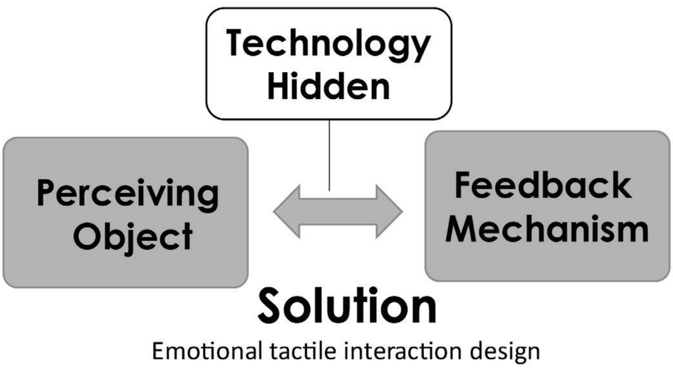


Figure 4. "Solution" Emotional tactile interaction design process.

References

App, B., McIntosh, D.N., Reed, C.L. and Hertenstein, M.J.: 2011, Nonverbal channel use in communication of emotion: how may depend on why, *Emotion*, **11**, 603–17.

Burleson, M. H., Trevathan, W. R. and Todd, M.: 2007, In the mood for love, or vice versa? Understanding the relations among physical affection, sexual activity, mood, and stress in the daily lives of mid-aged women, *Archives of Sexual Behavior*, **36**, 357–368.

Chang, Y.L., Lim, C.K., Chou, C.M., Huang, H., Sun, T.L. and Liu, I. C.: 2019, Using facial emotion recognition to observe the emotional changes of the elderly playing the pillow type device., *The 20th Asia Pacific Industrial Engineering and Management Systems (APIEMS 2019).*, Kanazawa City, Japan..

Field,, T.: 2010, Touch for socioemotional and physical well-being: a review., *Dev. Rev*, **30**, 367–83.

Guthier, B., Dörner, R., Martinez, H.P. and Zweig, K. 2016, Affective Computing in Games. Entertainment Computing and Serious Games, *in* R. Dörner, S. Göbel, R.M. Kickmeier and M. Masuch (eds.), *Lecture Notes in Computer Science*, Springer, Cham..

Huang, H., Lim, C.K., Sun, T.L., Chou, C.M. and Liu, I. C.: 2019, Evaluation of Elderly Gaming Devices Using OpenPose, *The 4th International Conference on Ambient Intelligence & Ergonomics in Asia (AmI&E 2019*, Taoyuan, Taiwan.

Kang, N. and Suto, H. 2013, How to Observe, Share and Apply in Design Process?, *in* A. Marcus (ed.), *Design, User Experience, and Usability. Design Philosophy, Methods, and Tools. DUXU 2013. Lecture Notes in Computer Science*, Springer, Berlin, Heidelberg..

Lim, C.K.: 2016, Memory of Things (MoT) Interactive memory product design. (Best Demo Award), *2nd International Conference on Digital Fabrication*, Tokyo.

Lim, C.K.: 2019a, “Pillow Fight” Board Game Design, *21 st International Conference on Human-Computer Interaction.*, Orlando, Florida, USA..

Lim, C.K.: 2019b, Pillow Fight: Application of Conductive fabric technology in activities for dementia, *Physical Ergonomics and Human Factor.The 10th International Conference on Applied Human Factors and Ergonomics (AHFE 2019)*, Washington D.C. USA..

Morrison, I., Löken, L. and Olausson, H.: 2010, The skin as a social organ, *Exp. Brain Res.*, **204**, 305–14.

Van, E.J.B.F. and Toet, A.: 2013, How to touch humans: guidelines for social agents and robots that can touch, *Humaine Association Conference on Affective Computing and Intelligent Interaction*, Geneva, 780–785.

Van, E.J.B.F. and Toet, A.: 2015, Social touch in human-computer interaction, *Front. Digit. Humanit.*, **2**, 1–14.

THE METHOD OF RESPONSIVE SHAPE DESIGN BASED ON REAL-TIME INTERACTION PROCESS

ZHE GUO[1], CE LI[2] and YIFAN ZHOU[3]
[1]*Hefei University of Technology*
[1]*guogal@hotmail.com*
[2]*Wuhan University*
[2]*26650299@qq.com*
[3]*University of Hawaii at Manoa/Tongji University*
[3]*yifanz@hawaii.edu*

Abstract. This project focuses on how real-time motion interaction caused by people could put potential drivers for parametric design innovation, which would enhance the link between form trigger and result. Begin with discussing of background in interactive digital design, this article starts from three aspects in turn. First, the shape generating method based on a mesh geometric data format is discussed, which is the precondition of this research. Then, several kinds of behavior interaction are selected to be the input data which directly or indirectly trigger and affect this responsive shape formation process mentioned in the former part. In the last part, this research will summarize and propose a complete set of interactive behavior-oriented responsive digital prototyping design and propose several corresponding application scenarios.

Keywords. Mesh algorithm; actuated interaction design; generative design.

1. Introduction

After years of accumulation of parametric design methods and digital manufacturing technology in the field of computer-aided architecture, interior and industrial design, a kind of consensus has been established, which makes these digital processes more intelligent and intuitive for designers and users.

In the past few decades, there have been a series of groundbreaking steps in developing interactive research by various research groups. Most of these attempts share a common goal in creating human-inspired shape morph methods. Tongji digital research group has established a set of complete system, which could convert human voice characters into a digital complex pattern that could be generated and displayed in real-time (Zhao, 2019). Expending plane to space, some research focused on looking at the interface between remote sensing and a responsive environment to explore the possibility of an interactive architecture that conditions and responds to the user's movements (Farahi, 2013), this method has not only been applied in architecture installation but also showed this deeply

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 345-354.

formation potential in body wearable architecture (Farahi, 2016). In the process of interaction with shapes, how can human behavior characteristics be captured and translated into triggers to control the morph of shapes is the key factor discussed in Fox's research (Fox, 2012).

It not hard to see the enthusiasm of designers to build an intelligent response deformation system by constructing the digital chain which makes it possible for designers and users to put intervene caused by human behavior into every phase of the digital design process to influence the direction of the results. The small difference of various individual behavior will lead to the richness of information reflected, which is exactly the charm of interaction design because it changes the stereotyped shape rule and endows the design result with uniqueness. As Behnaz Farahi states, "the main attempt in such a work, is to engage with geometries and shapes in order to understand dynamic material behaviors in relation to the specific human body", this project attempts to explore a method that is able to link complex shape generation and simple movement by converting human gestures into morph trigger. In this whole process, the role of designers will be changed from making a specific shape to formulating generating rules, meanwhile, users will participate in design decision making by intentional or unconscious behaviors, which is able to place more modality possibilities in it.

2. Methods of shape generation and interaction mode

2.1. RESEARCH ON SHAPE GENERATING RULES

2.1.1. Base mesh geometry attribute

In 3D computer graphics and solid modeling, a polygon mesh is a collection of vertices, edges, and faces that defines the shape of a polyhedral object. Mesh geometry has a high degree of freedom and simplicity in the expression of complex geometric form operation with concise geometric definition and data storage format. The faces usually consist of triangles (triangle mesh), quadrilaterals (quads), or other simple convex polygons (n-gons). Meshes are used for rendering to a computer screen and for physical simulation which is the best choice as the complex geometry manipulation in this research. Among types of mesh format, the face-vertex mesh is selected in this research that represent an object as a set of faces and a set of vertices, the order of vertices determines the direction of the mesh normal. This is the most widely used mesh representation, being the input typically accepted by the modern graphics hardware. The mesh consist of quads, according to the closeness of its edge can It can be classified into two categories, cube mesh, and grid mesh, which attribute showed in fig.1. These two meshes types are used as the base mesh geometry in our research.

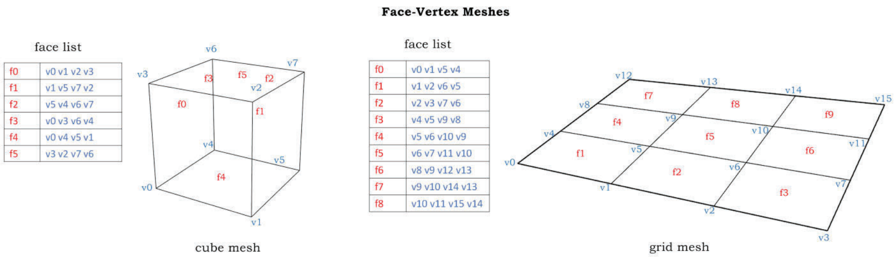


Figure 1. Face-Vertex Mesh definition format.

2.1.2. Mesh generation

One simplest quad mesh defined by four spatial vertices spatial coordinates and the order of vertices that defined as Face. The basic rule of shape forming in our research is based on the operation of mesh vertex. By moving certain vertices into a new spatial position and keeping the original vertex order in every face, the original mesh can realize topology deformation under unified rules. In the process of vertices movement, a mesh subdivision algorithm called Catmull-Clark is used to generate mesh detail and to make the whole shape successive. This subdivision algorithm can subdivide polygons with arbitrary topology is a technology used in 3D computer graphics, which creates smooth surface by subdivision surface modeling method. It was designed by Edwin Catmull and Jim Clark in 1978 as a generalization of bi-cubic uniform B-spline surface to arbitrary topology (Catmull, 1978). Starting from the mesh of any polyhedron, this is considered to be the advantage of the algorithm. The new polygon surface created in In every subdivision operation can be applied with the same subdivision rules, which are recursively defined by using the following refinement scheme. To start with the whole subdivision operation by taking a simple quads mesh as example, we defined all vertices, edges and face in the mesh separately as origin vertex, origin edges and origin face:

- For an origin face with vertices V1, V2, V3 and V4, added as a new “face point” Vf as follow:

$$Vf = \frac{V1 + V2 + V3 + V4}{4} \tag{1}$$

- For an origin edge, suppose that the two vertices of Ve on one side are v and w, and the two adjacent faces are F1 and F2 (the vertex of the face has been calculated as Vf1 and vf2 in former step). So the new “edge point” Ve corresponding to this edge is:

$$Ve = \frac{v + w + Vf1 + Vf2}{4} \tag{2}$$

- For an origin vertex V, suppose Q is the average value of the face point Vf of the polygons adjacent to V, V is adjacent to n edges, and R is the average value of the midpoint of the edges adjacent to V, then the new "vertex point" V0 after adjustment is:

$$V0 = \frac{Q}{n} + 2 \cdot \frac{R}{n} + (n-3) \cdot \frac{V}{n} \tag{3}$$

- How to generate edges after getting new vertices is the next important step. We follow next two rules: Firstly, each face point Vf is connected to the edge point Ve corresponding to the edge surrounding it to create new edges. After each vertex is adjusted, the new vertex point V 'is connected with the edge point Ve on its adjacent edge to create the other edges.

After a thorough study of this mesh generation algorithm, one conclusion can be drawn that the way these three basic vertices (face point, edge point, and vertex point) move will decide the whole mesh shape. In other words, by putting more rules to Catmull-Clark generation algorithm shows in Figure 2, via one unique or several functions to influence weights value determined face point and vertex point movement (edge point is defined by face point, so these two change will have internal correlation), abundant morph can be produced in these process.

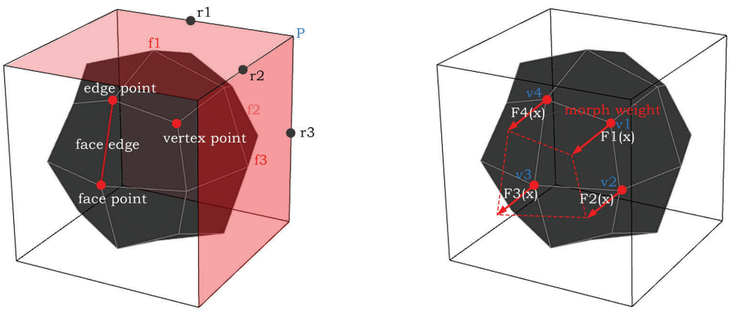


Figure 2. additional rules to Catmull-Clark algorithm.

2.1.3. Shape morph rules

In the cube mesh manipulation process, several different methods for calculating the point position transformation are established, which are expressed as the expression F(). The amplitude of vertex extrusion, the degree of smoothing, and the uniformity of disturbance are defined respectively as function Fa(), Fs(), and Fd(). Based on the traditional Catmull-Clark algorithm, the newly generated vertices after each iteration operation will participate in the next manipulation operation. Due to the certainty of the morph rules, this shape operation method can produce similar deformation results of the whole through subdivision logic. By change every weight function, various mesh shapes have the same topological configuration can be designed efficiently.

From the original cube mesh as the initial state of shape operation, each iteration will generate outward vertices by changing points spatial coordinate and add these new points to the mesh vertex set. Where the weight of the moving amplitude is controlled by the function Fa(). Parameter h determines the degree of vertex deviation as shown in Figure 3.

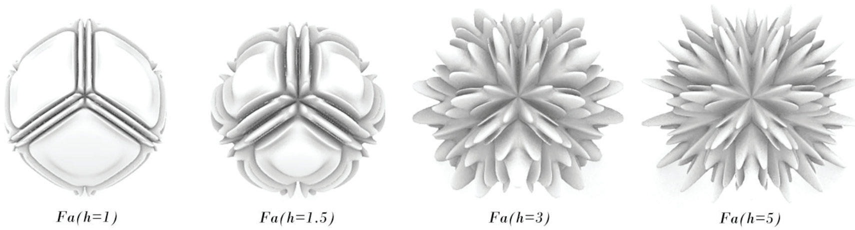


Figure 3. Fa() function define the weight of face extrude amplitude.

In one complete iteration, after the process that a new mesh face is formed by ordering the vertices as the original mesh order, the Catmull-Clark subdivision algorithm will run once to make every edge smooth(shown in Figure 4). During this step, the other two functions are applied to control subdivision weight in order to create more small bump detail onto the mesh surface. In the original Catmull-Clark algorithm, the new face points, edge points, and vertex points are generated according to the established moving rules in the subdivision process. While in our study, another additional function Fs() (like Fa() function) is added to control the displacement weights of the three points belong to a mesh. When the definition of the movement attributes of these three types of points is reorganized, it has more detail tension than the formal results of subdivision algorithm without additional function interference. As shown in Figure 5, when the face point, edge point, and vertex point are operated respectively using the same function and parameter, the results of subdivision form shows great difference. By combining different interference weight values, various forms of shape morph results can be generated which shows that this redefined algorithm has great derivative potential.

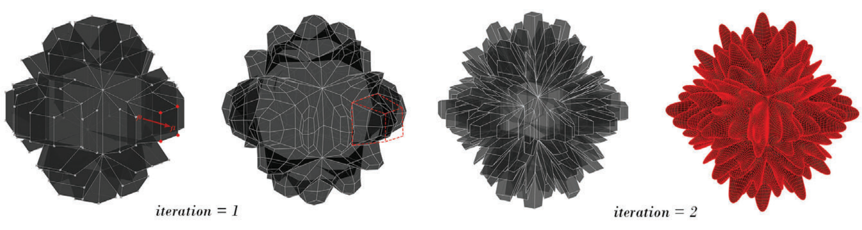


Figure 4. redefine Catmull-Clark algorithm by changing morph weight.

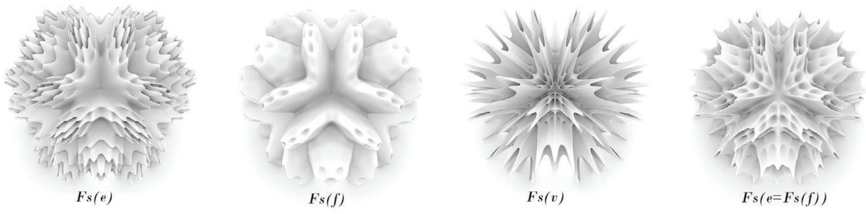


Figure 5. degree of smoothing, e means edge point, f means face point, v means vertex point.

Farther more, one more function can be added in the process we named as Fd() means uniformity of disturbance on the whole mesh. This function determines whether the vertices belonging to the mesh face should be extruded by setting the judgment conditions for the mesh face (Figure 6). Meanwhile, the Fs() function could be applied to subdivide the surface disturbance.

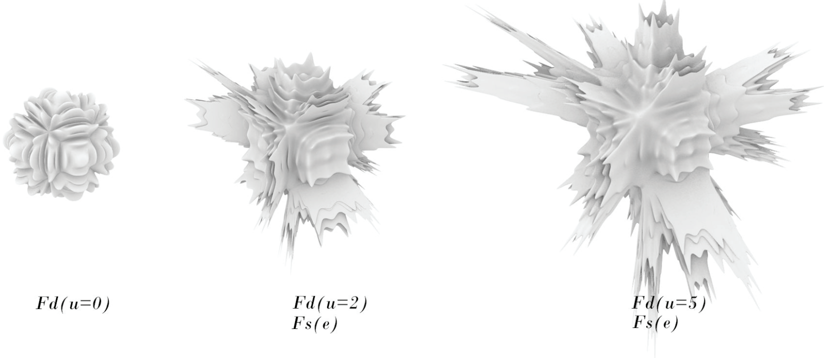


Figure 6. the uniformity of morph disturbance.

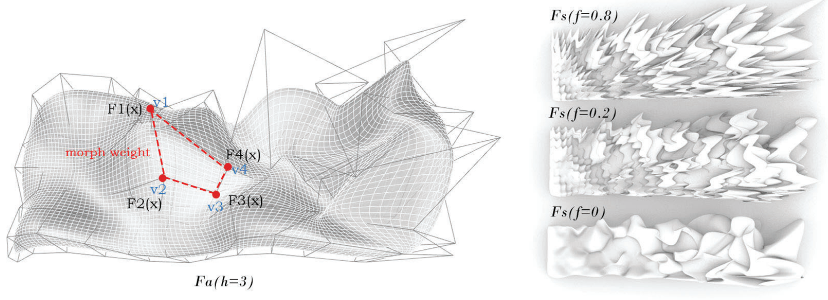


Figure 7. grid mesh basic morph manipulation define by Fa() and Fs().

These morph weight functions we build and apply here is be supposed to link with specific movement data collected and remapped by some kind of human behavior detecting equipment, which will be detailed in the next chapter. Consider the form operation of grid mesh, the morph rules similar to cube mesh are applied. From the original grid mesh as the initial state of shape operation, only the first iteration will generate outward vertices by changing points spatial coordinate randomly and add these new points to the mesh vertex set. Where the weight of the moving amplitude is controlled by a set of Berlin noises the function is defined as Fa(). Parameter h determines the degree of vertex deviation as shown in Figure 7. The higher the value of h, the greater the extrusion range.

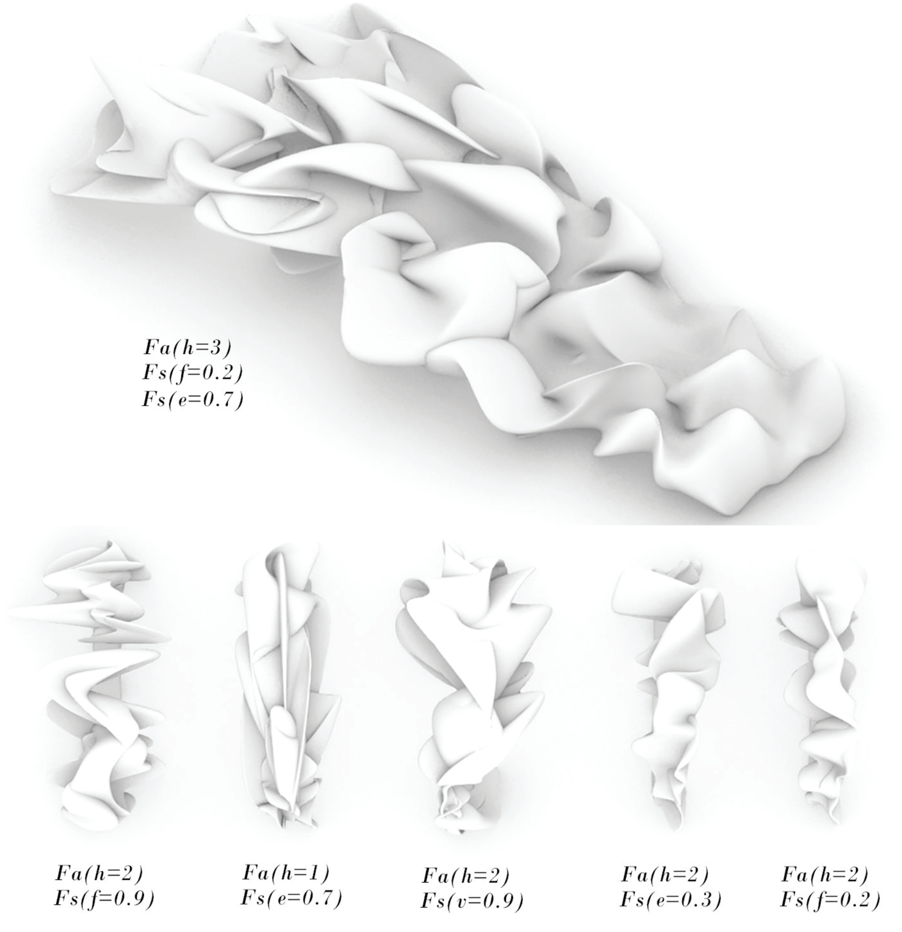


Figure 8. shape morph results using combined weight functions.

In the following subdivision iteration process, adding the weight function of each face point movement in the process of smoothing the mesh can form the subtle surface bump details showed in Figure 7. The value here represents the extent of turbulence. 0 value means no move for face point while 0.8 means the ratio of the vertex movement distance to the average extrusion value of the four vertexes touching the face. Via applying composite interference weight functions, we created some experimental shape morph which intuitively shows the difference formal beauty compared with the operation of cube mesh although the same morph rules applied in this process. The form results are shown in Figure 8.

2.2. INTERACTION DESIGN PROCESS

2.2.1. Workflow

In this research, a complete workflow for the part of interaction design is built as Figure 9 shows. By using behavior sensing equipment, such as leap motion or Kinect, a set of behavior characteristic data can be transformed into a series of spatial coordinate in real-time, which is supposed to be translated into the conditions that trigger the mesh shape generation through the mapping algorithm. In the last parts of how we can display this whole process, the VR and AR technique could be the first choice in follow up with further research to make this interactive design process more real and intense.

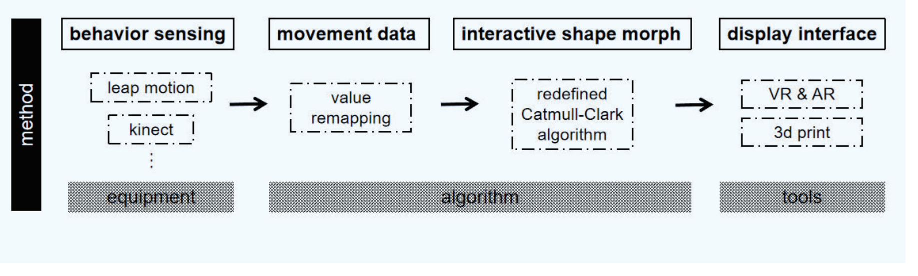


Figure 9. interaction design process.

2.2.2. Data remapping rules

In order to develop a responsive relationship with the user, these shape design systems need to be able to sense the behavior of the user by employing gesture sensors or infrared motion capture technologies in order to detect physiological responses such as range of limb movement. Ultimately, these shape design systems should be capable of using their dynamic morph to ‘elicit’ certain movement responses in the user. In this way, the interaction method turns one-way mode into two-way and will display more potential relationship between explicit shape result and implicit movement process.

Take the interaction design of the leap motion gesture capture device as an example: The leap motion device can output the spatial point coordinates of all finger joints of each hand, a total of 20. These data can be used to approximate the types of hand movements. Four gesture statements are defined showed in Figure 10, which are two fingers(two points), one finger(point), palm, and fist. In the process of hand movement, the certain position of these parts of hands will be updated in real-time, and the movement distance can be obtained by calculating the coordinates with the previous hand state. Through data mapping, the distance of the displacement is translated into the input value of those shape morph weight function, which can result in mesh generation and transformation.

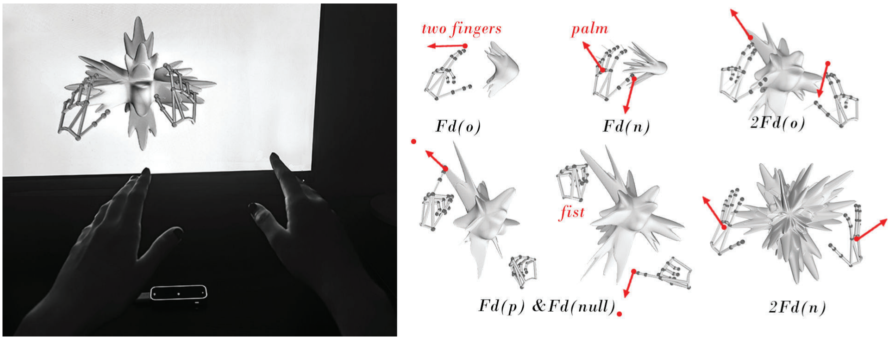


Figure 10. finger motion capture and data mapping into shape morph function.

Furthermore, a new gesture feature, the speed of palm movement could be defined and its data could also be linked to the function Fs() to realize detailed subdivision generation of mesh surface disturbance by quickly waving the palm (Figure 11). In a larger scale of behavior sensing, whole-body infrared motion capture devices such as Kinect will reflect its important value. Using the same data mapping method as hand motion capture we studied in this research, the motion data of body joints also can be translated into the input data of mesh morph function.

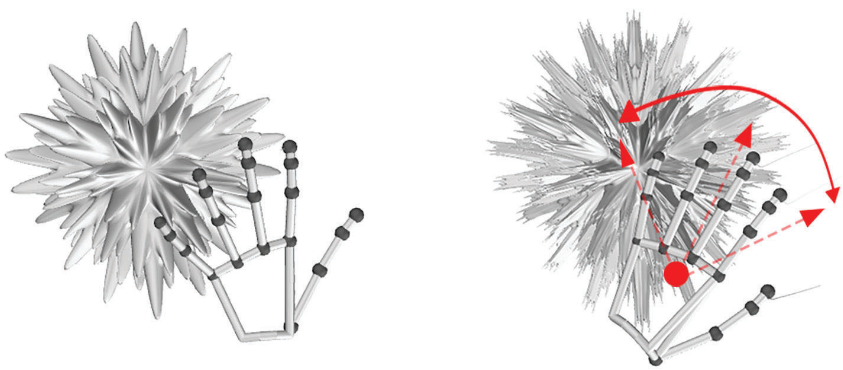


Figure 11. interactive action influences the generation details.

3. Conclusion

This research starts from mesh shape generation design, by decomposing and rewriting the iterative subdivision algorithm, we can formulate the external rules of the specific shape generation and transformation, and the preset data input terminal. The responsive form design method established in this project is completed by a computer algorithm, which will improve the speed, richness, and completion of the customized shape design process. The data input by different hardware can control the final modeling form, so this interactive design method established in our study has a very wide range of application expansibility. This kind of interactive design provides a low threshold and high richness for both designer and user in the digital design process through a way of natural participation. The practical value of this method is reflected in its reasonable combination with a variety of application scenarios and contents and has great market potential in digital art, cultural and creative design, and interactive experience.

References

Catmull, E. and Clark, J.: 1978, Recursively generated B-spline surfaces on arbitrary topological meshes., *Computer-aided design*, **10.6**, 350-355.

Farahi, B. B.: 2016, Caress of the gaze: A gaze actuated 3D printed body architecture, *ACADIA*.

Farahi, B. B., Leach, N. and Huang, A.: 2013, Alloplastic architecture: The design of an interactive tensegrity structure, *ACADIA*.

Fox, M. and Polancic, A.: 2012, Conventions of Control: A Catalog of Gestures for Remotely Interacting With Dynamic Architectural Space, *ACADIA*, **Synthetic Digital Ecologies**, 428-438.

Poppe, R.: 2007, Vision-based human motion analysis: an overview, *Computer Vision and Image Understanding*, **108(1–2)**, 4–18.

Roupé, M., Johansson, M. and Tallgren, M. V.: 2012, Using the human body as an interactive interface for navigation in VR models, *caadria*.

Sunesson, K.: 2008, Virtual reality as a new tool in the city planning process, Tsinghua, *Science and Technology*, **13(S1)**, 255–260.

Zhao, Y., zhu, W. and Yuan, P. F.: 2019, From Acoustic Data Perception to Visualization Design, *CAADRIA*, New Zealand.

BEAUTY IS IN THE EYE OF THE BEHOLDER

Improving the Human-Computer Interface within VRAD by the active and two-way employment of our visual senses

CAMERON WELLS[1], MARC AUREL SCHNABEL[2], TANE MOLETA[3] and ANDRE BROWN[4]
[1,2,3,4] *Victoria University of Wellington*
[1] *wellscam@gmail.com* [2,3,4] *{MarcAurel.Schnabel|Tane.Moleta|Andre.Brown}@vuw.ac.nz*

Abstract. Whether it is via traditional methods with pen and paper or contemporary techniques such as 3D digital modelling and VR drawing, the eye typically plays a mostly passive or consuming role within the design process. By incorporating eye-tracking deeper within these methods, we can begin to discern this technology's possibilities as a method that encompasses the visual experience as an active input. Our research, however, developed the Eye-Tracking Voxel Environment Sculptor (EVES) that incorporates eye-tracking as there design actor. Through EVES we can extend eye-tracking as an active design medium. The eye-tracking data garnered from the designer within EVES is directly utilised as an input within a modelling environment to manipulate and sculpt voxels. In addition to modelling input, eye-tracking is also explored in its usability in the Virtual Reality User Interface. Eye-tracking is implemented within EVES to this extent to test the limits and possibilities of eye-tracking and the Human-Computer Interface within the realm of Virtual Reality Aided Design.

Keywords. Human-Computer Interface (HCI); Eye-Tracking; Virtual Reality; modelling; sketching.

1. Introduction

Eye-tracking within the realm of art, architecture, and the broader context of design has typically taken the passive or investigative approach to implementation within the design process. Studies that objectively analyse how we as humans perceive various types of information and how we build assessments of our surroundings (Lisińska-Kuśnierz and Krupa 2020) discuss the traditional implementation of eye-tracking. However, little has been investigated in the domain of using eye-tracking technology and three-dimensional space concerning eye-tracking technology as an active implementation. Through the development of the design tool, the *Eye-Tracking Voxel Environment Sculptor* (EVES) will explore these ideas.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 355-364.

To begin using active eye-tracking within architectural space, Virtual Reality (VR) is deeply rooted within the core of our research. As noted by Carreiro and Pinto, through VR, the visual representation of architecture can have more robust understandings of virtual spaces (2013). Therefore, by combining these technologies, we can begin to improve and extend the Human-Computer Interface (HCI) within Virtual Reality Aided Design, or VRAD as presented by Donath and Regenbrecht (1995).

1.1. EYE-TRACKING VOXEL ENVIRONMENT SCULPTER (EVES)

Our investigation into the implementations of eye-tracking within VR environments began initially with the generation of 'gaze heatmaps', sitting firmly *within* the design process. By analysing where, when, and what a person is looking at within any particular environment, a designer can make design decisions accordingly. To continue to push eye-tracking to its limits, the development of EVES began to display eye-trackings potential to act as the design process.

EVES is a VR design tool that utilises eye-tracking as the input for a voxel-based modelling environment. The voxels allow for ease of sculpting and simplify the use of EVES as much as possible to allow users to learn how to use it quickly. Implementation of eye-tracking has been utilised within EVES as much as possible to understand its capabilities. In addition to the modelling input being controlled by the users‘ gaze, so is tool/brush selection and User Interface (UI) navigation. In general, bar some other features such as slight head and hand movements, EVES is controlled primarily via the users' gaze data (Figure 1).

Figure 1. Using EVES with HTC's Vive Pro Eye.

1.2. PRECEDENTS

The development of EVES can be broken down into two parts. The active use of eye-tracking and EVES's essence as a VR Design Tool. As such, these categories form the outline for which EVES takes a reference. The first part focuses more so on artists and their works which have experimented with Active Eye-Tracking before. In contrast, the VR Design Tools section explores existing instruments that share HCI traits and other operational similarities to EVES.

1.2.1. Active Eye-Tracking

In *"Active Vision: Controlling Sound with Eye Movement"*, Andrea Polli explores the use of active eye-tracking within music and notes on her ability to "control her eye in a very precise way to create specific sounds" (1999). She exemplifies humans' ability to utilise their eyes in a non-consummatory manner (despite the differences between auditory and visual art) by shifting the traditional method of melodic input from mouth and hand to that of the gaze. Behnaz Farahi explores the usage of this idea of active vision through her project Caress of the Gaze, whereby eye-tracking is implemented to manipulate a garment worn by a person whenever an observer looks at it (2016).

In the realm of drawing, artists Graham Fink and Sarah Ezekiel have both utilised eye-tracking as a direct method of input onto a digital canvas. While Fink explores the medium as an opportunity for 'purer' artistic expression directly from the subconscious to the canvas (Leander 2015), Ezekiel's exploration comes from that of necessity. Ezekiel is diagnosed with ALS (otherwise known as Motor Neuron Disease), which severely inhibits her ability to use her arms and body (Page 2020). While these technologies allow for increased interaction between human and computer, they also open gateways for those disadvantaged with disabilities.

1.2.2. Virtual Reality Aided Design (VRAD) Tools

The concepts behind VRAD and their supporting technologies greatly influence the field of architecture, design, and construction (Schnabel, 2009). Early VR programs like *HoloSketch* and *DDDoolz* have explored the usability of design tools through many different facets, such as HCI and modelling input. More recent examples like those of *SculptVR, Tilt Brush* and *Gravity Sketch* also explore a varying degree of different means of modelling and designing within virtual environments.

HoloSketch, while not utilising a Head-Mounted Display (HMD) like more modern examples of VR, explores the ability to interact and design with virtual 3D objects in front of a user. Through the use of a 'wand', these forms are visualised on a screen (Deering, 1995). *DDDoolz,* while similarly limited in comparison to modern VR technology, also investigated the applicability of VR within early design stages through the use of voxel-like massings (Achten, et al, 2000). Concerning more modern implementations of VR design tools, *SculptVR* takes a similar approach to modelling as DDDoolz with its integration of voxel and marching cubes. Other recent VR programs have different techniques such as *Tilt Brush's* planar stroke-based modelling and *Gravity Sketch's* NURBS-based modelling (Arnowitz et al. 2017).

1.3. DEVELOPMENT ENVIRONMENT

Through EVES development, two leading eye-tracking hardware were used, the *Tobii Eye-Tracker 4C* and *HTC's Vive Pro Eye.* The Tobii Eye-Tracker 4C is a monitor-mounted bar eye-tracker that gathers the users gaze data as they look at the screen. HTC's Vive Pro Eye, on the other hand, is an entirely in-built eye-tracker within the VR HMD. All things software has been developed within the *Unity3D* game engine.

2. Eye-Tracking 'Within' the Design Process (Passive)

This section of the research covers a brief explanation of developing a program that investigates the passive usage of eye-tracking within the design process. While not intrinsically related to EVES development, it is still a necessary step in the exploration of eye-tracking within VRAD.

2.1. EYE-TRACKING VIA VOXEL HEATMAP GENERATION

The intermediary program that was developed in this first stage of the research consists of two phases: i) the Recording Phase and ii) the Analysis Phase.

The Recording Phase involves a user or client to experiencing a space or environment within VR. During this time, the program gathers and stores their visual experience within an Octree data-structure. Almost everything is recorded, from where, when what and when, to how long a user looks at objects within the environment. The Analysis Phase then utilises this data recorded within the Recording Phase to generate a 3-dimensional voxel heatmap of the users' visual experience (Figure 2). In this phase, the user or designer can freely move around the environment to analyse the generated heatmap. Information about where and how long a user has looked at particular places is visualised as the heatmap. Information such as what is being looked at (along with other specifics) is displayed by hovering over individual voxels.

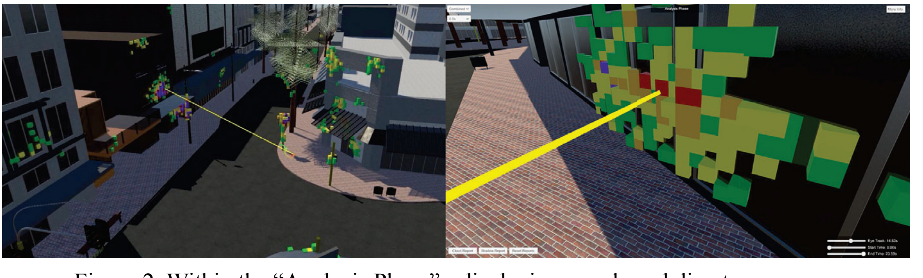


Figure 2. Within the "Analysis Phase" - displaying voxels and direct gaze rays.

3. Eye-Tracking 'As' the Design Process (Active)

This section of the research covers the development of EVES, which investigates the active usage of eye-tracking through VRAD. In this section, in-depth explanations of the operation and workings of EVES will be discussed and fleshed out.

3.1. VOXEL SCULPTING

At its core, EVES is essentially a voxel modelling tool that is controlled by the eye within VR. Voxels offer the opportunity for a user to sculpt as they might clay with their hands. This method allows for rough means of input without the user's overwhelming need to make precise modifications to their models. Further, despite their simplicity, voxels are capable of creating complex wholes due to their modular nature. Voxels can be generated and erased as well as modified via colour (Figure 3)

Figure 3. Voxels in EVES.

Other sculpting methods within the digital realm were also considered, such as marching cubes. Although marching cubes essentially work in the same way as voxels and boast smoother forms, it often requires a certain amount of precision from the user. This precision is needed when sculpting results in small meshes that would be problematic to manipulate and often make modelling difficult and tedious (Figure 4).

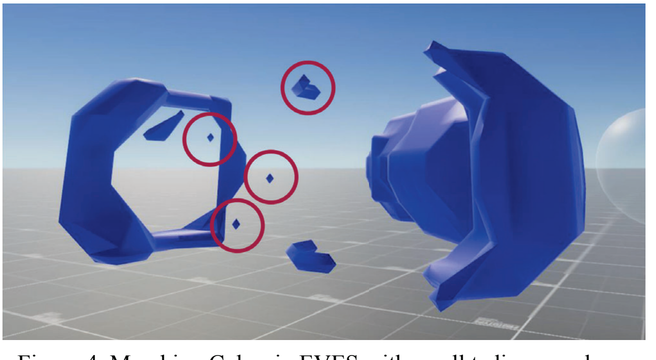


Figure 4. Marching Cubes in EVES with small tedious meshes.

3.2. METHODS OF INPUT

3.2.1. Active Eye-Tracking and HCI

EVES utilises eye-tracking in a very similar way to how both Fink and Ezekiel draw with their eyes, albeit rather than on a 2-dimensional canvas, we present it within a VR environment. Within EVES, a ray is projected into the VR environment. This ray is informed by the gaze data from the eye-tracking hardware and is then utilised as the input method to sculpt voxels and navigate in-program menus (Figure 5). Wherever the user looks within the environment, a guide-cursor follows to indicate where they will sculpt. The guide-cursor takes the form of whatever brush they currently have selected, and by pressing the trigger on the controller, voxels are sculpted and manipulated.

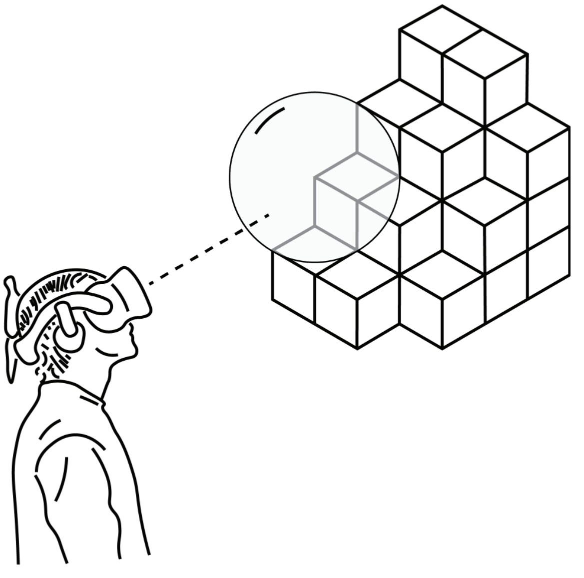


Figure 5. Eye-tracking data projected into the virtual environment to manipulated voxels.

As previously mentioned, in addition to gaze data being utilised for direct sculpting input, it is also the primary UI navigation and tool/brush selection method. In EVES, the controller is used as an anchor point for the UI. When looking at the controller, a user can focus on any icon in the menus to select it. Indicators display whether the icon is being focused on, or if it has been chosen. Interaction with the controller and the user’s hand is limited as much as possible to allow for simple operation. With the hand-controlled interaction bound to the thumb, the user controls simple values such as brush size and distance. With this operation method, the user does not have to continually look back to the UI, reducing interruptions to the primary modelling input.

3.2.2. Brushes and Tools

Brushes and tools in EVES are simply the differing ways a user's gaze generates and manipulates voxels. While brushes act as the base shapes that voxels are generated in (such as spheres and boxes (Figure 6)), tools alter how brushes act (such as single, line, and erasure (Figure 7)). Both brushes and tools allow for various uses that can be used in different ways to generate forms and environments through simple inputs. Like the Hollow variants and MorphBox, other brushes grant the ability to generate more complex spatial forms with relative ease. MorphBox specifically allows for multiple uses in and of itself. Walls, rooves, floors, windows, columns, and more can be generated via a two-point input system whereby the user defines a box's extents by selecting two opposing corners.

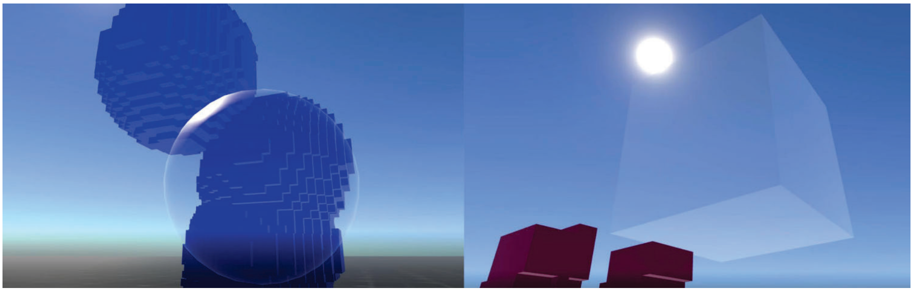


Figure 6. Sphere Brush (Left) and Box Brush (Right).

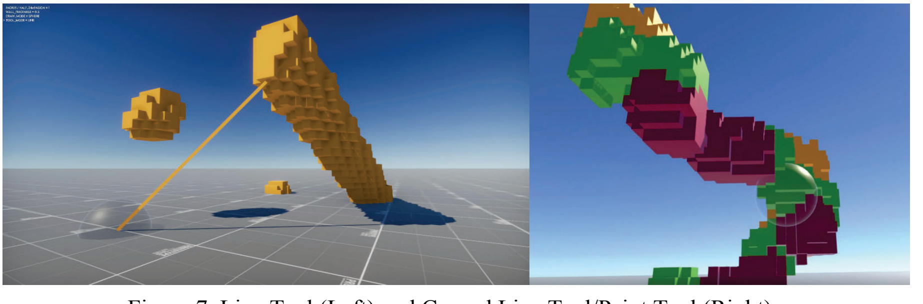


Figure 7. Line Tool (Left) and Curved Line Tool/Paint Tool (Right).

4. Outcomes

The development of EVES prompted further understanding of the potential for eye-tracking as a Human-Computer Interface within the realm of digital architecture and design. As explained, Eye-trackings usability can play different roles *within* or *as* the design process. Where Passive incorporation covers a more grounded approach, Active incorporation explores the more radical and artistic. By investigating the possibilities that eye-tracking can offer in these broader senses, we can understand how it may affect and benefit design.

4.1. THE PASSIVE ('WITHIN' DESIGN) APPROACH

When eye-tracking is incorporated in the design process as a passive method, a designer can track the visual experience of a user within any given space. By knowing what experiencers of space are visually drawn to, a designer can reliably validate and evaluate their behaviours within the architectural realm (Wang et al., 2019). This passive method enables a designer to confirm how their schemes operate and facilitate a connection between user and designer through VR and Mixed Reality (XR) tools. Not only that, but this approach highlights these visually active areas for the potential of revision or redesign if applicable.

Through the program's development in this phase, we were able to analyse points of visual interest, visual experience, and behaviours. In particular, one space that we tested took place at a city intersection of two roads - with plenty of distractions and hazards. The precedence of our visual attraction would tend to be for moving objects and colours and shapes that stood out from the rest of the scene. Cars, traffic lights, trees, and advertisements, for example, all tended to take up more visual interest than that of any architectural feature in particular. Although the scene favoured these aspects with regards to its particular setting, the passive approach highlighted these visual experiences that we had.

4.2. THE ACTIVE ('AS' DESIGN) APPROACH

When eye-tracking is incorporated in the design process as an active method, we can understand how we can use our VR/XR eyes and extend their capabilities within the virtual environment. The development of EVES investigated active eye-tracking in two ways: how the eye can influence a virtual experience via the control and navigation of the VRUI, and how vision can shape and mould the space a user inhabits.

Controlling or navigating anything with the eyes, whether it be the VRUI or the act of sculpting voxels, tends to take a bit of practice. Our bodies often run on performative or procedural movements; in other words, 'muscle memory' (Shusterman, 2011), Arguably, the act of looking and using our eyes would fall under this idea of effortless, spontaneous skill performance. However, shifting the eye's usage to that of manual control can offer a slightly steeper learning curve. For example, when inputting the two points to draw a line, one would often be looking towards the next action before completing the previous. This action would then cause the line to be generated so that we did not intend. In contrast, the VR UI operation tended to be the easiest obstacle to overcome, as it relied mostly on the user's existing muscle memory. Despite this, we found that once learning how to control our eyes, the operation of EVES became more instinctive and streamlined.

Despite the eventual ability to control EVES, there remained a relative warping of perceived space and environments when modelling. These distortions would often manifest through the shape and scale of modelled architectures. In "Vision and Touch", Rock and Harris discuss vision's influence over the sense of touch. This dominance over touch is present even if the eye is fed distorted images. Rock and Harris note on an observation by James J. Gibson whereby a subject runs their hand along a straight rod while looking through a prism. Despite the rod's linear form, the subject was said to have felt it as curved (1967). In this instance, the subject's vision overruled the touch of their hand, in contrast to reality. Tim Law et al. discuss a scalar distortion when designing VR spaces whereby subjects would often be more precise, yet less accurate. Often favouring the space to be much smaller (albeit more consistently) than it was when compared to other traditional sketching methods (2020).

In respect to EVES, vision and touch are inherently blended. Vision *is* the touch. Therefore, when considering the visual inconsistencies of designing within VR, such as those discussed by Law et al., it is not surprising that the user's perceived reality is modelled into a true-reality. EVES takes in the user's perceived shapes and scales and models them accordingly, not necessarily in a way we may consider to be accurate. Consequently, this creates the architectures and spaces that our eyes inhabit, not our bodies. The three dimensions of reality are translated into our minds as a two-dimensional plane and reinterpreted back into the third-dimension via EVES.

Through EVES's development, we have made available the possibility for a user to utilise their eyes within the virtual realm to 'consume' and extend its capabilities to 'generate' - a novel way to use one's senses. The HCI becomes more than just a person interacting with a computer and connecting and integrating with it (Schnabel and Chen 2011). It is this integration with VR technologies that, while these experiences tend to be visually focused, we can still explore what new ways people and designers can interact with the digital world (Rogers et al. 2019).

5. Conclusion

EVES at its core, is the exploration of the possibilities of eye-tracking within the virtual environment. Through passive and active means of implementation, the length and breadth of eye-tracking within a design or architectural context is investigated: first, the paper discusses eye-tracking as a tool that informs the design and is treated as being 'within' the design process; second, eye-tracking treats gaze as an extension, and therefore 'as' the design process. By extending the employment of eye-tracking, we can further the interactions between human and computer. Both the navigation of VR UI and considering vision as touch are integral to the scope of active eye-tracking. Allowing a users eye to sculpt and manipulate form directly amplifies the capabilities of what our eyes can do, beyond that of which is possible within the everyday context. Our eyes are 'touching the untouchable' (Schnabel et al. 2008) and become actors in the design generation.

References

Achten, H.H., de Vries, B. and Jessurun, J.: 2000, DDDoolz: A Virtual Reality Sketch Tool for Early Design, *CAADRIA 2000: Proceedings of the Fifth Conference on Computer Aided Architecture Design Research in Asia*, Singapore, 451-460.

Arnowitz, E., Morse, C. and Greenburg, D.P.: 2017, vSpline: Physical Design and the Perception of Scale in Virtual Reality, *ACADIA 2017 Disciplines & Distribution: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, Cambridge, Massachusetts, 110-117.

Carreiro, M.B.T. and Pinto, P.L.: 2013, The Evolution of Representation in Architecture, *Future Traditions - 1st eCAADe Regional International Workshop*, Porto, 27-38.

Cooper, Z.: 2020, *Unseen - Digital interactions for low vision spatial engagement*, Master's Thesis, Victoria University of Wellington.

Deering, M.F.: 1995, HoloSketch: A Virtual Reality Sketching/Animation Tool, *ACM transactions on Computer-Human Interaction*, **2**(3), 220-238.

Donath, D. and Regenbrecht, H. 1995, VRAD (Virtual Reality Aided Design) in the Early Phases of the Architectural Design Process, *in* M. Tan and T. Teh (eds.), *The Global Design Studio (Sixth International Conference on Computer-Aided Architectural Design Futures)*, National University of Singapore, Singapore, 313-322.

Farahi, B.: 2016, Caress of the Gaze: A Gaze Actuated 3D Printed Body Architecture, *ACADIA 2016 Posthuman Frontiers: Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, Ann Arbor, Michigan, 352-361.

Law, T., Lam, D. and Endang, J.: 2020, How rad(ical) is VRAD (Virtual Reality Aided Design)?, *IV2020 - 24th International Conference Information Visualisation*, Melbourne.

Lisinska-Kusnierz, M. and Krupa, M.: 2020, Suitability of Eye Tracking in Assessing the Visual Perception of Architecture - A Case Study Concerning Selected Projects Located in Cologne, *Buildings*, **10**, 20.

Page, T.: 2020, "CNN: Sarah Ezekiel: Artist paints with her eyes" . Available from <https://edition.cnn.com/style/article/sarah-ezekiel-artist-als-eye-gaze-spc-intl/index.html> (accessed 12th November 2020).

Polli, A.: 1999, Active Vision: Controlling Sound with Eye Movements, *Leonardo*, **32**(5), 405-411.

Rock, I. and Harris, C.S.: 1967, Vision and Touch, *Scientific American*, **216**(5), 96-107.

Roet, L.: 2015, "VICE: Graham Fink is Drawing with His Eyes" . Available from <https://www.vice.com/en/article/bmyvjv/graham-fink-is-drawing-with-his-eyes> (accessed 10th November 2020).

Rogers, J., Schnabel, M.A. and Moleta, T. 2019, Digital Design Ecology to Generate a Speculative Virtual Environment with New Relativity Laws, *in* J.-H. Lee (ed.), *Computer-Aided Architectural Design. "Hello, Culture". Communications in Computer and Information Science (CCIS)*, Springer, Singapore, 1028, 120–133.

Schnabel, M.A. and Chen, R.I. 2011, Design Interaction via Multi-touch, *in* Y. Luo (ed.), *Cooperative Design Visualisation & Engineering, CDVE, Lecture Notes in Computer Science,*, Springer, Berlin, 6874, 14-21.

Schnabel, M. 2009, Framing Mixed Realities, *in* X. Wang and M.A. Schnabel (eds.), *Mixed Reality in Architecture, Design, and Construction*, Springer, The Netherlands, 3-11.

Schnabel, M.A., Wang, W., Seichter, H. and Kvan, T.: 2008, Touching the Untouchables: Virtual-, Augmented- and Reality, *Beyond Computer-Aided Design, 13th Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA)*, Chiang Mai, 293-299.

Shusterman, R.: 2011, Muscle Memory and the Somaesthetic Pathologies of Everyday Life, *Human Movement*, **12**(1), 4-15.

Wang, B., Moleta, T. and Schnabel, M.A.: 2019, The New Mirror - Reflecting on inhabitant behaviour in VR and VR visualisations, *Intelligent & Informed (Proceedings of the 24th CAADRIA Conference)*, Wellington, Vol. 1, pp. 535-544.

Urban Analytics, Urban Modelling and Smart Cities

DIFFERENCES BETWEEN BEHAVIOR SIMULATION AND SPACE SYNTAX IN THE STUDY OF URBAN TEXTURE

Considering the Street System and Property Right Plots

CHUNXIA YANG[1], CHEN XU[2], CHENGZHE LYU[3] and MING ZHAN[4]
[1,3,4]*Tongji University*
[1,3]*{yang_arch|sansirorr}@163.com* [4]*zhanming@tongji.edu.cn*
[2]*East China Architecture Design & Research Institute*
[2]*xuchen_xiaomao@163.com*

Abstract. The study applies two methods of behavioral simulation and space syntax to study waterfront accessibility from the urban texture levels of street system and property plot, exploring two methods' differences, advantages and disadvantages in terms of simulation principle, fitting precision, and calculating results. The North Bund area of Shanghai is selected as the research sample. And the software of AnyLogic and Depthmap which are mostly used in the fields of behavior simulation and space syntax are used. The results are:Behavior simulation can visually reflect the usage condition of specific spaces through micro behavior data such as pedestrian flow, walking time, etc. But it has limitation in precision and stability of calculation, and the model need much time to construct and run if the site is large. Space syntax is more mature in accessibility analysis with high precise indexes such as choice and integration degree. However, the fitting precision between the output and real situation is lower than behavior simulation, and it can't directly evaluate the capacity and service level of the urban space. In general, both behavior simulation and space syntax can be applied to urban space research and have their own advantages and disadvantages, and complementary in between.

Keywords. Behavior simulation; space syntax; method comparison; urban texture; waterfront.

With the waterfront redevelopment around the world, and the functions of waterfronts have gradually shifted from industry to recreation. In 2017, the 45-kilometer waterfront spaces on both sides of the Huangpu River in Shanghai had been connected, which now become important leisure places for citizens. In 2020, Secretary-General Xi Jinping visited Yangpu Binjiang and proposed the urban construction policy of "People's cities are built by the people, and people's cities are for the people". He emphasized that people-centered development idea must be implemented, and the approach should be based on humanism and make urban design more scientific and refined (Xie, 2020).

However, there are still problems in waterfronts and surrounding areas. For example, destruction of traditional road network cuts the connection between waterfront and hinterland; super blocks reduce the accessibility, which may affect walking experience and reduce people's willingness to go to waterfronts. So, how to improve walking environments in such areas is worth studying.

Behavior simulation and space syntax are two typical tools used to study space accessibility. Behavior simulation relies on simulation platform to construct scenarios and agents to simulate self-organizing behaviors in urban spaces, which may reflect the conditions of space usage. Space syntax describes the spatial pattern of cities and analyzes space through topological calculations, which may reveal local and overall spatial accessibility and relevance.

This research chooses the software of AnyLogic and Depthmap which are mostly used in the fields of behavior simulation and space syntax to study waterfront accessibility, focusing on the urban texture levels of street system and property plot. It compares the two methods in the simulation principle, operation process, fitting precision, etc., which can help construct waterfronts more scientifically and delicately.

1. Key issues and solutions

1.1. HOW TO UNDERSTAND THE WALKABILITY OF URBAN SPACE FROM THE URBAN TEXTURE?

As a complex system, urban texture is not feasible to understand the interaction of its constituent elements as a whole. Only by decomposing it into several levels according to certain principles, and discovering the correlation between elements, can the overall nature of the urban texture be realized (Fang, 2008). After the urban texture is hierarchized, the quality of each "resolution" has a profound impact on the walkability of urban space. The Italian School believes that urban texture can be decomposed into levels of house types, land parcels, street elements, etc., and the sequence of different levels is inherently connected to achieve layered analysis (Nicola, 2002). The Conzen School believes that urban texture is formed by streets, plots, and buildings, etc. By linking the building and plot through the urban texture, it is possible to fully understand the structure, form, and historical evolution of the city (Conzen, 1960). On this basis, Karl Kropf added more micro-scale levels and proposed eight levels of overall urban texture, urban texture unit, plot sequence, plot, building, room, structure and tectonic node, material, etc. The higher the resolution level, the more specific the urban texture description is (Karl, 1996). The above viewpoints are based on different evaluation criteria, but what is the same is that they all have the levels of building, plot, and street.

Considering the operability of behavioral simulation and space syntax, this research takes two urban texture levels, street system and property plot to study the accessibility of waterfronts.

1.2. HOW TO EVALUATE WALKING SPACE?

Walking space evaluation systems have different perspectives. For example, Ewing scored 48 commercial street videos and determine the impact of street space elements on pedestrian performance. The influence system consists of five aspects: imagery, enclosed space, human scale, transparency and complexity, including dozens of quantifiable indicators such as passage width, visibility, and architectural diversity (Ewing, 2009); Chen divided the evaluation system into three aspects of accessibility, convenience, walkability, and quantitative indicators of walking distance, walking time, walking psychology, etc (Chen, 2012); Xu sorted out the evaluation factors for the quality of walking activities in commercial streets, and summarized them into four indicators of diversity, connectivity, pleasantness, communication, and pointed out seven important influencing factors such as continuous shop-front, dense road network, sitting facility (Xu, 2017).

According to the objectives, objects and characteristics of this study, walking space evaluation system based on the AnyLogic simulation platform is established including operability, safety, convenience and comfort (figure 1). The evaluation based on space syntax is relatively mature. Depthmap provides many indicators, among which Choice and Integration can visually express accessibility, so this study chooses these two for accessibility analysis.

Pedestrian demand	Influencing factors	Evaluation index based on Anylogic
Operability	Intermittent sidewalk conditions	Pedestrian particle detour situation
	Occupation of sidewalks	Pedestrian particle congestion
Safety	Separation of people and vehicles	Pedestrian particle distribution
	Crowd distribution facility	Pedestrian particle distribution, pedestrian density
Convenience	Sidewalk density	Pedestrian particle distribution, walking time
	detour distance	walking time
Comfort	Sidewalk	Pedestrian flow rate

Figure 1. evaluation system based on Anylogic.

1.3. HOW TO EXPLORE THE DIFFERENCES BETWEEN BEHAVIORAL SIMULATION AND SPACE SYNTAX?

Taking Shanghai North Bund area as sample, the study use behavior simulation and space syntax to analyze the waterfront accessibility from two urban texture levels: street system and property plot. Simulation principle, operation process and fitting precision of two experimental procedures and results are compared.

Behavior simulation has been increasingly used in urban design in recent years. Scholars interpreted the simulation results and used them as the basis for the evaluation of urban environment or design schemes, gradually forming a research process of “simulation-evaluation-optimization” cycle verification (Shcherbyna, 2016; Wang, 2018). On this basis, the study first establishes pedestrian and environmental models in Anylogic through the translation of pedestrian parameters and environment modules. Then, the relationship between pedestrians and environment is showed by simulating walking behaviors. The outputs can help evaluate walkability and the site problems may be found. According to it, some strategies can be proposed and renovation design may be made and simulated again to predict the effectiveness of the design.

Space syntax is widely used in the research of walking space. Existing researches mostly focus on street networks and analyze in a mesoscale perspective (Chen, 2019). In recent years, spatial syntactic analysis integrating multi-level urban texture elements has become the focus. Based on the GIS platform and built-in spatial syntax analysis plug-in, some scholars evaluated the urban pedestrian network from multiple levels (land use, accessibility, street design, etc.) by the output indicators such as connectivity, integration, and choice (Lee, 2020). On this basis, the study establishes models in Depthmap to calculate the integration and choice, and analyzes the accessibility of different street networks.

2. Research based on behavior simulation

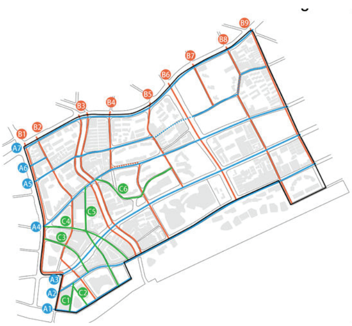
2.1. SITE DATA COLLECTION

2.1.1. Pedestrian flow of road section

It selects the morning peak hours of one workday 2019 and records the pedestrian volume of each road section to obtain current pedestrian flow data (figure 2).

2.1.2. Regional pedestrian volume

It establishes a pedestrian travel OD (origin-destination) model by constructing the pedestrian relationship among metro station, bus stations, waterfront area, office neighborhoods, residential neighborhoods, commercial neighborhoods, and external interfaces. During simulation, OD and DO data are combined to be the pedestrian volume (figure 3).



Pedestrian flow in morning peak hours (7:30 - 9:00 am)												
A1 Huangpu Road	20/40	20/20	20/20	20/20	20/20							
A2 Daming Road(North)	60/100	60/100	60/100	60/100	40/140	40/140	40/140	40/100	110/140	220/20	120/80	60/100
Daming Road(South)	40/140	40/140	40/140	40/140	40/100	40/100	40/100	40/340	100/80	20/100	220/40	40/20
A3 Changzhi Road(North)	20/40	20/40	40/20	40/20	460/60	460/60	300/120	400/340	100/140	80/100		
Changzhi Road(South)	20/50	20/50	10/10	10/10	10/10	40/10	680/180	680/180	60/80	60/80		
A4 Hanyang R - Tangshan R	140/80	140/80	140/80	280/180	280/180	280/180	280/180	60/100	60/100			
A5 Yuhang Road	200/80	200/180	240/200	120/80	120/80	80/140	120/180	120/180				
A6 Maplin Road	100/120											
A7 Zhoujiazui Road (South)	80/60	80/60	80/60	80/80	80/80	80/80	40/40	40/40				
B1 Wusong Road (East)	60/140	60/140	60/140	80/120	80/120	80/120	80/120	100/140				
B2 E'mei R - Wuchang R	160/100	160/100	160/100	100/260	100/260	100/260	60/140	140/100	140/100			
B3 Jiulong Road	160/260	140/160	120/80	40/60								
Liyang Road	160/260	340/320	140/120	100/80								
B4 Wuzhou R - Lvshun R	80/100	120/180	280/60	320/100	360/80							
B5 Shangqiu Road	100/120	100/120	200/80	200/80								
B6 Xinjian Road (West)	160/180	320/140	360/140	740/200								
Xinjian Road (East)	100/80	80/10	240/80	180/120								
B7 Tongzhou Road	80/100											
B8 Gaoyang Road	80/100	80/100	10/10	10/10	80/120	80/60						
B9 Dantu Road	40/60	40/60	80/60	40/60	80/100							
C1 Jinshan Road	60/20											
C2 Tiantong Road	60/20											
C3 Minhang Road	100/80	160/100	100/100									
C4 Tanggu Road	460/80	460/80	460/60	80/60								
C5 Nanxun Road	120/140	10/10	80/60	40/20								
C6 Xi'an Road	260/140	80/100										

Figure 2. current pedestrian flow data.

D \ O	North Bund Park	Metro Station	Bus Stop	Living Plots	Working Plots	Commercial Plots	Externals
North Bund Park	/						
Metro Station	√	/					
Bus Stop	√	×	/				
Living Plots	√	√	√	/			
Working Plots	×	√	√	×	/		
Commercial Plots	√	×	√	√	×	/	
Externals	√	√	√	√	×	√	/

North Bund Park	External A	External B	External C	External D	External E
Pedestrian Number (in / out)	36/12	108/24	120/12	108/36	132/48

North Bund Park	Walking	Metro	Bus	Car/Taxi	Bicycle
Percentage	80%	0	10%	10%	0

Metro Station	External 1	External 2	External 3	External 4	Total
Pedestrian Number (in / out)	400/280	180/1600	280/1480	80/1320	940/4680

Bus Stop	1	2	3	4	5	6	7	8	9
Pedestrian Number	60	96	48	24	30	24	18	18	18

Externals	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pedestrian Number	60	280	340	220	160	420	100	320	180	200	160	120	220	80

Figure 3. flow of people at OD elements.

2.1.3. Demographic data

When constructing the pedestrian flow related to residential and office neighborhoods, it is necessary to allocate proportionally based on the population data of different neighborhoods. The residential neighborhoods are mainly divided into three types and calculated separately: old-style lanes, multi-level determinant communities, and high-rise communities. The office neighborhoods are recorded the number of people who enter the office building during 8:00-9:30 on working days and estimate the total number of people in each office block.

2.2. MODEL CONSTRUCTION AND FITTING

2.2.1. Model construction

Based on AnyLogic platform, the behavior simulation model mainly includes three parts: 1)Pedestrian modeling is to define pedestrian particle parameters such as the size, speed, and distance between particles; 2)Environmental modeling is to translate urban space elements into environmental modules such as Wall and Area; 3)Behavioral process modeling is to construct the moving process of pedestrian particles, inputting the data of pedestrian flow and distribution methods obtained in different time sessions of the survey. Finally, statistical analysis components such as Ped Flow Statistics, Density Map, and Time Measure are placed in the AnyLogic model to facilitate better reading and analysis of simulation results (figure 4).

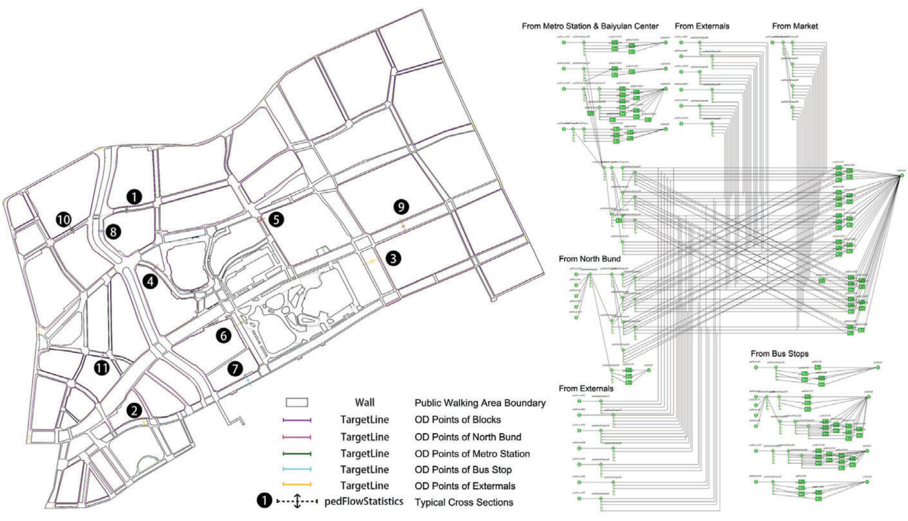


Figure 4. Anylogic model constraction.

2.2.2. Model fitting

The simulation is carried out for test, and 11 typical road sections are selected as samples to fit the pedestrian flow. If some output data are not fit for the current situation, adjustments are made by modifying the pedestrian distribution ratio, controlling the path direction or supplementing the relationship between pedestrians. For example, pedestrian flow on the red path is too high and the purple path is too low. Through site survey, it is found that pedestrians between the metro station and the Block W24 mostly choose the purple path, which does not match the simulation. By adjusting the allocation ratio of pedestrian flow, the data get more realistic (figure 5). After some adjustments, the model achieves a high degree of fitting, which proves that it can be used as a basis for further research.

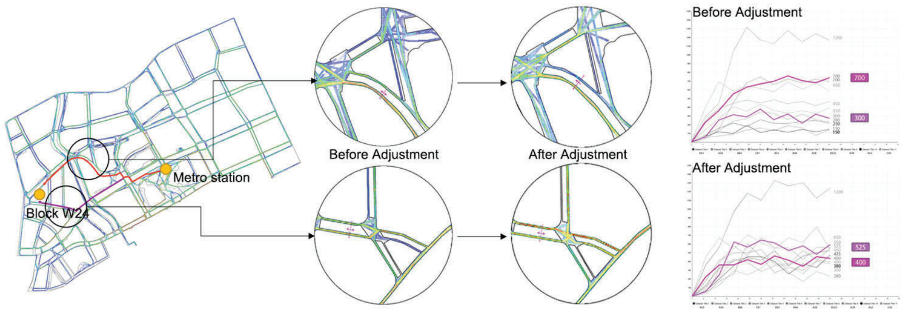


Figure 5. improvement of fitness.

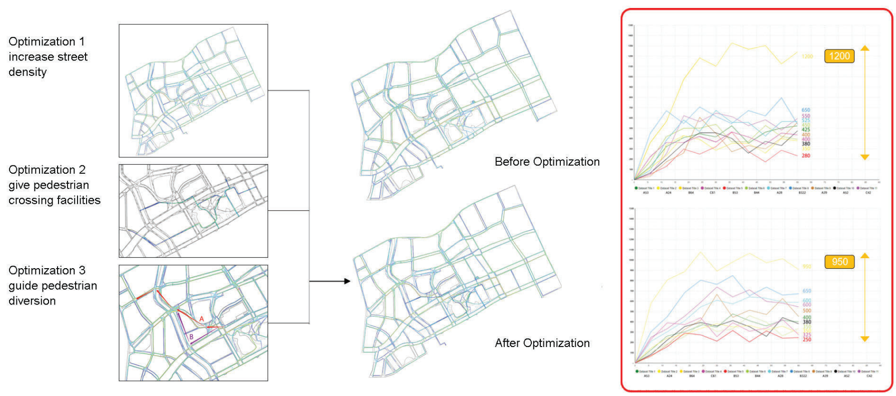


Figure 6. study on the level of street system.

2.3. STUDY ON THE LEVEL OF STREET SYSTEM

2.3.1. Evaluation of road network service level

It selectes the morning peak hours to perform simulation calculations, comparing the current situation with that in 1948. Three main problems in the current road network are found: The reduced road network density leads to serious detours; The grading of the road network leads to deterioration of the traversability; The misalignment of the sidewalk system results in low efficiency of the road network.

2.3.2. Street system optimization and re-simulation

To optimize the above three issues, it proposes some strategies including increasing street density, adding pedestrian crossing facilities, and adjusting the sidewalk system. Then it simulates again to verify the effectiveness of strategies. Comparing the re-simulation results with the previous one, it can be found that the overburdened traffic decreases, the distribution of pedestrians within the site is more even, and the entire road network is more efficient (figure 6).

2.4. RESEARCH ON THE LEVEL OF PROPERTY PLOT

2.4.1. Evaluation of road network service level

The same peak hours and comparing way are used to study property plot. Two main problems in the current property plot organization are found: The disparity in scale leads to the big gap in the accessibility of different regions; The confused division method changes some accessible roads to cul-de-sacs.

2.4.2. Property plot optimization and re-simulation

Some strategies are proposed. From the perspective of the feasibility of actual land rezoning, one is to open over-sized plots, and to open roads within the land as much as possible (Yang, 2018). The other is to make the division of existing plots better and make more scientific land parcels in planning plots. Through re-simulation, it is found that the allocation of pedestrian flow is more scientific and efficient (figure 7).

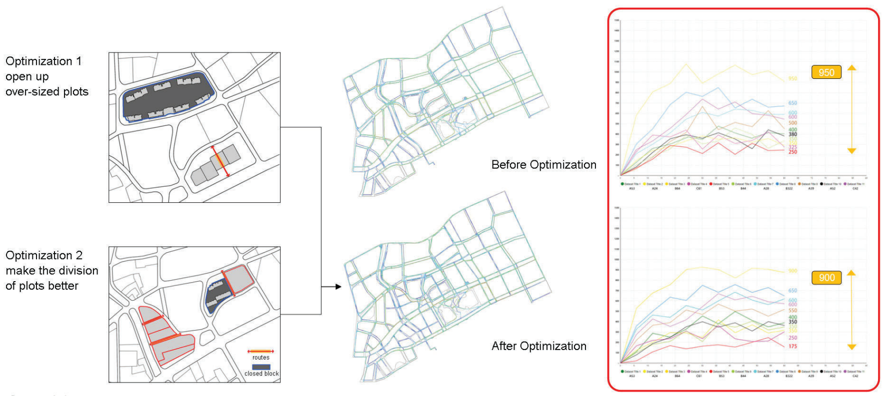


Figure 7. study on the level of property plot.

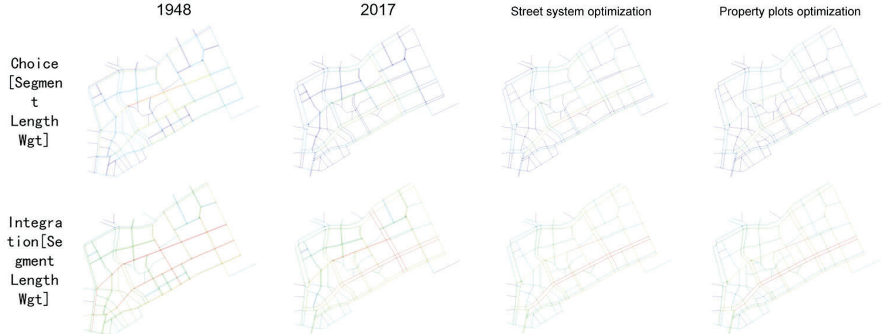
3. Research based on space syntax

3.1. MODEL CONSTRUCTION

It depicts the pedestrian network cad files of 4 scenarios including year 1948, year 2017, after the optimization of the street system, and after the optimization of the property plot. Among them, the wider roads and high traffic roads are drawn by two lines, while narrow roads, pedestrian and vehicle mixed roads are drawn with a single line. The axis unit is broken into independent line at crossings to translate the current pedestrian space better. It imports the cad file into the Depthmap and build the space syntax model.

3.2. STREET SYSTEM AND PROPERTY PLOT EVALUATION

It analyzes the Choice (Segment Length Wgt) degree and Integration (Segment Length Wgt) degree of the whole street network and waterfront streets. The road network calculation focuses on the average data. The standard deviation is used as a reference to reflect the evenness of accessibility. The result of the waterfront streets is obtained by taking the average data of the A8-11 south part of East Dongdaming Road which is adjacent to waterfront (Figure 8).



	Whole street network Choice[Segment Length Wgt] Average	Whole street network Choice[Segment Length Wgt] Standard deviation	Whole street network Integration[Segment Length Wgt] Average	Whole street network Integration[Segment Length Wgt] Standard deviation	Waterfront street Choice[Segment Length Wgt] Average	Waterfront street Integration[Segment Length Wgt] Average
1948	1. 958E+13	1. 789E+13	15838753	2433581	3. 062E+13	17547100
2017	1. 862E+13	1. 852E+13	13263304	2014104	4. 363E+13	14802025
Street system optimization	1. 92E+13	1. 931E+13	13449676	2059501	3. 776E+13	15233340
Property plots optimization	2. 032E+13	2. 033E+13	13770555	2138679	3. 875E+13	15543940

Figure 8. Depthmap experiment and result analysis.

The results show that the accessibility including traversability and reachability of the street network are the highest in 1948 and the lowest in 2017. However, through the optimization of the street network and the property plot, the data has ascended, indicating that the optimization has been effective. In terms of standard deviation, the results of 1948 and property plot optimization both indicate that the road network in some areas has never been highly accessible. The reachability of the waterfront streets has been improved through the optimization of the street network and property plot, which proves that the optimized scheme is beneficial for pedestrians from the hinterland to waterfront.

4. Comparison of behavior simulation and space syntax

4.1. SIMULATION PRINCIPLE

The principle of behavior simulation is space behavior theory, which simulates the real behavior activities in space through the model, including micro behavior data such as pedestrian flow, walking speed, and walking time. It visually reflects the usage status and service level of walking space. Space syntax abstracts three-dimensional space into topological graphics, and evaluates accessibility through indexes such as choice, integration, and depth.

4.2. OPERATION PROCESS

Behavioral simulation model requires detailed site research to ensure the effectiveness of the model. The model construction work is relatively large, but the AnyLogic platform is well developed and the operation is simple and easy to understand. The space syntax model is simple to construct, fast in calculation, and the output data can accurately reflect the accessible degree of the space.

4.3. FITTING PRECISION

Based on the bivariate correlation analysis by SPSS of 11 typical road sections, it calculates the fitting degree between the space syntax selectivity data and actual pedestrian volume, the fitting degree between behavior simulation results and actual one as well. It is found that the space syntax fits a little bit lower though it also meets the fitting requirements, while the behavioral simulation has a higher fitting degree and can make the simulation data more realistic through continuous modification.

4.4. LIMITATION

In terms of behavior simulation, the social force model of AnyLogic is less flexible in simulating leisure walking behavior and requires secondary development to realize certain details. In addition, the calculating precision is limited, the output data is unstable, the model construction is more complicated, and the calculating speed is slow. The limitation of space syntax is that the fitting between the simulation results and the real situation is not as good as the behavior simulation. When the research area is small, the drawing method of road network will have a certain degree of influence on the calculating results. On the other hand, the space syntax has an indirect connection with micro pedestrian behavior so it is not easy to evaluate the capacity and service level of the urban space in a certain way.

Technical	Operation	Fitting precision degree	Advantage
Behavior simulaiton	Based on real space	First-time simulation is moderate with the fitting precision degree of 0.744. After continuous optimization, fitness can reach 0,876, which is high.	1.Include indicators such as walking time, pedestrian flow, etc. 2.Reflect the service level of the pedestrian space
Space syntax	Based on topological distance and actual distance	Fitting precision degree is moderately 0,685, mainly because it does not consider the function ad capacity distribution of different plots.	1.Accurate quantitative results 2.Fast model construction and calculation

Figure 9. comparation of two technics.

But in general, both behavior simulation and space syntax can be applied to space research on the scale of urban design. Behavior simulation can visually reflect the usage of spaces, while space syntax is more mature in accessibility analysis. Both methods have their own advantages and are complementary (figure 9).

5. Research conclusions

Taking two urban texture levels of street system and property plot as examples, this research uses behavioral simulation and space syntax to conduct parallel experiments and comparative studies on waterfront accessibility. It is found that:

(1) The traditional behavioral simulation is mainly applied to the scenarios of indoor evacuation and pedestrian crossing at intersections. In this research, the OD travel model is used to analyze the rules of walking around a 140-hectare urban waterfront area. It shows that this method is valid in micro behavior simulation, which proves that behavior simulation application can be extended to larger-scale outdoor studies, making urban design more scientific and refined.

(2) The traditional urban texture research was mainly carried out from the perspectives of map-base relationship and topological relationship. Taking the view of self-organization behavior, this research combines the urban texture research with pedestrian behavior, which breaks through the qualitative analysis of traditional urban texture and provides a new way of quantitative research.

(3) It compares behavioral simulation and space syntax from the urban medium scale and found that the two technologies have their own advantages and disadvantages. Behavior simulation is good at visually evaluating and predicting the pedestrian capacity within urban space, while space syntax is better in calculating efficiency and quantization precision. If the two are combined to use, it can make research more convincing.

References

Chen, Y. and He, N.: 2012, Analysis of walkable environment and influential factors in rail transit station areas: case study of 12 neighborhoods in Shanghai, *Urban Planning Forum*, **06**, 96-104.

Chen, M.Z. and Zheng, Y.: 2019, Research on the Walkability Evaluation of Historical Urban Area, *Proceedings of ISSS 2019*, 9-15.

Conzen, M.R.G.: 1960, *Alnwick NorthumberlandA Study in TownPlan Analysis*, ORGE PHILIP & SON, LTD.

Ewing, R. and Handy, S.: 2009, Measuring the Unmeasurable: Urban Design Qualities Related to Walkability, *Journal of Urban Design*, **14(1)**, 65-84.

F, Y.G. and Liu, J.S.: 2008, Urban fabric organization based on complex system theory, *City Planning Review*, **10**, 32-37.

Kropf, K.: 1996, Urban tissue and the character of towns, *Urban Design international*, **1**, 247-263.

Lee, S., Yoo, C. and Seo, K.W.: 2020, Determinant Factors of Pedestrian Volume in Different Land-Use Zones: Combining Space Syntax Metrics with GIS-Based Built-Environment Measures, *Sustainability*, **12**, 1-15.

Marzot, N.: 2002, The study of urban from in Italy, *Urban Morphology*, **2**, 59-73.

Shcherbyna, O.: 2016, "Times Square Outdoor Advertising Effectiveness" . Available from <http://www.runthemodel.com/models/1241/> (accessed 20th Jan 2016).

Wang, Z.Z.: 2018, *WALKING SPACE DESIGN STRATEGIES BASED ON PEDESTRIAN SIMULATION*, Master's Thesis, Harbin Institute of Technology.

Xie, J.G. and Li, Q.: 2020, Promote the modernization of urban construction and governance in the new era under the guidance of the important concepts of the people's city, *PARTY&GOVERNMENT FORUM*, **07**, 4-6.

Xu, L.Q., Meng, R.X. and Chen, Z.: 10, Fascinating streets: the impact of building facades and green view, *Landscape Architecture*, **10**, 27-33.

Yang, C., Shi, M.i.n. and Geng, H.: 2018, Study on the pedestrian accessibility of waterfront area based on an understanding of urban fabric level: Taking the estuary area of Suzhou River in Shanghai as an example, *City Planning Review*, **42(02)**, 104-114.

CAN A GENERATIVE ADVERSARIAL NETWORK REMOVE THIN CLOUDS IN AERIAL PHOTOGRAPHS?

Toward Improving the Accuracy of Generating Horizontal Building Mask Images for Deep Learning in Urban Planning and Design

KAZUNOSUKE IKENO[1], TOMOHIRO FUKUDA[2] and NOBUYOSHI YABUKI[3]
[1,2,3]*Osaka University*
[1]*ikeno@it.see.eng.osaka-u.ac.jp* [2,3]*{fukuda|yabuki}@see.eng.osaka-u.ac.jp*

Abstract. Information extracted from aerial photographs is widely used in the fields of urban planning and architecture. An effective method for detecting buildings in aerial photographs is to use deep learning to understand the current state of a target region. However, the building mask images used to train the deep learning model must be manually generated in many cases. To overcome this challenge, a method has been proposed for automatically generating mask images by using textured 3D virtual models with aerial photographs. Some aerial photographs include thin clouds, which degrade image quality. In this research, the thin clouds in these aerial photographs are removed by using a generative adversarial network, which leads to improvements in training accuracy. Therefore, the objective of this research is to propose a method for automatically generating building mask images by using 3D virtual models with textured aerial photographs to enable the removable of thin clouds so that the image can be used for deep learning. A model trained on datasets generated by the proposed method was able to detect buildings in aerial photographs with an accuracy of IoU = 0.651.

Keywords. Urban planning and design; Deep learning; Generative Adversarial Network (GAN); Semantic segmentation; Mask image.

1. Introduction

1.1. BACKGROUND

Information extracted from aerial photographs is widely used in urban planning and design. For example, photographs allow for measurement of green coverage rates and sky view factors as well as confirmation of building locations and exteriors. As the use of unmanned aerial vehicle (UAV) technology has become more widespread, aerial photographs have become easier to take. Information that needs to be gathered in real time, such as damage to buildings during a disaster

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 377-386.

can be grasped using aerial photographs taken by UAVs. To obtain highly accurate information, it is necessary to capture many photographs in a short period of time. An effective method for detecting buildings in aerial photographs is to use artificial intelligence to ascertain the current state of a target region.

Recently, methods using deep learning have been proposed for object detection and segmentation. These methods can quickly and automatically detect target objects in images. It is also possible to detect buildings in aerial photographs by using this method. The accuracy of building detection is greatly influenced by the quantity and features of the dataset used to train the model, and thus it is necessary to adequately train the model for each target area. However, the building mask images used to train the model must be generated manually in many cases. Considerable time is required to generate mask images from aerial photographs for model training because many sets of aerial photographs and mask images are needed to train the model. Photoediting programs such as Adobe Photoshop and GIMP have a function for automatically clipping target objects. However, this function is not effective for generating specific mask images, such as buildings. Therefore, an efficient method to generate mask images is needed.

1.2. PREVIOUS RESEARCH

In recent years, many object detection and segmentation methods that use deep learning have been proposed. By providing training data, features are automatically calculated and objects are detected based on the calculated features. Methods that detect objective areas as rectangles in images by using a convolutional neural network (CNN) such as AlexNet (Krizhevsky et al. 2012) and You Only Look Once (YOLO) (Redmon et al. 2016). Semantic segmentation (Long et al. 2015) classifies each pixel into one of several categories and then segments the objects by their silhouette. A system for automatically calculating green coverage rates and sky factors by semantic segmentation (Cao et al. 2019) has also been developed. A deep CNN-based method for automatically detecting suburban buildings from high-resolution Google Earth images has also been proposed (Zhang et al. 2016) as a building detection method that uses deep learning. In addition, a fused fully convolutional network model has been proposed to perform building segmentation (Bittner et al. 2018). Some research is being conducted with the aim of improving the accuracy of Mask-R-CNN for detecting building footprint boundaries. Furthermore, a method combining Mask-R-CNN with building boundary regularization (Zhao et al. 2018) has been presented, and a method has been proposed for detecting different scales of buildings and segmenting buildings to have accurately segmented edges (Zhou et al. 2019). However, the building mask images for training the model must be generated manually in many cases, which requires considerable time and expense to build.

To overcome this challenge, a method has been proposed to automatically generate mask images of buildings by using VR 3D models for deep learning (Fukuda et al. 2020). By using a 3D virtual model, we can quickly and easily create datasets that include mask images. Given that normal virtual models do not have the realism of a photograph, it is difficult to obtain highly accurate detection results in the real world even when the image is used for deep learning training. High-precision rendering methods have been developed but they are generally difficult to use because many computers do not have high enough specifications. Using textured 3D virtual models with photographs can overcome this challenge (Ikeno et al. 2020). In addition, photographs may contain obstacles other than the target object. To remove these obstacles in photograph, image generation methods using Generative Adversarial Network (GAN) (Goodfellow et al. 2014) are used.

1.3. OBJECTIVE

The objective of this research is to propose an automatic generation method for horizontal building mask images by using 3D models with textured aerial photographs for deep learning. Specifically, we aim to improve the representation of the VR models by using textured aerial photographs on 3D models. Some aerial photographs include thin clouds, which degrade image quality. The thin clouds on these aerial photographs are removed by using GAN for improving training accuracy. The proposed method can automatically generate mask images by using these 3D models and GAN.

2. Proposed method

Our proposed method automatically generates building mask images and aerial photographs. The generated mask images are used to train the deep learning model for semantic segmentation. The proposed method loads 3D models that include terrain and building objects, classifies by building class and others class, switches between a model with all objects and one with only buildings, and finally generates two upper-view images of the models from multiple viewpoints. The game engine used in this method must be able to import 3D models, classify objects into the two classes, and output images while switching between display and non-display. Aerial photographs that include thin clouds are regenerated as images without thin clouds by using a GAN that can change from an image with one feature to another. This method can generate multiple sets of mask images and aerial photographs without thin clouds from a single 3D model. The flowchart and conceptual diagram are shown in Figures 1 and 2, respectively.

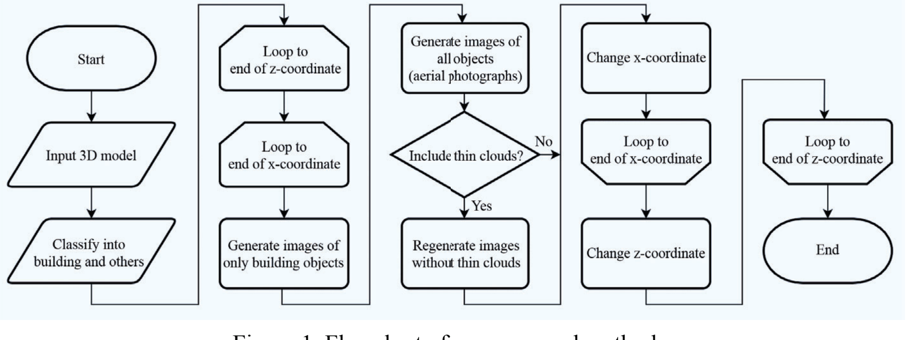


Figure 1. Flowchart of our proposed method.

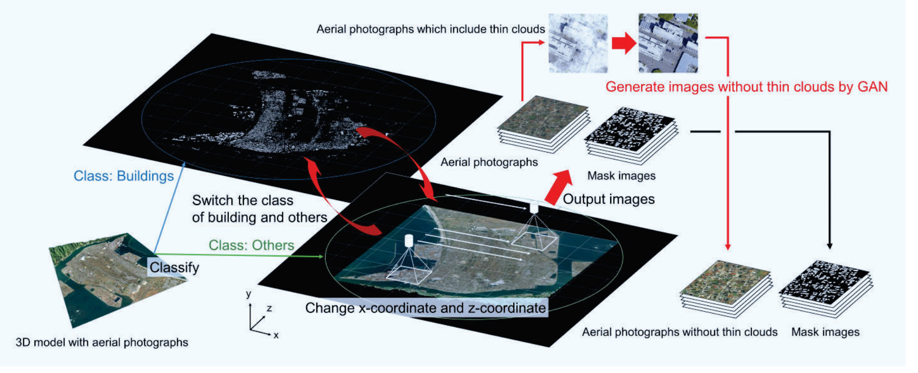


Figure 2. Conceptual diagram of our proposed method.

3. Prototype system

A prototype system was constructed to generate sets of mask images and aerial photographs without thin clouds by our proposed method. The automatic mask-image generation system using an enhanced 3D digital surface model was developed in the game engine Unity (Ikeno et al. 2020). The appearance of the 3D digital elevation model was enhanced by using textured aerial photographs. To build the systems to generate the datasets, Unity was used as a game engine because it can load 3D models.

The 3D models of the target areas were generated by using Autodesk InfraWorks. The building placement was determined according to fundamental geospatial data provided by the Geospatial Information Authority of Japan. The aerial photographs are pasted on objects in the terrain. The generated 3D model is shown in Figure 3.

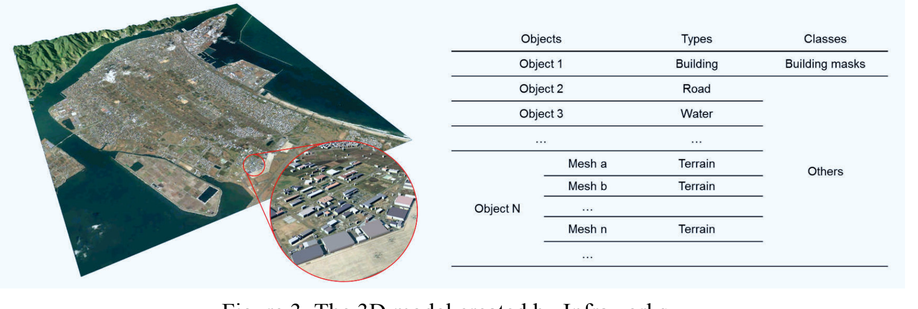


Figure 3. The 3D model created by Infraworks.

To generate thin cloud removal images, we used spatial attention generative adversarial networks (SpA GAN), which use a spatial attention network (Wang et al. 2019) as a generator. The architecture of SpA GAN is shown in Figure 4. The SpA GAN model trained on the open-source RICE dataset was used to generate thin cloud removal images from aerial photographs that include thin clouds. The color tone of the generated image was corrected to match the original aerial photograph. The specifications of the personal computer used to perform all of these tasks are shown in Table 1.

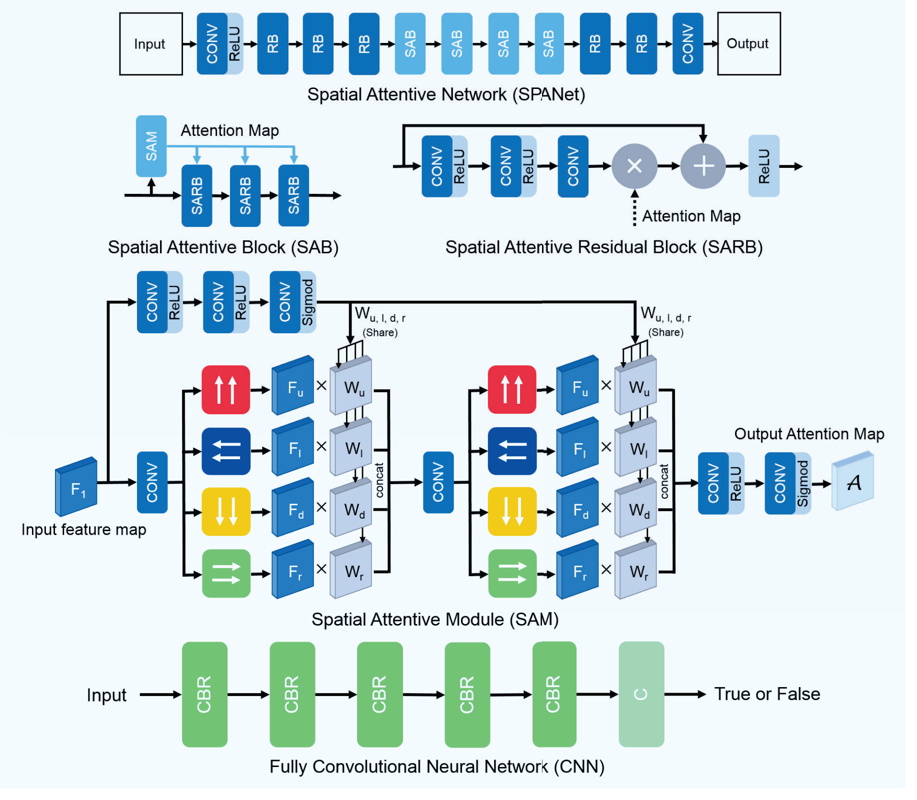


Figure 4. Generator and discriminator (Created by the author with reference to the literature).

Table 1. The specification of PC.

OS	Ubuntu 16.04 LTS
CPU	Intel(R) Core(TM) i7-3770K CPU @ 3.50GHz
GPU	Geforce GTX 1060
RAM	28.0GB

4. Results

4.1. AUTOMATIC GENERATION OF MASK IMAGES

The aerial photographs and mask images automatically generated by our proposed system are shown in Figure 5. The middle column shows automatically generated mask images generated by the prototype system and the right column shows manually generated mask images as ground truth. The white areas are the building masks. Our prototype system generated 6956 sets in 438 s.

Figure 6 shows the thin-cloud removal results by GAN. The left column shows aerial photographs including thin clouds and the middle column shows images in which the thin clouds were removed by GAN. The time required to generate 192 thin cloud removal images by GAN was 58 s.

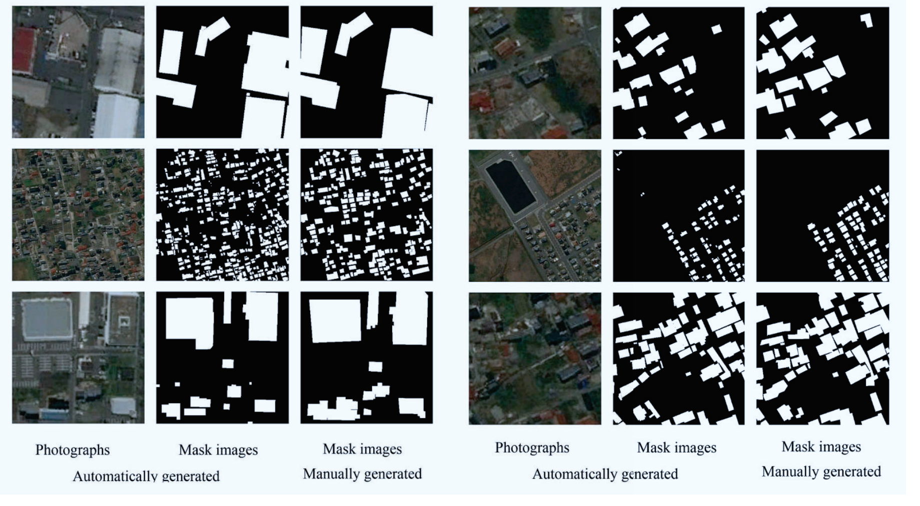


Figure 5. Generated aerial photographs and mask images.

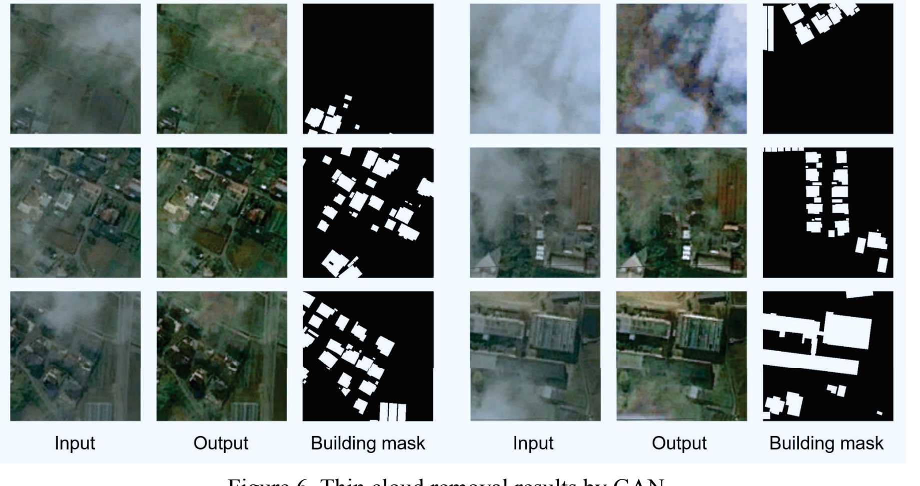


Figure 6. Thin cloud removal results by GAN.

4.2. BUILDING SEGMENTATION BY USING OUR TRAINED MODEL

To verify the accuracy of the generated dataset, the U-Net (Ronneberger et al. 2015) model was trained to detect buildings. U-Net can be used to detect objects accurately in units of pixels for the segmentation of buildings in aerial photographs. Sakaiminato City was chosen as the target area because it has several small buildings and a large proportion of land surface, neither of which are found in existing datasets. Model A is the model trained using unprocessed images and Model B is the model trained using images in which the thin clouds were removed by GAN.

The results for building detection in aerial photographs in Sakaiminato City by the trained model (Model B) are presented in Figure 7. The red areas are the predicted and true areas of buildings. For verification, Intersection over Union (IoU) (Everingham et al. 2015) was used, which is a metric that evaluates how similar predicted areas are to the ground truth. IoU was 0.651 as calculated using the sets of aerial photographs and mask images from the verification class.

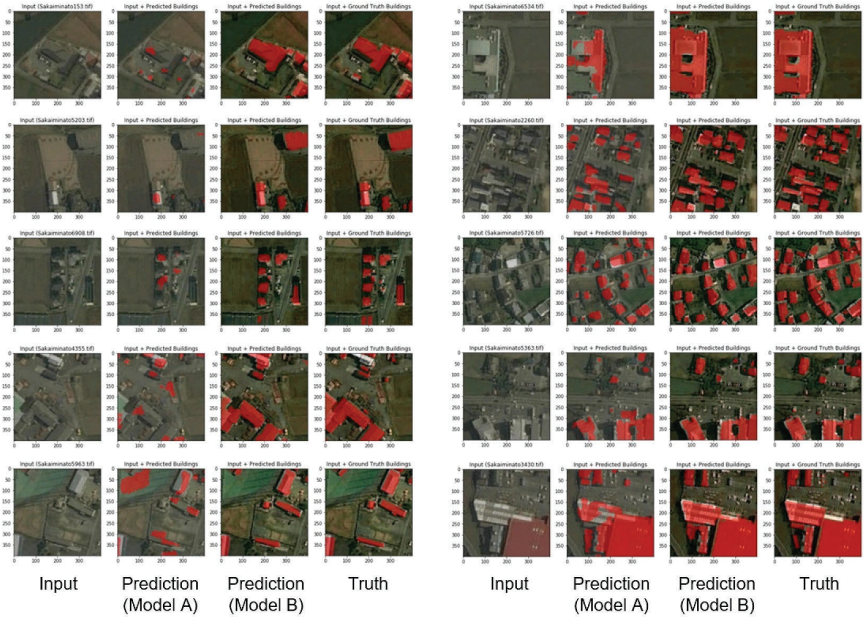


Figure 7. Results of detecting buildings by using model A and B.

5. Discussion

5.1. AUTOMATIC GENERATION OF MASK IMAGES

Our prototype system generated 6956 sets of mask images and aerial photographs without thin clouds in 438 s. The time to generate the mask images was reduced by automatically generating them from 3D models in comparison to the manual generating method. The mask images generated by our prototype system are nearly the same as those generated manually. This method generates mask images with detailed shapes. However, it was not able to generate mask images of small warehouses. It is, therefore, necessary to prescreen the generated mask images.

5.2. THIN CLOUD REMOVAL BY GAN

The buildings that were covered by the thin cloud cover in images in which thin clouds were removed by GAN are clearly visible. The training accuracy is expected to be improved because the contours of buildings can be clearly recognized when the model is trained. However, when buildings were covered with thick clouds, they remained hidden below the clouds. Areas in which thick clouds have been removed are complemented as the ground surface. This is because the RICE dataset used for training contains many images of the ground surface. Therefore, it is better to remove images in which buildings are completely hidden by thick clouds.

5.3. ACCURACY VERIFICATION

We trained the model on mask images automatically generated by our prototype system and evaluated the accuracy of the trained model for segmenting buildings in aerial photographs of Sakaiminato City. IoU was calculated for accuracy verification by using 1388 test images that were not used for training. The IoU of our trained model (Model B) was 0.651. A comparison of the accuracy of our trained two models (Models A and B) is shown in Table 2. The detection accuracy of Model B, which was trained on the images in which the thin clouds were removed by GAN was improved compared with the detection accuracy of unprocessed Model A. The accuracy, precision, and Recall of Model B were 94.3%, 84.4%, and 74.1%, respectively. Model B is a model with few false positives. In this validation experiment, U-Net was used for comparison with the existing dataset, but the accuracy might be improved by using a more accurate deep learning model.

Figure 8 shows the detection accuracy of each image. The detection accuracy was improved for most of the images, especially for those with a high percentage of buildings in the image. The number of images in which buildings were adequately detected (IoU is over 0.5) was 132 for Model A and 1177 for Model B. The threshold value indicating that the model detected buildings sufficiently well was IoU = 0.5 (Jabbar et al. 2017). This means that it is possible to detect detailed building contours in individual images. The removal of thin clouds by GAN made the building boundaries clearer and the accuracy of the training was improved.

Table 2. IoU of the trained models.

Training datasets	Objective area	IoU
SpaceNet (Rio de Janeiro)	Rio de Janeiro	0.602
Automatically generated datasets (unprocessed)	Sakaiminato	0.622
Automatically generated datasets (thin cloud removal processed)	Sakaiminato	0.651

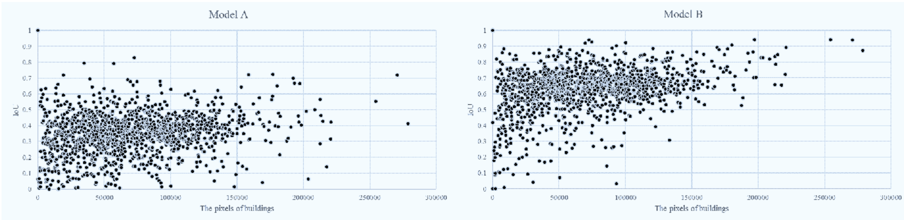


Figure 8. The detection accuracy of each image.

6. Conclusion

We improved the appearance of the 3D model by using aerial photographs as textures. We also improved the training accuracy of the deep learning model by removing thin clouds in the aerial photographs by using GAN. The prototype system using the proposed method in this study can automatically generate training datasets for deep learning, including aerial photographs and mask images, in a short time compared with methods requiring the manual generation of mask images. We believe that this method can be used not only for buildings in aerial photographs but also for other types of objects. It is expected that this method could be used to automatically generate supervised datasets for objects such as roads and rivers in aerial photographs as well as buildings seen from street level. In addition, we believe that the mask images generated by this method can be used not only as training data for deep learning but also for visualization to understand cities. The conclusions of the present study are summarized below.

- Our prototype system can generate sets of aerial photographs in which thin clouds are removed by GAN as well as mask images from a 3D model.
- Aerial photographs before and after the removal of thin clouds by GAN were compared.
- The model-trained datasets generated by our prototype system can detect buildings in aerial photographs with an accuracy of IoU = 0.651.

Future work will aim to train a deep learning model by using the datasets generated by our prototype system and evaluate the accuracy of the trained model.

Acknowledgement

This research has been partly supported by JSPS KAKENHI Grant Number JP19K12681.

References

"RICE_DATASET" : 2019. Available from <https://github.com/BUPTLdy/RICE_DATASET> (accessed 19th September 2020).

"SpaceNet" : 2019. Available from <https://explore.digitalglobe.com/SpaceNet-Thank-You.html> (accessed 9th September 2019).

"Photoshop" : 2020. Available from <https://www.adobe.com/products/photoshopfamily.html> (accessed 13th September 2020).

"GNU Image Manipulation Program (GIMP)" : 2020. Available from <https://www.gimp.org/ > (accessed 13th September 2020).

"Site of basic map information" : 2020. Available from <https://www.gsi.go.jp/kiban/> (accessed 10th September 2019).

"SpA-GAN_for_cloud_removal" : 2020. Available from <https://github.com/Penn000/SpA-GAN_for_cloud_removal> (accessed 19th September 2020).

Bittner, K., Adam, F., Cui, S., Körner, M. and Reinartz, P.: 2018, Building Footprint Extraction From VHR Remote Sensing Images Combined With Normalized DSMs Using Fused Fully Convolutional Networks, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **11**, 2615–2629.

Cao, R., Fukuda, T. and Yabuki, N.: 2019, Quantifying Visual Environment by Semantic Segmentation Using Deep Learning, *Proceedings of the 24th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2019)*, 623–632.

Everingham, M., Eslami, S. M. A., Gool, L. V., Williams, C. K. I., Winn, J. and Zisserman, A.: 2015, The PASCAL Visual Object Classes Challenge: A Retrospective, *International Journal of Computer Vision*, **111**, 98–136.

Fukuda, T., Novak, M., Fujii, H. and Pencreach, Y.: 2020, Virtual reality rendering methods for training deep learning, analysing landscapes, and preventing virtual reality sickness, *International Journal of Architectural Computing*, **16th September 2020**, https://doi.org/10.1177/1478077120957544.

Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A. and Bengio, Y.: 2014, Generative adversarial nets, *Proceedings of the 27th International Conference on Neural Information Processing Systems (NIPS)*, 2672–2680.

Ikeno, K., Fukuda, T. and Yabuki, N.: 2020, Automatic Generation of Horizontal Building Mask Images by Using a 3D Model with Aerial Photographs for Deep Learning, *Proceedings of eCAADe 2020*, 271–278.

Jabbar, A., Farrawell, L., Fountain, J. and Chalup, S. K.: 2017, Training Deep Neural Networks for Detecting Drinking Glasses Using Synthetic Images, *Neural Information Processing*, 354–363.

Krizhevsky, A., Sutskever, I. and Hinton, G. E.: 2012, ImageNet classification with deep convolutional neural networks, *Proceedings of the 25th International Conference on Neural Information Processing Systems (NIPS 2012)*, 1097–1105.

Long, J., Shelhamer, E. and Darrell, T.: 2015, Fully Convolutional Networks for Semantic Segmentation, *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 3431–3440.

Redmon, J., Divvala, S., Girshick, R. and Farhadi, A.: 2016, You Only Look Once: Unified, Real-Time Object Detection, *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 779–788.

Ronneberger, O., Fischer, P. and Brox, T.: 2015, Unet: Convolutional networks for biomedical image segmentation, *International Conference on Medical Image Computing and Computer-Assisted Intervention*, 234–241.

Wang, T., Yang, X., Xu, K., Chen, S., Zhang, Q. and Lau, R.: 2019, Spatial Attentive Single-Image Deraining with a High Quality Real Rain Dataset, *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 12262–12271.

Zhang, Q., Wang, Y., Liu, Q., Liu, X. and Wang, W.: 2016, CNN based suburban building detection using monocular high resolution Google Earth images, *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, 661–664.

Zhao, K., Kang, J., Jung, J. and Sohn, G.: 2018, Building Extraction from Satellite Images Using Mask R-CNN with Building Boundary Regularization, *Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, 247–251.

Zhou, K., Chen, Y., Smal, I. and Lindenbergh, R.: 2019, Building segmentation from Airborne VHR Images Using mask R-CNN, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 155–161.

SUBJECT-SPECIFIC PREDICTIVE MODELLING FOR URBAN AFFECT ANALYSIS

ROHIT PRIYADARSHI SANATANI[1],
SHAMIK SAMBIT CHATTERJEE[2] and ISHITA MANNA[3]
[1]*School of Planning and Architecture, New Delhi*
[1]*rohitsanatani@yahoo.co.in*
[2]*Independent researcher*
[2]*chatterjeesshamik@gmail.com*
[3]*THSTI, Faridabad*
[3]*imanna.work@gmail.com*

Abstract. Recent developments in crowd-sourced data collection and machine intelligence have facilitated data-driven analyses of the affective qualities of urban environments. While past studies have focused on the commonalities of affective experience across multiple subjects, this paper demonstrates an integrated framework for subject-specific affective data collection and predictive modelling. For demonstration, 10 field observers recorded their affective appraisals of various urban environments along the scales of Liveliness, Beauty, Comfort, Safety, Interestingness, Affluence, Stress and Familiarity. Data was collected through a mobile application that also recorded geo-location, date, time of day, a high resolution image of the user's field of view, and a short audio clip of ambient sound. Computer vision algorithms were employed for extraction of six key urban features from the images - built score, paved score, auto score, sky score, nature score, and human score. For predictive modelling, K-Nearest Neighbour and Random Forest regression algorithms were trained on the subject-specific datasets of urban features and affective ratings. The algorithms were able to accurately assess the predicted affective qualities of new environments based on the specific individual's affective patterns.

Keywords. Urban Affect; Subjective Experience; Predictive Modelling; Affect Analysis.

1. Introduction and Background

The affective qualities of urban environments play a major role in shaping the lived experiences of citizens. Different urban areas 'feel' different due to their different perceptual and experiential qualities, and, as a result, give rise to very different emotional responses among urban dwellers. These varied experiential qualities are often homogenized, and described simply as urban 'character'. Moreover, the parameters of urban experience are usually referred to as the 'intangible' and 'subjective' qualities of the urban realm.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 387-396.

For long, this so called ‘intangible’ nature of such qualities had resulted in them being situated outside the purview of quantitative inquiry and data driven analysis. Recent developments in the fields of computer science, environmental psychology and geo-informatics have, however, begun to open up new methodological frameworks for the collection, visualization and analysis of big-data pertaining to urban affect. Crowd-sourced platforms have become powerful tools for collecting large datasets of environmental and affective parameters. Developments in machine-learning, notably computer vision, have made it possible to extract urban features from sources such as panoramic street-view images, crowd sourced photographs or social media data. These have been correlated with user-reported affective appraisals to build predictive models capable of evaluating the experiential qualities of urban areas.

Of greater interest, however, is the ‘subjective’ nature of the experiential realm. Much of the data driven analyses carried out so far have relied on the commonalities of experience across multiple subjects that constitute a dataset, rather than the subject-specific affective nuances that often make urban experience so unpredictable. A single urban environment can give rise to varied subjective experiences across individuals. A number of subject-specific factors such as cultural background, personality traits, prior experiences and the like become important in this regard. As a result, no two citizens ever experience a city or an urban environment in the exact same way. The broad domain of subjective experience has long been the central focus of studies in the phenomenology of architecture and the urban, and has given rise to multiple theoretical positions and points of view. There have, however, been very few data driven frameworks which attempt to engage with subject-specific experiential qualities within a quantitative framework.

This research attempts to provide a step in that direction. There is immense potential for the adoption of existing data collection and analysis methodologies for the synthesis of a data driven framework for subject-specific predictive affect-modelling. Such a framework will rely on the analysis of subject-specific affective data to train predictive models and thus automate the evaluation of new urban environments based on the affective nuances of the concerned subject.

2. Data driven urban affect analysis

Recent quantitative studies in urban affect have focused on specific experiential parameters such as liveliness, pleasantness, diversity, stress, safety, attractiveness and the like. Huang and Gartner (2016) employed mobile applications allowing users to report affective responses to urban environments on scales such as calm-hectic, diverse-monotonous, safe-unsafe, and appealing-unattractive, thus generating ‘affect maps’ of the city. Similar studies have used geo-tagged Twitter, Flikr and Instagram data to produce ‘smell maps’ (Quercia, et al., 2015) and ‘sound maps’ (Aiello, et al., 2016) of urban areas. The ‘Urban Emotions’ project (Zeile, et al., 2015) combined the use of social media data, app based affective appraisals and objective measurements from wearable sensors to extract, visualize and analyze the affective qualities of cities.

Allied lines of inquiry have focused on employing machine learning algorithms for urban feature extraction from big data sources, and the subsequent visualization of specific perceptual parameters of urban areas. Li (2015) applied pixel classification techniques to Google Street View (GSV) images to calculate Green View Indices and analyze perceived greenery across lower Manhattan. Shen et al. (2017) sampled thousands of GSV images and applied the SegNet (Badrinarayanan, et al., 2017) semantic labeling tool to identify greenery, sky, buildings, roads and vehicles, which could then be represented and analyzed through an interactive visual analytics system. Verma (2018) employed mobile app based image collection platforms coupled with object detection and semantic segmentation models in order to compute and map the perceptual parameters of naturalness, diversity and sky view of a localized urban area.

Further research directions have correlated urban features and affective parameters based on such large training datasets. Naik et al. (2014) relied on a crowd-sourced web based scoring system of perceived safety for over 1 million urban scenes collected through Google Street View images. Urban feature values extracted from the scenes were correlated with safety scores using support vector regression to generate predictive safety maps for 21 US cities. Along similar lines, Dubey et al. (2016) applied Convolutional Neural Networks (CNNs) to predict affective qualities along the parameters of safe, lively, boring, wealthy, depressing, and beautiful.

There is, thus, immense potential for the development of an affect analysis framework that builds upon the methodologies tested out in allied disciplines in order to engage with the subject-specific perceptual and affective qualities of urban environments. While there have been initial advances in the development of similar predictive frameworks for the analysis of architectural enclosures (Sanatani 2020), extending such research directions to tackle subjective experience in the urban realm can lead to promising results.

3. Framework for subject-specific urban affect modelling

The very first step towards an analysis of the 'subjective' affective qualities of the urban realm is the collection of subject-specific data. The framework would need to rely upon datasets that reflect the unique lived experiences of particular individuals at various points in space and time. For predictive modeling, data pertaining to both the form-space-activity parameters of an area, as well the reported experiential qualities of that area need to be collected. The urban parameters (or features) can then be correlated with the experiential qualities for the predictive evaluation of new areas.

3.1. PARAMETER SYNTHESIS

As seen in prior studies, the realm of urban affect can be broken down into specific parameters which focus on specific aspects of the urban experience. Some parameters, such as beauty or attractiveness may tend to primarily capture the visual qualities of the urban realm. Parameters such as perceived safety on the other hand may capture the sensorial as well as the social dimensions of experience. Urban comfort and stress may be influenced greatly by ambient environmental parameters, while perceived familiarity may be strongly driven by prior experience.

While many studies have examined perceptual parameters such as perceived enclosure, greenery, sky view etc, these may not be considered to be affective parameters per say. In fact, these may be considered to be independent parameters which influence the dependent parameters of urban affect. For example, perceived greenery may play a role in determining the rated beauty of an area, depending on the subjective preferences of the individual. Since the focus of this paper is the realm of affect, only a set of dependent affective parameters were shortlisted for the framework.

Based on a critical review of past studies (Huang and Gartner, 2016, Dubey et al., 2016), the following affective parameters were synthesized: **Liveliness, Beauty, Comfort, Safety, Interestingness, Affluence, Stress** and **Familiarity**. The parameter of Familiarity had been included initially as a dependent parameter, as the field observers had been asked to rate how familiar they perceive that area to be. However, in all cases, the post-survey discussions indicated that their ratings reflected how often they have visited that particular area in the past. As a result, this parameter was considered as an independent parameter for the study.

3.2. DATA COLLECTION FRAMEWORK AND TOOLS

10 field observers from diverse linguistic, professional and geographical backgrounds participated in the project **(Table 1)**. For collection of the data points regarding urban features and affective appraisals, an open source mobile application (ODK Collect) was used. Mobile app based data collection has a high degree of scalability, and a framework relying on such tools can be deployed for much larger studies involving larger sample sizes. Affective appraisals of different urban environments within a ˜5 sq.km area in and around Saidulajab in South Delhi were collected. The area was chosen keeping in mind accessibility within the restrictions imposed due to the COVID-19 pandemic. The area also presented a significant diversity of urban character, and thus elicited a wide range of affective responses for further study and analysis. Data collection took place over multiple days, and covered responses between 8 AM in the morning and 7 PM in the evening.

Table 1. Physical and socio-cultural attributes for all observers.

	Observer									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Gender	male	female	male	male	female	male	male	female	male	male
Age	27	29	22	26	26	23	30	23	31	32
Knowledge Domain	Urban Designer	Landscape Architect	Engineer	Architect	Interior Designer	Architect	Project Manager	Economist	Project Manager	VFX Artist
Native Region	West Bengal	Rajasthan	Rajasthan	Haryana	New Delhi	Andhra Pradesh	West Bengal	West Bengal	Tripura	Bihar

Data points were recorded by the observers through a custom form generated for the ODK platform. The form collected the rated values of the 8 affective parameters, along with the geo-location of the observer and the current date and time. In addition, for each data point, the form allowed the observer to take a single photograph along his/her field of view, and record a ˜5 second audio clip of the ambient environment. These were then used for the extraction of urban features as described in the following section. On an average, each observer rated ˜50 scenes, the data for which were synced to a common cloud server for further processing.

3.3. FEATURE EXTRACTION FRAMEWORK AND TOOLS

The collected datasets thus comprised of affective appraisals across subjects for diverse urban environments at different times of day. For analysis and predictive modeling, the key urban features for analysis needed be decided upon, and these features for each of the environments needed to be extracted from the photographs. Based on a review of past methodological approaches, a semantic segmentation approach was taken forward. This allowed for an effective analysis of the key elements within the observer's visual field at the time of rating. A pixel segmentation model, DeepLab (Chen et al., 2017) trained on the CityScapes dataset (Cordts et al., 2016) was adopted for this purpose. The model classified each pixel of the dataset into one of 20 categories (such as road, building, car, person etc.) commonly occurring in urban scenes **(Fig. 1)**. Similar categories such as roads and sidewalks, buildings and walls, etc were then clubbed together, and the total assigned pixels for each category were expressed as a percentage of total pixels in the image. This resulted in the following values (on 100) for each scene: **built score, paved score, auto score, sky score, nature score**, and **human score**.

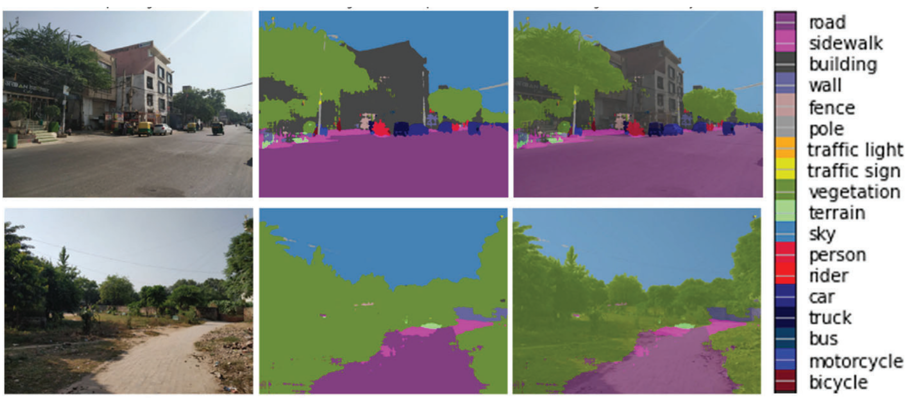


Figure 1. Semantic segmentation of urban scenes.

While a feature extraction model trained on the 'Urban Sounds' dataset (Salamon et al., 2014) was tested out for the semantic labeling of audio clips, the training classes were not found to cover the common ambient sounds occurring in the recordings captured in this study. Manual semantic labeling was thus carried out for preliminary analysis. With the extraction of the key visual parameters, the dataset now comprised of both the dependent affective ratings as well as the independent urban features **(Table 2)**. This data could now be used as training data for predictive modelling using appropriate machine learning algorithms.

Table 2. Key dataset parameters (Observer 1).

	liveliness	beauty	comfort	safety	intrstngnss	affluence	stress	built_score	paved_score	auto_score	sky_score	nature_score	human_score
count	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000	85.000000
mean	4.929412	5.105882	6.011765	7.141176	5.376471	5.176471	4.600000	32.302438	25.200189	3.041879	10.604261	25.292933	2.173679
std	1.956602	1.739072	1.499953	1.114332	1.765924	1.589972	1.226687	26.689994	7.743308	3.679877	12.375720	22.311774	2.760550
min	1.000000	1.000000	3.000000	4.000000	1.000000	2.000000	2.000000	0.000000	9.164469	0.000000	0.000000	0.230225	0.000000
25%	4.000000	4.000000	5.000000	7.000000	4.000000	4.000000	4.000000	4.519368	19.205404	0.389160	0.892578	5.516927	0.376302
50%	5.000000	5.000000	6.000000	7.000000	5.000000	5.000000	5.000000	28.963542	24.530192	1.429443	5.360840	19.770833	1.241618
75%	6.000000	6.000000	7.000000	8.000000	7.000000	6.000000	5.000000	57.562337	31.091309	3.956624	18.760742	38.232259	2.702393
max	9.000000	9.000000	9.000000	9.000000	9.000000	8.000000	8.000000	84.028890	41.054036	12.966471	43.085531	77.514242	14.260661

3.4. PRELIMINARY DATA ANALYSIS

Correlation matrices **(Fig. 2)** were generated for each observer to understand the relationships between the independent variables extracted from the images and the dependent variables rated by the observers. These allow the framework to form user-specific baselines on the basis of the ratings recorded by specific individuals. Given the aim of the framework, a baseline generalized on a sample population data would be inapplicable and inaccurate.

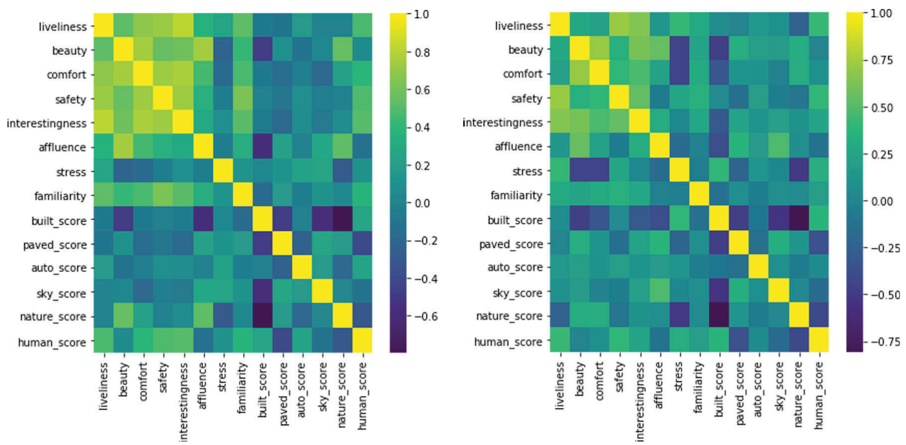


Figure 2. Correlation matrices for Observer 1 (left) and Observer 2 (right).

3.4.1. Subject specificities and affective nuances

On a preliminary analysis of the training data, certain subject-specific nuances were observed. Observers 2, 5, 3 & 10 were found to have high inverse correlations between nature_score and rated stress (r = -0.51, -0.57, -0.72, -0.61), unlike the other observers where there was negligible correlation. Moreover, notable direct correlations between built_score and rated stress appeared for Observers 2, 3, 5 and 8. Similarly, a significant correlation between nature_score and rated beauty (r = 0.56, 0.54, 0.6, 0.69, 0.54) was seen in observers 1, 4, 5, 6 and 10 while the correlation was lower or negligible for the others. Observer 1 also showed a significant correlation (r = 0.51) between people_score and rated 'interestingness', which was not seen among the other observers of the dataset. This would appear to indicate a possibly unique relationship for this observer wherein they appear to identify areas with more people as more interesting. However, all subjects showed an inverse correlation between built_score and rated beauty, indicating that certain general trends might emerge in larger datasets.

While most observers had a high correlation between 'safety' & 'liveliness', observers 5,6 and 8 showed low correlations between these 2 variables. It is interesting to note that there was significant diversity across female observers (r = 0.19, 0.33 and 0.72) showcasing the subject specificities within gendered safety perceptions in the public realm. Reviewing human_score and rated liveliness, observers 1, 2 & 10 showed a significant positive correlation (r = 0.47, 0.42, 0.44) which was much lower for the other observers. Analyzing built_score and affluence, it was seen that Observers 1,2 and 4 to 8 had a high negative correlation (r = -0.33 to -0.75) in contrast to the remaining observers. However, all observers reported a high positive correlation (r = 0.4-0.82) between rated 'affluence' and rated 'beauty'.

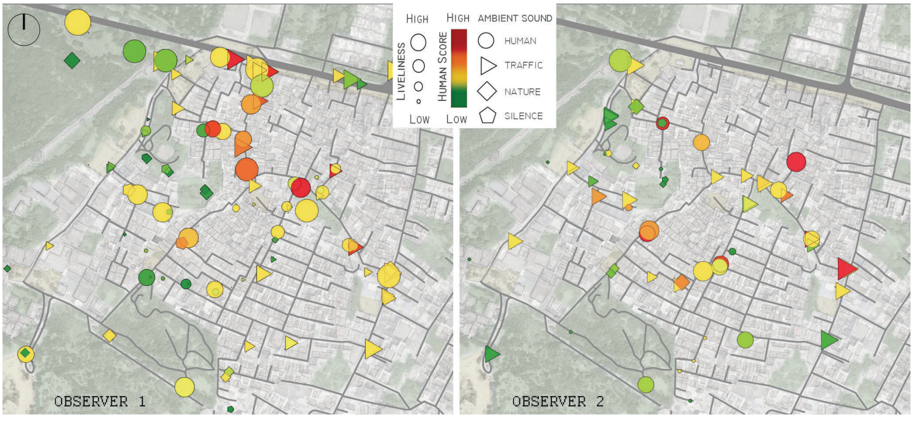


Figure 3. Correlations between rated 'liveliness', human_score, and ambient sound for Observers 1(left) and 2(right).

On analyzing specific data points, certain notable patterns emerged. In large, public open spaces (parks, playgrounds etc.), it was seen that, despite a low human_score, some subjects had rated the area high on the liveliness scale **(Fig 3)**. However, the audio recordings for these areas were labeled 'human', indicating the presence of human activity in the ambient surroundings. Thus, it can be seen that, due to the auditory inputs received by the observer, there was an awareness of groups of people located nearby, which led to the observer's "perceived liveliness" of the area. Similarly, a higher liveliness score was recorded on major roads which had a higher auto score even though these areas had a lower human score. Both these parameters thus influenced liveliness perceptions for some subjects.

Such nuances, revealed through the preliminary analysis, showcases the widely differing emotional impacts of urban environments, and the complex relationship between the physical and the emotional realms in cities. Though further research is required, the initial findings show the complexity of integrating positive emotional responses when designing urban environments for specific user-groups or communities. It also justifies the need for adopting a subject-specific approach, so as to ensure that singular affective nuances of people can be catered to.

3.5. PREDICTIVE AFFECT MODELLING

Having established the subjective nature of the affective ratings, the individual data sets were taken up for predictive modelling. Each scene rated by the subjects had thus the 6 extracted features that were considered to be independent parameters (predictor variables), and 7 rated affective qualities (dependent variables). For initial demonstration of the framework, possible correlations between dependent variables were not taken into account, and the affective ratings were considered to be independent of each other. Separate machine learning models were thus trained for each of the affective qualities.

3.5.1. Algorithm Selection and Error Metrics

Since the affective ratings were collected as numeric data on a 1-9 scale, the models would be predicting the values of single a continuous variable for each affective quality. It was thus necessary to choose an appropriate regression algorithm for this purpose. While non-linear and support vector regression models were tested out, K-Nearest Neighbor (KNN) and Random Forest (RF) Regression algorithms were decided to be most appropriate for initial demonstration. The relatively small training data size for each subject, along with the presence of possible confounding variables supported this choice.

Table 3. Key error metrics for the predictive framework.

	Root mean squared (RMS) error													
	Liveliness		Beauty		Comfort		Safety		Interestingness		Affluence		Stress	
	KNN	RF	KNN	RF	KNN	RF	KNN	RF	KNN	RF	KNN	RF	KNN	RF
Observer 1	1.67	1.77	0.98	0.95	1.23	1.43	0.96	1.22	1.56	1.69	1.19	1.27	0.85	0.86
Observer 2	1.45	1.87	1.45	1.22	1.12	1.39	0.71	1.1	1.72	1.62	1.29	1.68	2.34	2.41
Observer 3	0.43	0.64	0.94	0.5	0.88	1.13	0.92	1.32	1	1.08	1.29	1.53	0.58	0.92
Observer 4	2.54	2.18	2.43	2.48	1.85	1.85	1.98	2.42	2.32	2.29	2.12	1.78	1.84	2.01
Observer 5	2.1	1.97	1.67	1.42	1.94	2.32	2.12	2.28	2.07	1.81	1.18	1.67	1.52	1.57
Observer 6	1	2.43	0.74	1.49	1.41	1.84	1.26	1.33	1.3	1.92	1.19	1.84	1.84	2.02
Observer 7	1.73	2.95	1.96	2.73	1.29	2.11	1.41	1.88	2.19	2.88	1.72	2.08	1.94	2.31
Observer 8	1.25	1.19	1.49	1.73	1.47	2.25	0.54	0.7	0.85	1.2	1.07	1.16	0.71	1.28
Observer 9	1.7	1.69	2.45	2.47	1.29	1.46	1.38	1.34	1.29	1.42	1	1.87	1.29	1.85
Observer 10	0.29	0.46	1.02	1.16	1.3	1.3	0.33	0.25	0.95	1.31	0.27	0.47	0.54	0.96
Mean	**1.416**	**1.715**	**1.513**	**1.615**	**1.378**	**1.708**	**1.161**	**1.384**	**1.525**	**1.722**	**1.232**	**1.535**	**1.345**	**1.619**

The regression algorithms were built in Python using the using the scikit-learn library (Buitinck et al. 2013). In the current version of the framework, the algorithms were able to predict the values of the 7 affective parameters with an average root mean squared (rms) errors of **1.37** (KNN) and **1.61** (RF), on 9-point scales between 1 to 9. **Table 2** describes the key error metrics of the predictive model.

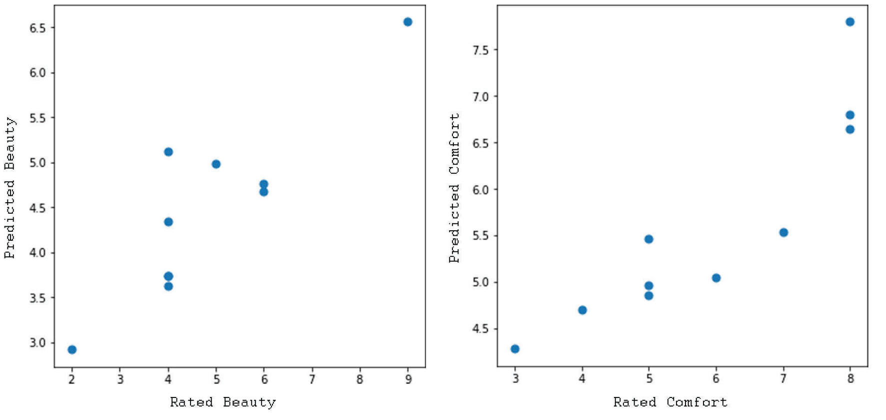


Figure 4. Predicted vs Rated Values of Beauty (left) and Comfort (right) for Observer 1.

4. Opportunities, Challenges and Future Directions

Though in an initial stage of development, this paper attempts to engage with subject-specific experiential qualities within a quantitative data driven framework. Data-driven design and planning strategies within the realm of urban experience often run the risk of homogenizing diverse lived experiences across citizens and communities. This framework adopts the very same methods to address this very issue.

Given the relative ease of collecting user-specific data through personal mobile devices, such a predictive framework may be taken forward for multiple use cases. While route optimization systems in urban areas often provide quickest or shortest routes based on real time data along multiple parameters such as traffic conditions, restrictions etc., affect-based route suggestion based on individual preferences also has great potential. Along similar lines, recommender systems for urban leisure as well as tourism can rely upon such predictive models. Moreover such a framework may be utilized to gain valuable insights into the nuances of affective response for specific demographic groups/communities.

Such directions however do pose multiple challenges. Prediction accuracy becomes critical for the success of such a framework, and the accuracy of the models depends greatly on the consistency of user responses. The choice of affective variables, the data collection methodology, and the user interface become extremely important in this regard. The methodology demonstrated in this framework has scope for refinement keeping such factors in mind. Moreover, any kind of user-specific predictive modeling gives rise to concerns regarding data privacy. Building trust amongst target users of tools which cater to the previously discussed use-cases thus also becomes a major factor. It is hoped that appropriate steps to engage with such challenges are synthesized in the near future, and that this line of inquiry serves as a step towards data-driven analyses of subjective experience in cities.

References

Aiello, L.M., Schifanella, R., Quercia, D. and Aletta, F.: 2016, Chatty maps: constructing sound maps of urban areas from social media data, *Royal Society open science*, **3**(3), 150690.

Aspinall, P., Mavros, P., Coyne, R. and Roe, J.: 2015, The urban brain: analysing outdoor physical activity with mobile EEG, *British journal of sports medicine*, **49**(4), 272-276.

Badrinarayanan, V., Kendall, A. and Cipolla, R.: 2017, Segnet: A deep convolutional encoder-decoder architecture for image segmentation, *IEEE transactions on pattern analysis and machine intelligence*, **39**(12), 2481-2495.

Buitinck, L., Louppe, G., Blondel, M., Pedregosa, F., Mueller, A., Grisel, O., Niculae, V., Prettenhofer, P., Gramfort, A. and Grobler, J.: 2013, API design for machine learning software: experiences from the scikit-learn project, *arXiv preprint arXiv:1309.0238*.

Chen, L.C., Papandreou, G., Kokkinos, I., Murphy, K. and Yuille, A.L.: 2017, Deeplab: Semantic image segmentation with deep convolutional nets, atrous convolution, and fully connected crfs, *IEEE transactions on pattern analysis and machine intelligence*, **40**(4), 834-848.

Cordts, M., Omran, M., Ramos, S., Rehfeld, T., Enzweiler, M., Benenson, R., Franke, U., Roth, S. and Schiele, B.: 2016, The cityscapes dataset for semantic urban scene understanding, *Proceedings of the IEEE conference on computer vision and pattern recognition*, 3213-3223.

Dubey, A., Naik, N., Parikh, D., Raskar, R. and Hidalgo, C.A.: 2016, Deep learning the city: Quantifying urban perception at a global scale, *European conference on computer vision*, 196-212.

Huang, H. and Gartner, G. 2016, Using mobile crowdsourcing and geotagged social media data to study people's affective responses to environments, *in* C. Capineri (ed.), *European Handbook of Crowdsourced Geographic Information*, Ubiquity Press, 385-399.

Li, X., Zhang, C., Li, W., Ricard, R., Meng, Q. and Zhang, W.: 2015, Assessing street-level urban greenery using Google Street View and a modified green view index, *Urban Forestry & Urban Greening*, **14**(3), 675-685.

Naik, N., Philipoom, J., Raskar, R. and Hidalgo, C.: 2014, Streetscore-predicting the perceived safety of one million streetscapes, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops*, 779-785.

Ojha, V.K., Griego, D., Kuliga, S., Bielik, M., Buš, P., Schaeben, C., Treyer, L., Standfest, M., Schneider, S. and König, R.: 2019, Machine learning approaches to understand the influence of urban environments on human's physiological response, *Information Sciences*, **474**, 154-169.

Quercia, D., Schifanella, R., Aiello, L.M. and McLean, K.: 2015, Smelly maps: the digital life of urban smellscapes, *arXiv preprint arXiv:1505.06851*.

Salamon, J., Jacoby, C. and Bello, J.P.: 2014, A dataset and taxonomy for urban sound research, *Proceedings of the 22nd ACM international conference on Multimedia*, 1041-1044.

Sanatani, R.P.: 2020, A machine-learning driven design assistance framework for the affective analysis of spatial enclosures, *RE: Anthropocene, Design in the Age of Humans, Proceedings of the 25th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2020)*, 741.

Shen, Q., Zeng, W., Ye, Y., Arisona, S.M., Schubiger, S., Burkhard, R. and Qu, H.: 2017, StreetVizor: Visual exploration of human-scale urban forms based on street views, *IEEE Transactions on Visualization and Computer Graphics*, **24**(1), 1004-1013.

Verma, D., Jana, A. and Ramamritham, K.: 2018, Quantifying urban surroundings using deep learning techniques: a new proposal, *Urban Science*, **2**(3), 78.

Zeile, P., Resch, B., Dörrzapf, L., Exner, J.P., Sagl, G., Summa, A. and Sudmanns, M.: 2015, Urban Emotions–tools of integrating people's perception into urban planning, *From vision to reality for vibrant cities and regions. Proceedings of 20th international conference on urban planning, regional development and information society*, 905-912.

IN-BETWEEN SPACES: DATA-DRIVEN ANALYSIS AND GENERATIVE DESIGN FOR PUBLIC HOUSING ESTATE LAYOUTS

KWAN KI CALVIN WONG[1] and JEROEN VAN AMEIJDE[2]
[1,2]*The Chinese University of Hong Kong*
[1]*kkwongcalvin123@gmail.com* [2]*jeroen.vanameijde@cuhk.edu.hk*

Abstract. As Hong Kong constructs increasingly high-density, high-rise public housing estates to increase land use efficiency, public in-between spaces are more constrained, which impacts the quality of social relations, movements and daily practices of residents (Shelton et al. 2011; Tang et al. 2019). Current planning practices are focused on the achievement of quantitative performance measures, rather than qualitative design considerations that support residents' experiences and community interaction. This paper presents a new methodology that combines urban analysis and generative design for the regeneration of social housing estates, based on the spatial and social qualities of their in-between spaces.

Keywords. Social Housing; Public Open Space; Generative Design; Urban Planning.

1. Introduction

Nearly half of Hong Kong's population is living in public housing estates, in public rental housing (31%) and subsidised home ownership schemes (17%). The government housing programme was started in the 1950's to resettle squatter home camps and expanded in the 1960's in response to a large population influx and social unrest (Yung, 2008). Similar to how in Europe large scale social housing projects were constructed as part of the post-war atmosphere of solidarity, the Hong Kong housing programme was systematised to ''help to build a sense of community and greater social integration among Hong Kong's people'' (Yu 1997, p. 543). To maximise the efficiency of the estates in relation to a limited amount of available land, Hong Kong's public housing is characterised by high-rise slab blocks or towers arranged in dense patterns with limited public spaces or greenery in between.

Over time, the planning strategies for public housing estates have gradually developed towards self-sufficient estates, through incorporation of comprehensive retail and public facilities such as for sports, recreation and socializing. In recent decades, the public space configurations have shifted from open spaces as the heart of community to retail malls to serve this function (Wang & Chen, 2018). With the increase of density, the under-supply of open spaces has become a problem in Hong Kong (Lai, 2017).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 397-406.

Studies show that the quality of life of public housing tenants can be significantly improved through access to socialising spaces, recreational and green spaces, and community facilities (Saunders et al., 2014; Gou et al., 2018). Well-planned public spaces in housing estates can facilitate people's interaction with neighbours and the surrounding context, which contributes to public housing residents' well-being and integration within society (Zheng et al., 2015; Lau & Murie, 2017). However, studies have found that there is a mismatch in the type of public spaces that is provided, as spaces are found to be unequally distributed, overprogrammed or overregulated (Lai, 2018; Chow, 2018). There is a need for more precise studies into the actual use of public spaces in public housing, to understand how to improve their quality and effectiveness, to make more effective use of limited urban space.

2. Urban Theory: Neighbourhood Design and the Sense of Community

The design philosophy of Hong Kong's housing estates can be traced to the Town Planning movement, inspired by Clarence Perry's 'neighbourhood unit concept'. The idealistic vision was to create new urban communities which would be integrated and harmonious, containing residential buildings, community facilities and services for the residents. The physical layout of the housing estates was based on assumptions around the needs of local residents, aiming to give ''rational and idealised form to support their patterns of life and sense of community'' (Kan 1974, p. 160).

The 'failure' of several well-known international examples of public housing, such as the Pruitt-Igoe projects in St. Louis (demolished 1972-76) or the Heygate Estate in London (demolished in 2011-14), has demonstrated that the quality, management and sense of ownership of the public spaces plays a significant role in maintaining the reputation and social success of public housing (Glendinning & Muthesius, 1995). In Hong Kong, public housing estates are generally considered successful, but public spaces are designed to satisfy basic needs, rather than seen as an opportunity for the comprehensive design of community support infrastructure. The rigid planning of functions across estates results in a lack of adaptation to changing needs of the population.

Jane Jacobs (1961) argued that urban regeneration should considered the needs of city dwellers, in contrast to the Modernist practice of top-down urban planning. She suggested that housing should be connected and related to the city, so that they allow people and urban fabric to build on the city's diversity. William Whyte (1980) demonstrated correlations between human behaviours and urban form, which can be translated into design guidelines for the design and management of better-quality open spaces. Whyte's methodologies included the use of direct observation of users, and statistical analysis of their activities. Through watching how people use a space and by comparing users' reaction to different urban elements, we can form an understanding about which elements contribute to good quality public spaces.

3. Methodology

Figure 1. Nam Shan Estate in Sham Shui Po, Hong Kong.

Nam Shan Estate, one of the older public housing estates in Hong Kong that has lively public spaces (Fig. 1), was chosen to investigate the two key initial questions of this research:

- Which aspects contribute to the socialization of open space?
- How can we quantify the social performance of different open spaces?

3.1. FIELD OBSERVATIONS AND MAPPING OF SOCIAL ACTIVITIES

A series of site visits with a group of observers was organised to take snapshot observations of the amounts of people across the site, and the types and durations of social activities that they were engaged in. Several typical time periods were selected, such as weekday lunchtime, afternoon and evening, to capture typical short-term public space uses by various user groups which included residents as well as visitors from the surrounding district.

The activities in the open spaces of the estate were mapped into the estate plan, and categorized into various groups, to assists in the analysis of the different estate spaces. The type of activities was documented, as well as the duration of each activity (Fig. 2.1). Customised computational tools for the analysis and visualisation of closeness between people allowed to discern areas with higher potential for social interaction (Fig. 2.2).

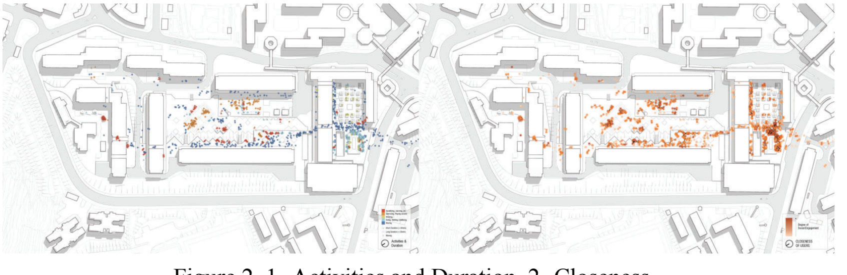


Figure 2. 1. Activities and Duration, 2. Closeness.

3.2. URBAN MORPHOLOGY ANALYSIS

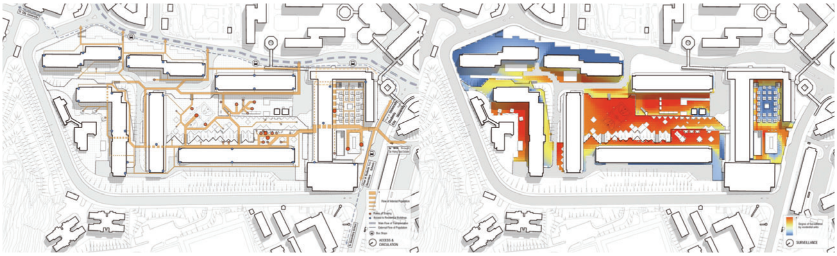


Figure 3. 1. Access and Circulation, 2. Surveillance by residential units.

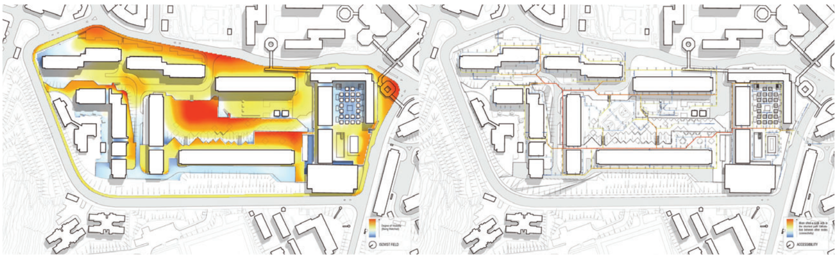


Figure 4. 1. Visibility, 2. Accessibility.

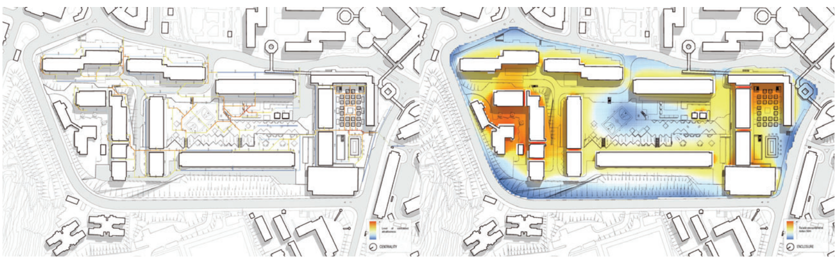


Figure 5. 1. Centrality, 2. Enclosure.

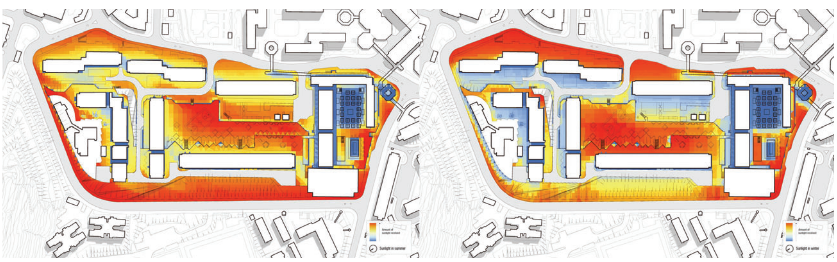


Figure 6. 1. Summer Sunlight, 2. Winter Sunlight.

In addition to the human-centric studies, a series of space-centric analyses was done to understand and visualise the housing estate's various in-between spaces.

Access and Circulation demonstrates how people travel between their individual housing blocks and the major destination points inside and around the estate's site boundary. Based on the observations of flow intensities along the different connecting pathways through the estate, different line thicknesses are visualised (Fig. 3.1).

Surveillance indicates the level of surveillance for each grid point of the public spaces, by analysing the lines of sight, viewing angles and distances to all visible surrounding windows (Fig. 3.2). Obstacles such as canopies or landscaping affect the value, creating different levels of privacy.

Visibility analyses how much of the surrounding area can be observed by subjects in the public space, viewing other areas of the estate (Fig. 4.1). This aspect is related to the sense of orientation, supervision and control, and may be linked to the public or private character of the spaces. Introvert people or behaviours may be found in areas with less visibility, while extrovert people may seek out more connected and visible sites.

Accessibility considers the attractiveness of origins and destinations around the estate, and evaluates the in-between spaces according to number of times a node is included in the shortest path calculation between these end nodes. The resulting value indicate whether a space is close to the main pathways through the estate, and whether it is convenient to be accessed (Fig. 4.2).

Centrality uses a similar analysis of shortest paths between possible origin and destinations, but considers all options of routes. Higher values indicate better connectivity to the other spaces in the estate (Fig. 5.1).

Enclosure is determined by the relative amount of building façades surrounding each space within a specified distance (Fig. 5.2). In addition to visibility, this analysis helps to understand the level of privacy of the activities that may take place. The amount of enclosure also indicates whether spaces are internalised in the estate, with less exposure to the surrounding urban context.

Summer Sunlight and *Winter Sunlight* analyse the amount of sunlight each area receives, using a computational tool to calculate solar radiation (Figs. 6.1 and 6.2). As Hong Kong's climate is relatively warm and humid during most periods of the year, shaded and well-ventilated outdoor spaces are much more suitable for social activities than spaces that receive direct sunlight.

4. Data Interpretation

By applying a scoring system with seven measurements as defined in section 3.3, the physical urban qualities of different open spaces were quantified and rated. This data was then translated into visual graphics to study possible correlations with the activity conditions found. Figure 7 shows each space described through circular diagrams. The upper one demonstrates the user behaviour interpreted from the data collected, while the lower circle shows the quantified results from the urban morphology analyses. The results highlighted in orange are the qualities that are found to have the most influence on the type of use of each specific space.

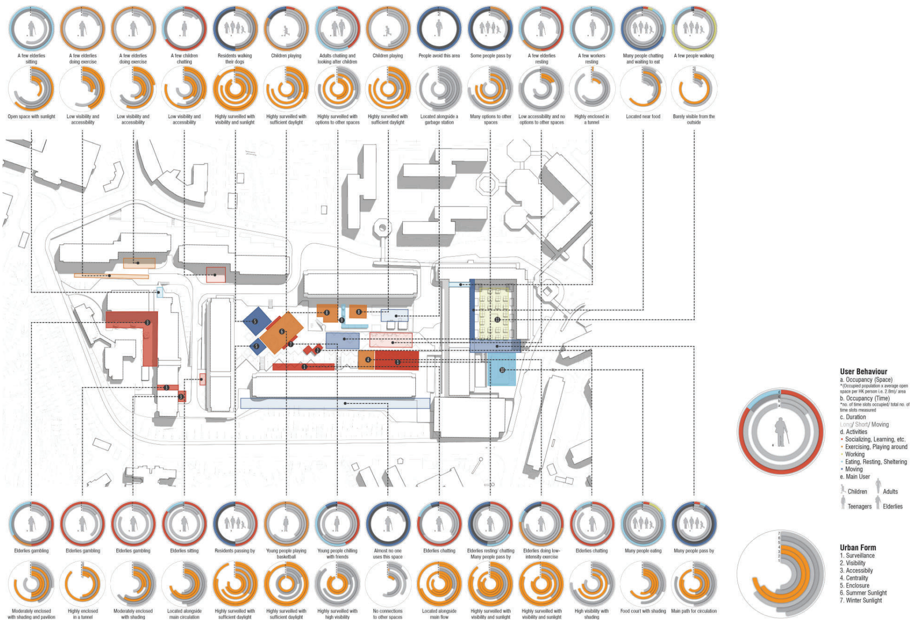


Figure 7. Interpretation of spatial analyses and observational data of activities.

Maslow's Hierarchy of Needs, also known as the Pyramid of Needs, offers a classification of different types of needs and desires ranging from basic needs to self-actualization. The categories translate into different aspects, including food, safety, love and self-esteem, which can be understood as the motivations for different types of everyday activities (James, 2019). We can differentiate shared facilities that address immediate physical needs such as to provide shelter or rest, from those that support mental health needs or personal development. This creates an evaluative framework to rate each of the different public spaces, and evaluate their importance regarding personal growth and community interaction.

A reflection on the use and spatial properties of Nam Shan Estate shows that the estate has several well-used spaces located in the large central area of the estate due to their connectivity, visibility and centrality, while there are several underused spaces around the perimeter. There is little variation in the spatial qualities of the central spaces, to cater for introvert or extrovert residents. Spaces for different age groups are separated from eachother through distance or through barriers. Older men gathering to play games and gamble seek out unattractive tunnel spaces as these are the only ones with limited surveillance. There seems to be a potential to improve the use of several perimeter spaces, although the quality of these remains limited due to the arrangements of the buildings on the site. These bad performing spaces have low visibility and accessibility, and low amounts of enclosure.

5. Explorations around Data-driven Generative Design

The analysis described above indicated several key opportunities for improvement of Nam Shan Estate, if it can be speculated that the space distribution, circulation network or even the building distribution on site could be redesigned. As this estate was inaugurated in 1977, it may be redeveloped in the medium-term future, as is being undertaken with other public housing estates that have an aging building stock and relatively low site density. As part of our study, we developed a methodology that allowed to explore several urban design solutions for the regeneration of the estate, based on the spatial and social qualities of their in-between spaces. To research the methodology, we explored how the generative design can be linked to the outcomes of the public space analysis, using this as a design driver for the generation of new estate layouts.

5.1. GENERATIVE DESIGN METHODOLOGY

Figure 8. Generative process with the help of computational algorithms.

A computational workflow was set up with the help of Rhino/Grasshopper and Wallacei, a recent plugin developed by Makki, Showkatbakhsh & Song (2019) for analytical and evolutionary design development.

The control variables in this generative process were the Gross Floor Area (GFA) and area of open spaces. In the first stage of testing, twelve buildings were set up to have similar dimensions as the existing building blocks on site, resulting in a similar GFA as the existing estate. The areas of open spaces were also pre-defined, with dimensions based on their importance for socialization.

The independent variables were the locations of buildings, orientations of buildings and the locations of open spaces. The site was first split into grids, and sliders were created to move and snap the objects onto the grids, anywhere within the site boundary. The buildings were also provided with options to turn with a degree of 90 to allow more variations in urban layout (Fig. 8).

While running the Genetic Algorithm as part of the Wallacei platform, a number of combinations were generated and evaluated against several fitness criteria. A scoring system was used for evaluation, with objectives set up to minimise collisions of buildings and spaces, maximise desired connections of spaces, and maximise the physical qualities which were found conducive for the particular activity in the site analysis stage.

As the process cycles through numerous estate layout options, for each option the locations and qualities of public open space were analysed, using the same evaluation criteria as in our earlier research. The process searched for building arrangements which produce public spaces with the highest possible scores, matching a pre-programmed list of public spaces and connections to support the estate residents. This list contained an improved offering of facilities similar to the existing, adjusted based on the research findings about which types of spaces were most in demand. An additional improvement introduced was to create connections that offer 'intergenerational collaboration', taking reference from the international precedents which bring users of different demographics together and enhance the degree of user diversity in a space.

5.2. GENERATIVE DESIGN OUTCOMES

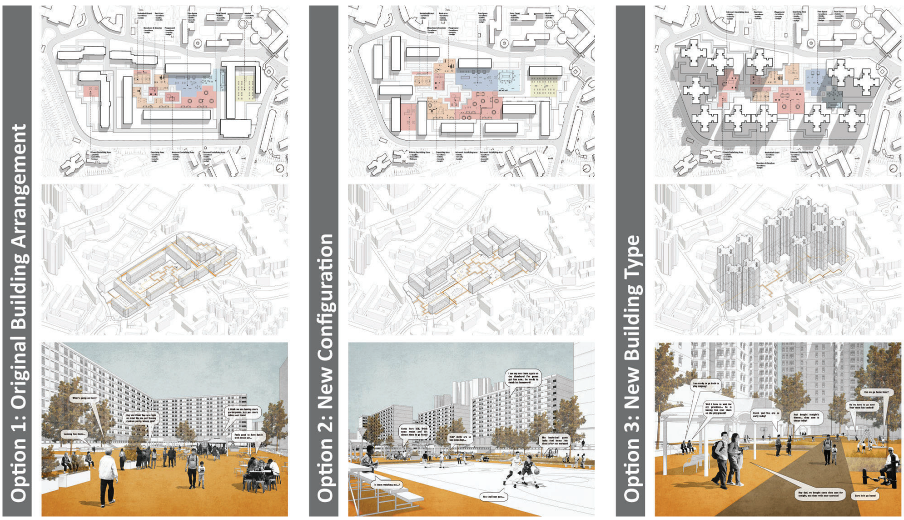


Figure 9. Three outcomes based on different requirements.

5.2.1. Option 1: Original Building Arrangement

For this option, the positions of the buildings were left unchanged. Public space and facilities were relocated at better positions in relation to the urban form and in relation to eachother. The outcomes were as following:

- The food court was moved near the central area to attract more people and to have the possibility to let users expand into a neighbouring open space,
- A flexible open space at the centre of the estate serves as attractor point and meeting space within the circulation network,
- More varied spaces emerge as separate introvert spaces are located at the eastern and southern perimeter.

5.2.2. Option 2: New Slab Building Configuration

In this scenario, the site coverage by buildings was left unchanged, yet buildings and public spaces were allowed to reorganise to achieve better spatial conditions and interrelationships for the public spaces. This resulted in an optimised solution in which:

- The buildings moved towards the site boundary to create a larger central open space,
- More gaps between buildings were created to provide more connectivity to all spaces,
- A wider range of different (more public and more private) open spaces was created, yet with better visibility and connectivity between the different spaces and potential user groups.

5.2.3. Option 3: New Cruciform Tower Configuration

In the third scenario, the building typology was changed from 'slab' to the 'Harmony' type, keeping the site coverage similar but increasing the Floor Area Ratio (FAR). The buildings and public spaces were allowed to reorganise to achieve better quality public spaces and interrelationships. The result of this was:

- The towers were located around the site boundary to create a large central open space,
- The public spaces would receive more shading in summer,
- A higher degree of surveillance onto the public spaces, in particular in corner areas of the public spaces in between several buildings,
- A less wide range of different types of open spaces was created, due to the repetitive nature of the more compact footprint towers.

6. Conclusions

The ambition of this research was to explore new data-driven methodologies for the analysis and creating of public spaces in public housing estates, to address the insufficient qualities of current open spaces and the lack of planning methods aimed at user-experience, social interaction and community formation. Although there are many complex factors involved in predicting the success of public spaces, linking spatial analysis to environment-behavioural studies can offer new insights into the effectiveness of urban design. Analysing social aspects such as human activity patterns through spatial and quantified data offers new research opportunities in-between generative design and social science, enabling human-centric planning that creates environments that promote liveliness in public housing estates, enhancing social engagement, community support and public health and well-being.

This study has investigated how priorities and outcomes can be changed in planning processes for high-density housing, when the different physiological, psychological and self-fulfilment needs of residents are taken as a starting point for space planning rather than as an afterthought. This type of human-centric planning, when further developed with more accurate constraints around the technical, economic and environmental performance of public housing estates, could deliver urban living environments from all ages and backgrounds. As it has become clear that the doctrine of maximum efficiency is inadequate to deliver quality of life, it is time to rethink which other types of optimisation criteria can be used to create housing environments that support people and communities in Hong Kong, and other cities with similar needs around the world.

References

Chow, A.: 2018, *Geospatial Analysis of Public Open Space Accessibility in Hong Kong*, Civic Exchange and Hong Kong Jockey Club Charities Trust, Hong Kong.

Glendinning, M. and Muthesius, S.: 1995, *Tower Block: Modern Public Housing in England, Scotland, Wales and Northern Ireland*, Yale University Press, for the Paul Mellon Centre for Studies in British Art, New Haven.

Gou, Z., Xie, L., Lu, Y. and Khoshbakht, M.: 2018, Quality of Life (QoL) Survey in Hong Kong: Understanding the Importance of Housing Environment and Needs of Residents from Different Housing Sectors, *International Journal of Environmental Research and Public Health*, **15**(2), 219.

Jacobs, J.: 1961, *The Death and Life of Great American Cities*, Random House, New York.

James, L.: 2019, *Implications and Application of Maslow's Hierarchy of Needs in Community Change Initiatives*, Ph.D. Thesis, Valdosta State University. Political Science.

Kan, A.: 1974, *A study of neighborly interaction in public housing: The Case of Hong Kong*, Chinese University of Hong Kong. Social Research Centre.

Lai, C.: 2017, *Unopened Space: Mapping Equitable Availability of Open Space in Hong Kong*, Civic Exchange, Hong Kong.

Lai, C.: 2018, *Open Space Opinion Survey*, Civic Exchange and Hong Kong Jockey Club Charities Trust, Hong Kong.

Lau, K.Y. and Murie, A.: 2017, Residualisation and resilience: public housing in Hong Kong, *Housing Studies*, **32:3**, 271-295.

Saunders, P., Wong, H. and Wong, W.P.: 2014, Deprivation and Poverty in Hong Kong, *Social Policy & Administration*, **48**(5), 556-575.

Shelton, B., Karakiewicz, J. and Kvan, T.: 2011, *The Making of Hong Kong: From Vertical to Volumetric*, Royal Asiatic Society, Hong Kong.

Tang, W.S., Lee, J.W.Y., Hui, T.W. and Yip, M.K.C.: 2019, The "Urban density" question in Hong Kong: From absolute space to social processes, *City, Culture and Society*, **17**, 46-53.

Wang, Y. and Chen, J.i.e.: 2018, Does the rise of pseudo-public spaces lead to the 'end of public space' in large Chinese cities? Evidence from Shanghai and Chongqing., *Urban Design International*, **23**, 215–235.

Whyte, W.: 1980, *The Social Life of Small Urban Spaces*, Project for Public Spaces, New York.

Yu, S.W.K.: 1997, The Hong Kong Government's Strategy for Promoting Home Ownership: An Approach to Reducing the Decommodifying Effects of Public Housing Services, *International Journal of Urban and Regional Research*, **21**(4), 537-553.

Yung, B.R.: 2008, *Hong Kong's Housing Policy: A Case Study in Social Justice*, Hong Kong University Press, Hong Kong.

Zheng, W., Shen, G., Wang, H. and Lombardi, P.: 2015, Critical issues in spatial distribution of public housing estates and their implications on urban renewal in Hong Kong, *Smart and Sustainable Built Environment*, **4**(2), 172-187.

MEASURING SUSTAINABILITY AND URBAN DATA OPERATIONALIZATION

An integrated computational framework to evaluate and interpret the performance of the urban form.

DIELLZA ELSHANI[1], REINHARD KOENIG[2],
SERJOSCHA DUERING[3], SVEN SCHNEIDER[4] and
ANGELOS CHRONIS[5]
[1,2]*Bauhaus University Weimar*
{}@uni-weimar.de
[3,5]*Austrian Institute of Technology*
[3,5]*{serjoscha.duering|angelos.chronis}@ait.ac.at*
[4]*Bauhaus University Weimar*
[4]*sven.schneider@uni-weimar.de*

Abstract. With rapid urbanization, the necessity for sustainable development has skyrocketed, and sustainable urban development is a must. Recent advances in computing performance of urban layouts in real-time allow for new paradigms of performance-driven design. As beneficial as utilizing multiple layers of urban data may be, it can also create a challenge in interpreting and operationalizing data. This paper presents an integrated computational framework to measure sustainability, operationalize and interpret the urban form's performance data using generative design methods, novel performance simulations, and machine learning predictions. The performance data is clustered into three pillars of sustainability: social, environmental, and economical, and it is followed with the performance space exploration, which assists in extracting knowledge and actionable rules of thumb. A significant advantage of the framework is that it can be used as a discussion table in participatory planning processes since it could be easily adapted to interactive environments.

Keywords. Generative design; data interpretation; urban sustainability; performance simulation; machine learning.

1. Introduction

Given the changes the world has undergone over the last decades, the necessity for sustainable development has skyrocketed. Yet, to balance social equity and economic potential with the environmental-focused design is quite a lofty challenge. The urban agendas are fostering the call for a more sustainable development followed by tools for action. Besides, many attempts towards quantifying quality in the domain of sustainable development are ongoing.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 407-416. © 2021 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Many researchers have already made substantial contributions to this discussion (Cotgrave & Riley, 2013), presenting answers for how sustainable a project can be and what impact such a sustainable project has on the world. The traditional evaluation method of urban spaces is either by analyzing and interpreting secondary data such as open-source data or generating data from surveys and focuses on humans behaviors and more on an individual level (Marans & Stimson, 2011). Similarly, there have been several checklists on measuring sustainability introduced and assisted in urban design.On the other hand, frameworks that can estimate the impact of changing elements within the urban systems are in high demand (Achary et al., 2017). They make the planning process more manageable, where designers combine their design instinct with performance data. In this context, data mining, generation, and analysis gain more significance, especially in early design phases (Nembrini, 2012). By providing an enormous number of analysis parameters that influence specific performance metrics, one can increase a designer's capacity to achieve design goals based on urban performance. The recent advances in computing urban layouts' performance have opened new paradigms of performance-driven and evidence-based urban design. Applying performance-driven design could create a workflow that allows us to have overall feedback on the design's performance and have an iterative process of advancements based on the formation of ideas and their evaluations (Lawson, 2006). Collating digital computation and humans' creativity offers the possibility to manage the urban system's complexity and allows the ability to test vast design options in a short manner of time. Interpreting urban data, either mined from open source data platforms, generated from simulations, or different computational methods would assist the early stages of design as guidance towards urban design. To operationalize data, understand why a design performs in the way it does, and avoid mistakes in the planning process, a sound understanding between the design parameters and the different performance criteria is crucial (Bielik et al., 2019). This understanding could lead to extracting knowledge on actionable guidance for designers. However, analyzing many aspects of an urban space leads to several data layers and an almost unmanageable amount of information. As beneficial as having many urban data layers might be, it also creates a challenge in finding relevant datasets (Ribeiro, 2015). This way, data can also be confusing if the approaches toward dimensionality reduction and data interpretation are inadequate. Even more, impracticable data can be deficient because quantifying a design's performance does not necessarily provide insight or guidance on why it performs better or worse and how to improve the urban layout. More research is needed on quantifying urban sustainability in new urban development projects, as well as filtering the information and clustering it in an operationalizable format, which is interpretable and easy to understand by all the stakeholders. Additionally, extracting knowledge on actionable guidance for designers based on the performance data would contribute to the early stages of sustainable urban planning. In response to the research gaps, this paper presents an integrated computational framework to operationalize and interpret the performance of urban forms; Which algorithmically builds a generative urban design model, adjusts methods to quantify urban performance in each pillar of sustainability in real-time, and it correlates the input design parameters with the outputs that indicate the performance.

2. Architecture of the Framework

The framework uses the state of the art methodologies on urban design: algorithmic urban planning, generative design methods, performance simulations, agent-based urban dynamic models, and machine learning predictions. Solution space exploration and performance data analysis follow each calculation, from where data is interpreted, and general rules of thumb derived. The primary work environment where the framework is implemented is Rhino and its visual programming language Grasshopper environment. The framework is consisted out of three parts the algorithmic generation of urban form, the evaluation part where existing methods are adapted, extended, and aggregated; and the data analysis part.

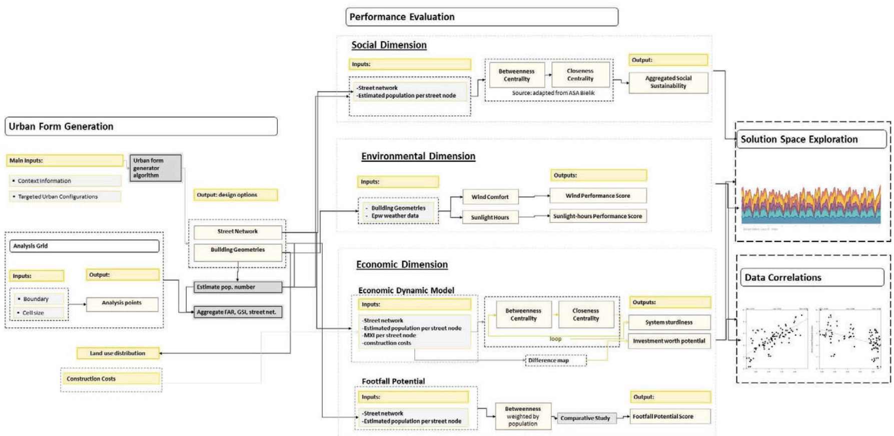


Figure 1. Architecture of the framework.

2.1. THE GENERATIVE DESIGN ALGORITHM AND PRINCIPLES

The first part of the framework is the generation of the urban form. This paper employs a generative design method, which from the algorithmic process and specific input parameters enables exploring different complex urban forms. As input parameters, the generative model uses the street network orientation and the density indicators because density has been a relevant metric in urbanism since the small settlements' formation until their evolutions into villages or cities. In the book 'The Radiant City,' Le Corbusier et al. (1967) state that cities need a specific density for the machine-age man, which would provide short travel time between housing, jobs, and other attractive locations in the city. Furthermore, Jan Gehl (2010) states that urban density is a critical factor in understanding how cities function. With COVID-19, the global pandemic faced in 2020, the debate around whether highly dense areas and compact cities are the goals of urban planners comes into question. Berghauser Pont and Haupt, in their Book

Spacematrix: Space Density and urban form, present several density metrics that explore urban density as crucial information in designing and reading the city and categorize the building structures into different categories of urbanity. The density metrics that it elaborates on are the FAR floor area ratio and the GSI Ground space index.Regarding street network orientation, Geoff Boeing - a researcher in urban planning- (2019), indicates that the street network orientations assist in understanding the histories of places' urban development. Furthermore, he claims that street network orientation is also helpful when evaluating the current network system. Based on the orientation of streets planners, it could be critical and explore further design proposals. Given the aforementioned, the algorithm that generates design options uses the street network orientation, Ground Space Index (GSI), and Floor Area Ratio (FAR). The street network snaps to the existing streets by creating superblocks. Within those areas regular grid of street nodes are generated, the main streets rotate for 20 degrees after each iteration, offering the option to explore various street network orientation. While the size of the footprint(amount of space that it takes in the plot) is based on the targeted Ground Space index, The Floor Area ratio is based on the buildings' height.The street network segments are categoried based on their closest direction out of four main ones (North-South, Northwest -Southeast, West-East, Southwest-Northeast), and their meter length presented in % per each design design case, which output 4 numbers that indicates the amount of street lenghts in the corresponding orientation. The overall density and street network are validated after the generation; the information is aggregated in the analysis grid. The overall average is used as an aggregated indicator, which is used to correlate the output performance.

2.2. PERFORMANCE INDICATORS DERIVATION ON THE THREE PILLARS OF SUSTAINABILITY

The indicators are categorized in the three pillars of sustainability: social, environmental, and economical. The study focuses on evaluation metrics that highly depend on the urban form. This way, the designer can contribute as much as they can towards finding the best performing solution.

2.2.1. Social Sustainability Evaluation Method

The social dimension of sustainability states a social organization system that tackles the equalities and relations between humans. Societies do more than only exist in space (Hillier B. H., 1984). They act and interact with each other. Precisely those mutual relationships between individuals and human interactions make their behaviors social (Weber, 1991). An essential social factor of equality that depends on the built environment is equal access. Urban issues that reflect unequal accessibility can lead to consequences that affect the whole city as a complex system, such as social segregation or exclusions. Consequently, it is crucial to keep in mind the accessibility while designing. This study adapts space syntax metrics with demographic data to measure social segregation and access to significant quarters of the designed urban layout. Some parts of the city are livelier, based on their connectivity properties, which can be considered spots with high interaction potential since more people frequent them. To see how integrated people to other society are, one can measure the accessibility of every individual to the lively spots. This analysis can be done using street network represented in a graph. A method that estimates the pedestrian flows and calculates the access to the lively areas is presented from Bielik, et al. (2018). This paper uses the same approach, and just it first estimates the population number based on the building geometries. And it uses this information as a weight in the betweenness centrality calculation. The results are on the street network, so the information is aggregated in an analysis grid. The process is repeated for all the generated cases, and from the global values, based on Jenks natural breaks, five category bounds are defined. The sum of favorable locations is used as an aggregated indicator in social sustainability.

2.2.2. Environment Sustainability Evaluation Method

Lately, with the threat of climate change, and the significant impact of the built environment on climate, microclimate analysis is a must in the early stages of design. The geo-located wind speeds and solar radiation are the only microclimatic parameters that depend widely on urban planning (Reiter, 2010). Hence, this study focuses on sunlight hours and wind comfort performance of the urban form. In order to have instant feedback on the performance, the research uses pre-trained machine learning models of CIL (City Intelligence Lab of AIT) to predict the microclimate analysis. The ML model that predicts the wind comfort is trained on computational fluid dynamics CFD simulations. Based on each point's wind factors, the results are categorized on the Lawson Wind Comfort Criteria. Because of the high wind speed, the areas exposed to the last two categories are considered dangerous, and the rest is safe and provides pedestrian comfort in terms of wind. The percentage of the safe regions is used as an aggregated performance indicator for the design option. This process is repeated for all design cases, the overall results are remapped in a scale from 0 to 10 (where the higher the number the more pedestrian comfort offers the design). The sunlight hours similarly are predicted using ML models of Infrared. The threshold of vulnerable spots and good performing areas is set by defining the place's purpose and the corresponding sunlight hours demand (while people might need a minimum of two hours of sunlight, some vegetation types demand over six hours). In this study, we set the threshold to 5,5 hours. The areas that are exposed to less than 5,5 hours of daily sunlight are considered vulnerable. The amount in % of the good performing spots is used as a performance indicator. Similarly as in the wind comfort, the process is repeated for each case, and the result values are remapped in a range from 0 to 10.

2.2.3. Economic Sustainability Evaluation Method

The economic potential of a designed option is tightly related to the time dimension. Agent-based models and analytical economic models cannot be integrated easily into the design process (Karimi, 2012). However, combining existing workflows, this research puts together a hypothetical economic dynamic model to understand how resilient the city as a complex system is. Additionally, it gives insights on the investment worth the potential of a spot. The workflow is consisted out of: spacematrix and MXI; this information is brought as destination weight to the evolved configurationally properties of streets by Bielik et al. (2019), creating an endless cycle of simulating the pedestrian movement flows and accordingly the land use distribution. From this model, this research outputs two performance indicators: The worth investment potential and the system sturdiness. For the investment worth potential, the dynamic model's first and last stage is used to create a difference map. This difference map is showing if the place would become more attractive or less in time. Afterward, the results are overlapped with the constructions costs based on the landuse of the building. Overall results in the grid are summed up, and in one single number. The same process is repeated for every case, and the overall performance indicators are remapped in a scale from 0 to 10. On the other hand, the system sturdiness tracks the number of iterations that there are still changes in the system. If the number is higher it means that that the system changes slow, and it is more robust. The list of the performance indicators of each case is remapped in a scale from 0 to 10. Besides the dynamic model, the research employs an indicator that can be used as a proxy to choose locations with high economic potential, which is the footfall potential. It estimates the pedestrians in each street node, using betweenness centrality. As aggregated indicator, is used the fraction between the maxima in the site with the overall global maxima in the context. The results of each case are stored on a list, and remapped in a scale from 0-10.

3. Application of the Framework and Performance Space Exploration

The framework is applied in a new development site in Vienna. The locations' significance lies in its connectivity with Vienna and a large amount of greenery in the surrounding. Based on Vienna Sustainable Development Strategies, the site's development should be based on its residents' social equalities, offer them job opportunities, a healthy environment, and sustainable development. Therefore the location is considered a good base for the study. Based on the given floor area ratio, ground space index, and the street network rotation, hundred and one cases are generated. As aforementioned in the methodology part, this step is followed by elaborating the geometrical solution space and performance space in each performance indicator.

3.1. SOCIAL DIMENSION PERFORMANCE SPACE

3.1.1. ASA - Aggregated Social Sustainability

As an outcome, the aggregated social sustainability (ASA) value seems to be tightly related to street network configurations. From the correlations of ASA value with the street orientation, in general, we can see that the higher the amount of northwest-southeast and the southwest-northeast oriented street amount, the value of the integrity is lower. And oppositely, if the streets are oriented in north-south or west-east, the ASA value is high. From the context, we can also associate that the existing network is dominating in the north-south and west-east orientation. This street orientation matching while designing could be a basis to draw a rule of thumb to inform the design decisions.

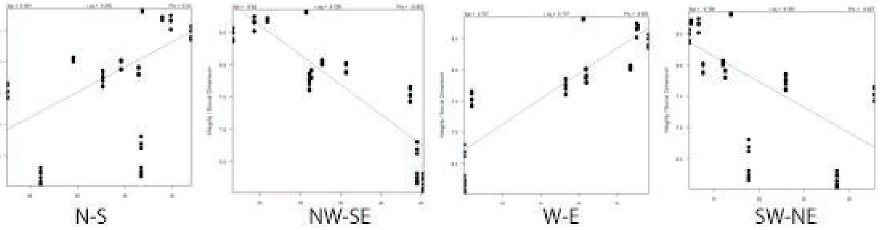


Figure 2. Correlation of the aggregated social sustainability(ASA) with the four street network orientations.

3.2. ENVIRONMENTAL DIMENSION PERFORMANCE SPACE

3.2.1. Wind Comfort

Concerning the correlation outcomes, there is seen a medium positive linear association between the pedestrian comfort in terms of wind and the floor area ratio of the design (see fig.2 left). There is a small linear association between the pedestrian comfort in terms of wind and the design's floor space index. This correlation does not necessarily indicate that the higher the floor area ratio, the higher the wind comfort, and it does not imply causation. An explanation of this is that the higher the building's volume creates more wind shadow, which could lower the wind speed and offer higher pedestrian comfort. Besides, it is seen from the performance, open spaces tend to be less comfortable for pedestrians, and most of the time, dangerous. So, in a sustainable urban layout, there should be a good balance and composition between built and non-built spaces.

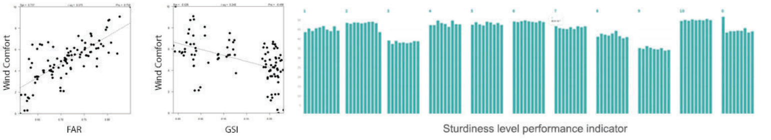


Figure 3. Left: Correlation of the wind comfort with the density metrics (FAR and GSI); Right:Sturdiness level performance indicator grouped by the street type (indicated above the grouped bar charts).

3.2.2. Sunlight Hours

The highest R-squared value comes from the correlation of the aggregated sunlight hour performance indicator with the floor area ratio. There is a very low association between the design option's sunlight performance and the design's floor space index. Similarly, between sunlight hours and the street network orientations, there is no clear correlation. On the other hand, the scatterplot shows a low negative linear association between the design option's sunlight performance and the design's floor area ratio. A high floor area ratio, causing a lack of sunlight, can be argued that more shadow is created from high-rise buildings.

3.3. ECONOMIC DIMENSION PERFORMANCE SPACE

3.3.1. System Sturdiness

Based on the correlation's outcome, one can indicate that the built structure has a relation with the system sturdiness. With a 0.35 R-squared, there is seen a moderate negative correlation between the floor area ratio and the design's sturdiness level. On the other hand, there is a positive correlation between the ground space index with the system sturdiness. It might have happened since the building volumes are used to estimate the population number, and this data was aggregated in the street network and used as an initial weight. On the other hand, the street network has a close relationship with the system sturdiness level; this can also be seen in Figure 3, right side, where the design options with the same street network have very similar system sturdiness levels. However, the street orientation perhaps doesn't capture all factors affecting sturdiness, and further parameters should be tracked from the urban form. It worth to mention, that further research is needed to understand the performance of the system sturdiness level.

3.3.2. Investment worth potential

There is seen a moderate negative relationship between the floor space index and the investment worth potential. Based on the outcome, built structures with higher construction costs should be allocated in areas where the value remains stable or appreciates. To reduce risk, the build structures with lower construction costs should be allocated in worse-performing areas. However, this model does not consider market values, which would have increased the work's complexity, but it would doubtlessly also augment the workflow.

3.3.3. Footfall Potential

The footfall potential indicator doesn't have a strong linear correlation with the spatial configurations (FAR, GSI, Street network orientation). However, based on the grouped bar graphs, the same street network design cases perform very similarly in terms of footfall potential. To understand what is precisely is causing the changes, further studies can be done. Multiple linear regression models can be applied to correlate the performance data further by isolating the effects of either FAR, GSI, or the street network orientation. In conclusion, we can assume that it would contribute to the footfall potential if the designed streets align with the existing street network.

4. Summary, Conclusion, and Future Research Work

The comprehensive framework gives insights on how sustainable a design option is based on the input geometry. One can visualize all performance indicators at the same time and understand the trade-offs better. Additionally, importance weighting can be implemented to each metric so that the framework adapts accordingly to the project's challenges and goals. A notable advantage of the framework is that it can be used as a discussion table in participatory planning meetings since it could be easily adapted with interactive environments.

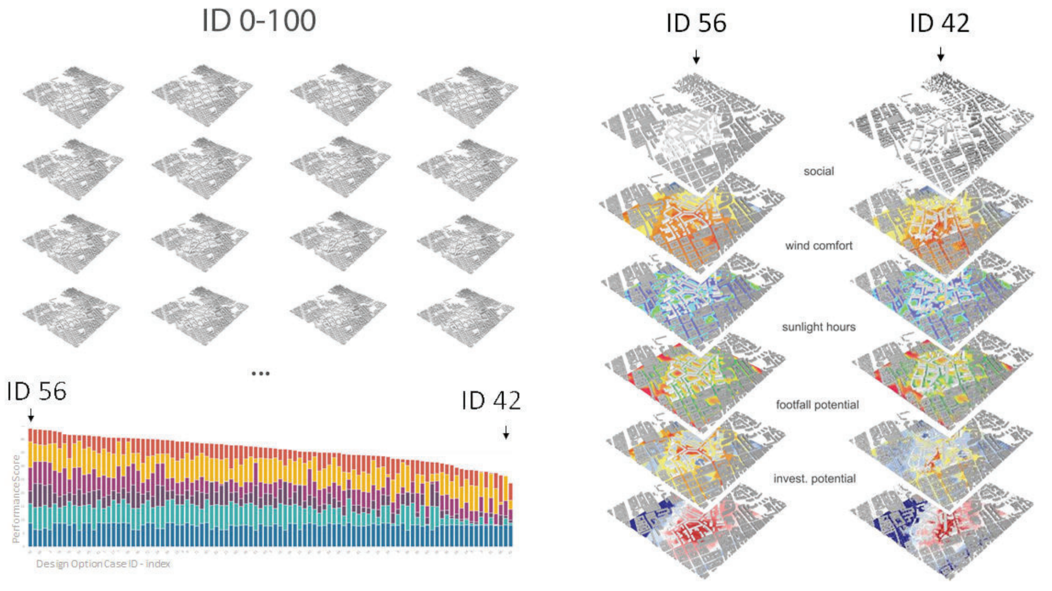


Figure 4. 101 Design cases, and their ranking based on the sum of all performance indicators in an equal weighing system. Each color represents one metrics, and the value from every metrics in a scale from 0-10 was added to the performance axis y. The best and worst performing design options are visualized in the right side of the figure. .

From the research, some general rules of thumb derived. First, people would have more access to liveable spots regarding the social dimension if we match and align the existing street network's orientation with the new design ones. Secondly, to perform better in terms of environment an urban layout should consist of diverse building typology and have a reasonable proportion between the built and non-built areas. On the other hand, while high and large buildings create wind shadow, at the same time, they block the sunlight. So, compromises should be made, and the optimum solutions based on the initial goals could assist which design is more sustainable for the location(This also includes weighting score for every performance indicator). As a general rule in the economic aspect, designed streets should align with the existing street network. However, this study could not define what exactly should be changed to have a design that would have higher investment potential. Similarly, the system sturdiness with the input parameters shows a high correlation. Still, it is hard to conclude since this correlation does not necessarily indicate impact, and further studies can be done on the topic.

As promising as the framework appears, it does not cover all issues related to measuring sustainability. However, it presumably is a supplement to the existing tools. There are several directions on how the framework could be augmented or improved:

1. Input parameters: only floor area ratio, ground space index, and street network orientation seem to be deficient in explaining the urban performance; additional

input parameters could be added.

2. Performance indicators: further research could be done in the economic dimension; its performance indicators could be tested in several real locations.
3. Data Analysis: simple linear correlations tend to be insufficient to explain some phenomena in the design's performance; therefore, multiple linear regression models, or MCDA-based models for assessment, can be applied to operationalize further the performance data.
4. Data filtering algorithms can be built, such as footfall potential in areas with dangerous wind speeds or similar approaches combining the results.

As promising as the framework appears, of course, it does not cover all issues related to measuring urban sustainability. And further study should be done because the topic itself is complex, and cities are complex structures, and the interdisciplinary field makes it complicated to come up with simple workflows.

References

Achary, A., Guven, E. and Uyar, G.: 2017, City planning using integrated urban modeling. Jeddah Structure Plan, *Proceedings of the 11th Space Syntax symposium*, London.

Bielik, M., Koenig, R., Fuchkina, E., Schneider, S. and Abdulmalik, A.: 2019, EVOLVING CONFIGURATIONAL PROPERTIES – Simulating multiplier effects between land use and movement patterns, *12th Space Syntax Symposium*, Beijing.

Bielik, M., Koenig, R., Schneider, S. and Varoudis, S.: 2018, Measuring the Impact of Street Network Configuration on the Accessibility to People and Walking Attractors, *Networks and Spatial Economics*, 18 (3).

Le Corbusier, -, Knight, P., Levieux, E. and Coltman, D.: 1967, *The radiant city: Elements of a doctrine of urbanism to be used as the basis of our machine-age civilization*, New York: Orion Press.

Cotgrave, A. and Riley, M.: 2013, Total sustainability in the built environment, *the built environment*, Basingstoke: Palgrave Macmillan.

Duering, S., Chronis, A. and Koenig, R.: 2020, Optimizing Urban Systems: Integrated optimization of spatial configuration., *SimAUD 2020*, Vienna (Online).

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

Hillier, B.: 2010, Spatial sustainability in cities: organic patterns and sustainable forms, *Proceedings of the 7th International Space Syntax Symposium*, Royal Institute of Technology (KTH): Stockholm, Sweden, pp. p. 1.

Hillier, B. and Hanson, J.: 1984, *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 (4)**, 297–318.

Lawson, B.: 2006, *How designers think. The design process demystified*, Bryan Lawson. 4th ed. .

Marans, R. and Stimson, R.: 2011, Investigating quality of urban life: Theory, methods, and empirical research, *Journal of Regional Science*, **52 Issue 2**, 45, 1-29.

Weber, M.: 1978, *Max Weber : selections in translation / edited by W. G. Runciman ; translated by E. Matthews.*, Cambridge : Cambridge university press.

RESEARCH ON THE INFLUENCE OF MICROCLIMATE ON RECREATION BEHAVIOR IN URBAN WATERFRONT PUBLIC SPACE

Based on Multi-agent Behavior Simulation

CHUNXIA YANG[1], MENGXUAN LIU[2], MING ZHAN[3], CHENGZHE LYU[4] and ZHAOXIANG FAN[5]
[1]*College of Architecture and Urban Planning Tongji University, Shanghai Key Laboratory of Urban Renewal and Spatial Optimization Technology*
[1]*yang_arch@163.com*
[2,3,4,5]*College of Architecture and Urban Planning Tongji University*
[2,4]*{liumengxuan93|sansirorr}@163.com* [3]*945581064@qq.com*
[5]*archifan@sina.com*

Abstract. Microclimate is one of the important components of the city environment. Previous researches on public space focused on the influence of spatial forms on user behavior, while ignoring the microclimate elements. This makes it difficult to be authentic of further recreational behavior simulation. The study puts forward a new path to study the influence of microclimate on recreational behavior. Taking the waterfront public space as an example, through the combination of field investigation and microclimate simulation, the influence of wind, temperature, and sunshine environment on residents' recreational is explored, and the influence will be merged into the recreational behavior simulation. In the process of behavior simulation, the microclimate environment classification evaluation map is used. The study committed to achieve a higher degree of adaption between behavior simulation results and actual conditions. The study introduced microclimate influence factors on the basis of the influence of urban spatial form and service facility elements on behavior activities in the past. Based on that, we optimize the simulation method of urban public space recreational behavior, and improve the accuracy of space diagnosis through showing the impact of microclimate on the behavior of people in the space more objectively and intuitively.

Keywords. Behavior simulation; Microclimate; Waterfront public space.

1. Introduction

Urban waterfront public space has a special microclimate effect, which can make people directly experience the environment in the space. Meanwhile, people's choice of suitable microclimate environment for outdoor activities results in differences in the use of public space .

GEHL J et al. (1987) first studied the relationship among outdoor microclimate, thermal comfort and behavior. Relevant studies have shown that pedestrians' responses to microclimate are unconscious, but often lead to different use of urban space (Li SG, 1994). But the current research methods of microclimate and behavior are mostly based on mathematical models, whose expression is relatively abstract and lack of intuitive visual expression.

In recent years, behavior simulation has gradually expanded from evacuation behavior simulation to public space recreation behavior simulation (Kevin M et al, 2019). Although more and more scholars are beginning to use visual and refined behavior simulation methods to diagnose existing problems in public spaces, it still ignore the influence of environmental factors such as microclimate on human psychological and physiological feelings. This paper uses computer simulation analysis to study the relationship between waterfront space recreational behavior and microclimate, so as to obtain more refined experimental conclusions.

The microclimate defined by climatology refers to the small-scale climate of the ground boundary layer, which is affected by ground vegetation, soil, topography, water bodies and artificial structures (Landsburg H, 1974). This article focuses on the microclimate conditions that have a significant impact on crowd behavior, namely wind speed, temperature and sunshine. In terms of the relationship between people's behavior value of microclimate conditions, this research is based on the comprehensive environmental perception-behavior theoretical model proposed by Fisher et al. (1984). This theory involves the causes and changes of the microclimate environment's influence on public space behavior. In addition, the crowd itself has a certain degree of self-regulation ability, and people will choose a relatively good microclimate environment to continue outdoor activities; when the microclimate factors exceed the self-regulation ability of the activists, it will affect the degree of occurrence, duration and frequency of space activities (Figure 1).

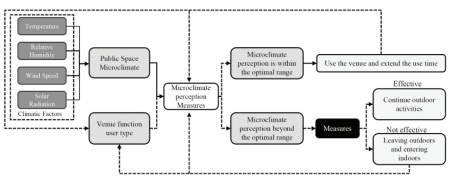


Figure 1. A model of the influence of microclimate on the behavior of people in public space.

This study explores the impact of microclimate environment on the recreational behavior of urban waterfront public spaces and incorporate this effect into the recreational behavior simulation to optimize the behavior simulation method. Through the method of behavior simulation, it can objectively and intuitively show the influence of microclimate on the behavior of people in the space and accurately diagnose the existing problems in the space.

2. Methodology

2.1. RESEARCH OBJECT

Shanghai has a subtropical monsoon climate with obvious seasonal changes. In 2020 , the summer in Shanghai continued from May 11 to October 4. In order to fully investigate the relationship between microclimate and crowd behavior, this study selected October 2nd, a holiday with a large number of people in the space with abundant activities. The sunrise time of the day is 05:48 and the sunset time is 17:38. Taking people's outdoor activities and sunset time into account, the specific research time is determined to be 7:00˜17:00. The study area selects a public space of 100*100m around the public square on the east bank of the Huangpu River in Shanghai, which has a richer internal space form (Figure 2).

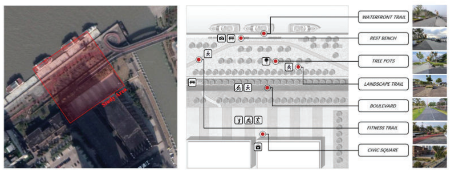
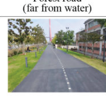
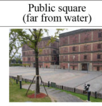
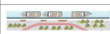
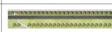
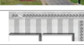


Figure 2. Study area and spatial element distribution.

2.1.1. Types of spatial patterns

Due to the large changes in the spatial form and many spatial elements in the site, in order to facilitate observation and investigation, the site is divided into strip-shaped space and planar space according to its characteristics, and divided into 4 spatial areas according to the waterfront to the remote water (Table 1). We determine the current status of the main spatial elements in each site for detailed research.

Table 1. Current status of physical space environment in public space.

Space type	Ribbon space		Planar space	
Space code	T1	T2	T3	S1
Features	Waterfront road (near water)	Landscape road (next to water)	Forest road (far from water)	Public square (far from water)
Photos				
Floor plan				
Facilities	Bench	Bench	Bench, drinking fountain	None

2.1.2. Characteristics of crowd recreational behavior

In this study, there are two main methods for obtaining crowd recreational behavior. One is to conduct "behavioral mapping" on recreational activities of people in different spaces in the venue; the other distributes questionnaires to obtain the crowd's demands through the use of space in the venue, and provide data support for subsequent behavior simulations.

According to the “behavioral mapping”, behaviors in the venue mainly include strolling, cycling, viewing, resting, etc. Among them, young people have a wide range of behavioral activities. The behavioral activities of middle-aged and elderly people mainly focus on strolling, viewing and resting. Teenagers mainly focus on cycling and strolling, and most of them along with their parents.

According to the questionnaire statistics, people have a high evaluation of the microclimate status of the waterfront public space, and people have the most significant feelings about changes in sunshine (35%), wind speed (26%), and temperature (24%). Therefore, this study chooses sunlight, wind environment and temperature as the most microclimate influencing factors, and explores their impact on the behavior of people in the space.

2.2. RESEARCH PATH

Firstly, through field research, understand the current situation of the site and the current state of recreational behavior.

Secondly, we use Envi-met and Ladybug for grasshopper software to simulate the temperature, wind speed and sunshine of the public space. In order to facilitate the spatial evaluation of the microclimate of the public space, and to facilitate the spatial evaluation of the distribution of wind in the public space, the public space is uniformly divided into a grid of 10m*10m (the grid size is determined by facilitating the distinction between the sites The difference between stroke, temperature and sunlight helps to simulate the behavior after overlay analysis, and also avoids the calculation complexity caused by too many grids). From the perspective of outdoor climate comfort, based on the simulation results of temperature, wind speed and solar shadows in the site, the site is graded and scored by comfort, and the microclimate conditions of the square are completed through means of superposition analysis on various microclimate elements evaluation.

Finally, different attractiveness parameters are set for spaces and facilities under different microclimate conditions, and Quelea for grasshopper is used to simulate the behavior of people in the waterfront public space site. Through multiple fitting adjustments, clear simulation method are established, then through the analysis of the output image, the existing problems in the public space are diagnosed. The specific process is shown in Figure 3.

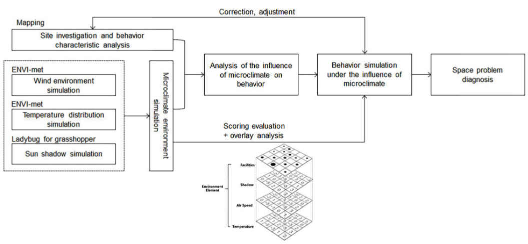


Figure 3. Research path diagram.

2.3. SIMULATION METHOD

2.3.1. Numerical simulation method of wind environment and temperature

Envi-met is the most commonly used microclimate simulation method in existing research. In recent years, many related studies have compared measured data and simulated data to prove that Envi-met has good accuracy for small and medium-scale microclimate simulations in Shanghai (Jiang YF et al, 2019).

The simulation area of each space is established in the ENVI-met4 software. The model is mainly used to establish a grid corresponding to the actual the location and height of the building, the underlying surface material of the public space as well as the type and location of vegetation and set the relevant climate and boundary parameters of the site. The grid of the simulation space is set as 50 (x) × 50 (y) × 20 (z). The latitude and longitude are set according to the geographic location of the citizen square, and the air temperature and humidity are limited based on the data from the Shanghai BaoShan Meteorological Station that day.

2.3.2. Field Sunshine Simulation Method

We use the modeling plan exported by Envi-met as the background base map of Rhino6 to establish a 3D volume model of the same size, and build a 3D model of the trees in the site according to the tree position and actual crown and stem size of the base map, and at the same time to fully reflect the interior of the site Shading conditions, the modeling scope extends a part of it, including all buildings that cast shadows on the site. Using the Ladybug plug-in of Grasshopper to build a battery pack that analyzes the duration of sunshine.

2.3.3. Behavior simulation method

In this study, the Quelea plug-in in Grasshopper was used to simulate crowd behavior. Quelea can release particles regularly according to a certain trajectory through preset particle parameters, and the particles can be used as a simulation of human behavior to provide the possibility of environmental optimization. We use Quelea to simulate the behavior of waterfront activities under the influence of microclimate and compile the activity trajectory of waterfront public space, so as to better cope with the complexity of the urban waterfront space environment and the randomness of behavior activities.

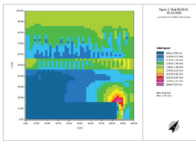
3. Analysis of the influence of wind environment, temperature and sunshine on recreational behavior

3.1. WIND ENVIRONMENT SIMULATION AND ANALYSIS

3.1.1. Field wind environment simulation

The simulation results from 7:00-17:00 of the day (Table 2) show that the wind environment of the waterfront public space is comfortable. In terms of wind speed distribution, only the north side of the citizen square (S1) is caused by the formation of a vortex effect due to the wind obstruction, resulting in local strong winds. According to the effect of different wind speeds on human comfort, the simulated wind speeds at each point are divided into 7 levels. The determination of the levels is mainly based on the Soligo standard (Soligo MJ et al, 1998), and based on the simulation results and the weather conditions of the day. It is refined on the basis, and the specific levels are shown in Table 4. And because the wind speed in each space does not change significantly in a day, it is combined into the same one public space wind speed level distribution evaluation map.

Table 2. Wind seed simulation and wind grading diagram.

Wind speed simulation	Wind grading diagram
	

3.1.2. The impact of field wind environment on recreational behavior

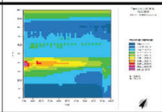
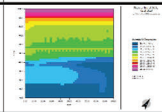
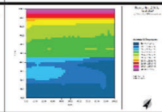
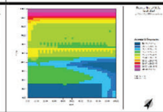
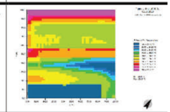
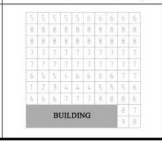
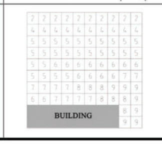
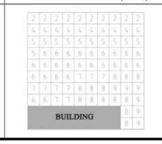
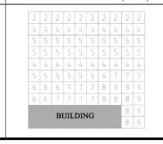
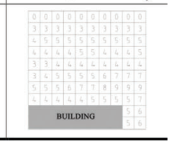
From the comparison of the wind environment classification evaluation map and the survey results, it can be seen that the wind environment has more influence on the behavior in the flat square in the waterfront public space than that in the strip space. According to the survey, the behavior in the square is mainly in the form of tennis, badminton and other sports, with longer stays and higher requirements for wind speed; while the behavior in the strip space is mostly dominated by walking and riding. The feeling of wind speed is not obvious and lack of autonomy and selectivity. In addition, the influence of wind speed on sitting and resting behaviors has different effects due to different recreational purposes. Sitting and resting for the purpose of viewing often choose a space with a closer waterfront landscape, which is less affected by the wind environment. Sitting and resting for the purpose of socializing and resting, they are more inclined to choose less wind speed and surrounding highly compatible space.

3.2. SIMULATION AND ANALYSIS OF SITE TEMPERATURE DISTRIBUTION

3.2.1. Simulation of field temperature distribution

In terms of temperature distribution, the T3 belt space has a high canopy closure and abundant plants, which has a significant cooling effect on the site during the day. On the contrary, T1 and T2 have a larger hard pavement area, so the temperature during the day is higher. Square S1 is different in daytime temperature due to changes in architectural shadows and wind environment, but this change often does not cause differences in space usage. Also in order to facilitate the evaluation of the temperature distribution in the space, according to the range of the simulated temperature results, the temperature of each point obtained by the simulation is divided into 10 levels (Table 3).

Table 3. Simulation of temperature distribution of the field by time period.

Time	7:00-9:00	9:00-11:00	11:00-13:00	13:00-15:00	15:00-17:00
Temperature simulation					
Temperature grading diagram					

3.2.2. The influence of field temperature distribution on recreational behavior

The impact of temperature on crowd behavior is often manifested in a more macroscopic form, such as the relationship between temperature changes in a year and the number of people in the site. This study can be seen from the statistical data of the temperature and the number of people in different periods of the site (Table 4). The period of the highest temperature and the strongest sunlight between 11:00 and 13:00 is the period with the least number of people in the site. From 13:00 to 15:00 in the afternoon, the site temperature drops, the sunshine weakens, and the microclimate comfort level rises. At this moment, the number of people reaches its peak, and after 17:00, there are still a large number of people coming here to take a walk and rest, which matches the high daytime temperature and low at night.

Table 4. Comparison table of filed temperature and number of people (5min).

Time	7:00-9:00	9:00-11:00	11:00-13:00	13:00-15:00	15:00-17:00
Temperature（max）/℃	24.12	25.96	27.44	26.53	25.51
Number of people	32	42	26	75	65

Since the human body responds slowly to temperature changes in space, in most cases, the influence of temperature on behavior is often reflected in shadow areas that can be directly recognized by people. This phenomenon is common in striped spaces (such as jogging, cycling) is particularly prominent.

3.3. SIMULATION AND ANALYSIS OF FIELD SUNSHINE HOURS

3.3.1. Simulation of field sunshine hours

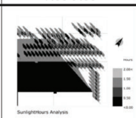
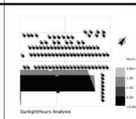
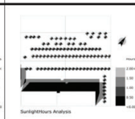
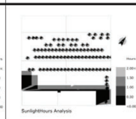
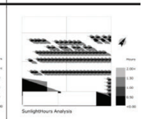
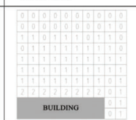
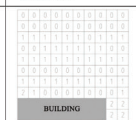
The sunshine situation is related to the height and form of the building on the north side of the area. In the design of waterfront public space, the distance, height and density of waterfront buildings largely determine the duration of sunshine in the public space. In the survey site, most of the trees in the belt-shaped space are planted in one row, among which the distance between T1 and T2 trees is relatively too far, causing strong sunlight at noon. The space of the planar square is affected by the shadow of the building, and the sunshine conditions change strongly within a day, which can provide a certain shade and cool space for the area in the hot summer. In this study, the sunshine duration within 2 hours was also used as the standard to evaluate the comfort of the sunshine environment in the site, the score decreased with the increase of sunshine duration (Table 5).

3.3.2. The impact of field sunshine on recreational behavior

Sunshine can generally be judged visually, so it has the most direct impact on crowd behavior. This influence is mostly reflected in the choice of route in the strip space. People judge the shadow range before entering the space and choose the space with better shading conditions to continue their behavior activities. This choice causes the difference in the number of people in the space at the same time. In the belt-shaped space, the influence of shading on behavior increases as people stay in the space for longer.

And this kind of shadow-seeking behavior is particularly prominent in the planar S1. The area of people's activities in the space increases with the increase of the shaded area (Table 5). In the evening, because the absence of sunlight, the sort of activity on the square became abundant which present an irregular distribution.

Table 5. Simulation of sunshine hours, activity type and area in the field.

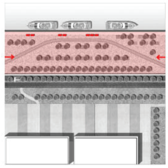
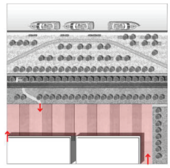
Time	7:00-9:00	9:00-11:00	11:00-13:00	13:00-15:00	15:00-17:00
Shadow simulation					
Shadow grading diagram					
Activity type (area)	Dance, ball sports (About 1088 m²)	Ball games (About 385 m²)	Walk the dog, walk (About 125 m²)	Pass (About 20 m²)	Walk the dog, walk (About 97 m²)

4. Simulation and diagnosis of recreational behavior under the influence of microclimate

4.1. SIMULATION OF RECREATIONAL BEHAVIOR UNDER THE INFLUENCE OF MICROCLIMATE

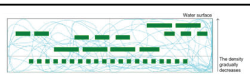
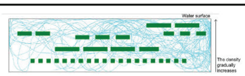
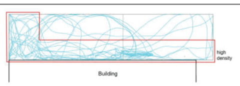
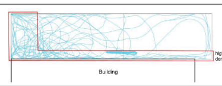
First, the study input the data obtained by the questionnaire as a control parameter into the simulation system. Because there is a height difference between T3 and T1, T2, and S1, and the distribution of attraction points in T3 is extremely limited. Therefore, only T1, T2, and S1 were selected for the simulation experiment of recreational behavior. And the connection between T1 and T2 is relatively high, so they are simulated uniformly. According to the current situation of the site, we set the bench as a attraction point. In this process, the influence of microclimate on behavior is not considered, and the simulation results are shown in Table 6. It can be seen from the simulation results that the distribution of pedestrians is relatively even, which cannot completely match the "Behavioral Mapping" in the survey.

Table 6. Simulation of recreational behavior ignoring microclimate elements.

Space code	T1 & T2	S1
Simulation area, attraction point and agent emission point		
Recreational behavior simulation ignoring microclimate factors		

The study incorporates the influence of microclimate elements into the simulation of recreational behavior, and selects two time periods when microclimates have a greater impact on behavior during 11:00-13:00 and 13:00-15:00. In this process, there are mainly two ways to adjust the behavior simulation results: First, by adding an attraction factor in the center of the grid with a better graded evaluation. Second, adjust the existing parameters of attracting particles, such as setting the bench in different graded evaluation grids to different attractive parameters. So as to form a behavior simulation result that matches the actual situation with a higher degree (Table7).

Table 7. Simulation of recreational behavior ignoring microclimate elements.

	11:00-13:00	13:00-15:00
T1 & T2		
S1		

4.2. DIAGNOSIS OF SPACE USAGE UNDER THE INFLUENCE OF MICROCLIMATE

According to the simulation results in Table 7, from 11:00 to 13:00, due to the strong sunshine on the site, the recreational behaviors of T1 and T2 are mostly concentrated on the far water side with more trees, resulting in a lack of activities on the water side. At this time, the venue is mostly passing behavior and people avoid discomfort caused by staying in the venue for a long time. From 13:00 to 15:00, the site's sunshine intensity decreases and the temperature drops, so the recreational behavior approaches the waterfront side. And due to the lack of retention points on the far water side, the corresponding spatial vitality is reduced. As for the S1 space, most recreational behaviors occur in the shadow space close to the building, and the overall utilization of the site is very limited. The distance between the site and the waterfront landscape is relatively long, and the interior lacks shading facilities and recreational facilities. As a result, the interior is mostly used for walking, cycling, and dog walking. The quantity of residences is small, and the daytime space in the site lacks vitality.

5. Discussion and conclusion

The purpose of this research is to propose a new approach to study microclimate and recreational behavior. In the past, during the process of recreational behavior simulation in public spaces, the impact of microclimate on human physiology and psychology was often ignored, and it was difficult to keep consistent with the behavior of people in the real environment. In the process of behavior simulation, this study uses the hierarchical evaluation map of the microclimate environment to adjust the results of behavioral simulation by two methods: one is to adopt the method of adding spatial attraction points in the grid with higher hierarchical evaluation. The second method is to adjust the parameters of attracting particles in different microclimate evaluations, so that the behavioral simulation results can form a higher degree of adaption with actual conditions. This research can be improved from the following aspects:

(1) In order to obtain enough recreational behavior samples in the selection of the survey date, this study selected the microclimate data of the late summer during the holidays in early October. At this time, residents' behaviors showed more acceptance of microclimate. Subsequent research can investigate the influence of microclimate on behavior during the hot summer season as a comparative study.

(2) Subsequent research will set different weights for wind environment, temperature environment and sunshine hours when superimposing microclimate elements to reduce the error caused in the evaluation.

(3) We need more discussions on the individual attributes, such as the impact of microclimate on people of different genders and different ages. Besides, Quelea as simulation software of behavior and residence behavior is relatively limited. Subsequent research can use Pedsim for grasshopper in combination with it to better simulate the behavior of space under the influence of microclimate.

Acknowledgements

This research was sponsored by the Open Subject (2020010203) of Shanghai Key Laboratory of Urban Renewal and Spatial Optimization Technology, also supported by the "Research on the Vitality Reshaping of Urban Waterfront Renewal Area–Based on Multi-agent Behavior Simulation" project.

References

Fisher, J.D., Bell, P.A. and Baum, A.: 1984, *Environmental psychology*, Rinehart & Winston.

Gehl, J.: 1987, *Life between buildings: using public space*, Van Nostrand Reinhold, New York.

Jiang, Y., Han, X., Shi, T. and Song, D.: 2019, Microclimatic impact analysis of multi-dimensional indicators of streetscape fabric in the medium spatial zone, *Int. J. Environmental Research & Public Health*, **16**, 952.

Kevin, M., Matthias, B. and Silvia, T.: 2019, Nearby outdoor recreation modelling: an agent-based approach, *Urban Forestry & Urban Greening*, **40**, 286-298.

Landsberg, H.: 1947, *Physical climatology*, Gray Printing.

Li, S.G.: 1994, Users, *J. the Kyushu Dental Society*, **10**, 95-109.

Soligo, M.J. and Irwin, P.A.: 1998, A comprehensive assessment of pedestrian comfort including thermal effects, *J. Wind Engineering & Industrial Aerodynamics*, **77**, 753-766.

STUDY OF MEASUREMENT AND ENVI-MET SIMULATION OF WINTER NIGHT IN NANPING VILLAGE UNDER WET AND COLD MICROCLIMATE BASED ON URBAN ROUGHNESS

HU WEI[1] and XIANG KE[2]
[1,2]*School of Architecture, South China University of Technology*
[1]*arhuwei@mail.scut.edu.cn*

Abstract. This study selects four urban roughness parameters of building density, FAR, building dispersion ratio, and green rate to study the wet and cold microclimate in the winter night. According to the combination of 7 points' measurement and 36 grids' ENVI-met simulation, this study obtains microclimate research data. The significants of the winter night wet and cold microclimate is focused on improving the somatosensory temperature, and this study splits the target into two related directions, one is to extend the duration of comfortable temperature and humidity, another is to expand the comfortable area of temperature and humidity. By coupling analysis of urban roughness and the comfortable ratio, this study found out 11 relationship lines between urban roughness and nighttime microclimate in NanPing village. These laws offer the design strategy for NanPing Village's future development from three directions. These also provide a solution to achieve a low carbon, sustainable built environment.

Keywords. Urban Roughness; Microclimate; Climate measurement; ENVI-met; Sustainable development.

1. Introduction

China's latest "Green Building Evaluation Standard" highlights the concept of people and focuses on the relationship between people and the environment. In response to the principle of green building, Currently, the majority of design lacked forward-looking concept in the early steps, leading to some buildings' lacking climate-comfortable design in the exterior space. In the actual project, most green design concentrates on the late design or architectural technology. (Johansson E,2006;Asadi S,2014;Yahia MW,2018). Some adjustments in the early stage determine the final result.

Urban Roughness is the data expression of space form and space restrictions in urban design. The design and quantitative optimization of urban roughness could make contributions to the city's sustainable development.(Emmanuel R, 2006;Johansson E,2013).This study selects four parameters for the settlement characteristics of the village, including building density(C), floor area ratio FAR(R), building dispersion ratio(T), and green rate(D). (Y.K., 2009;Perini K, 2014; Sharmin T, 2017)

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 427-436.

The microclimate is a meteorological term that is smaller in scope than the surrounding climate range and the recent near-surface climate (Zhang X, 2016). Some researchers conducted a correlation study between urban design and microclimate and proposed the expression of urban roughness in urban design(Ding wowo 2012).Microclimate can be studied through on-site measurement of climate data and small-scale construction virtual model. ENVI-met is a microclimate simulation software based on the principles of thermodynamics and fluid mechanics.ENVI-met dynamically simulates the interaction between surface, air, and vegetation within a small scale of the city. (Jendritzky G,1981; Bruse M, 1998; Wiener, J.M., 2005;Zhang,H.2011; Lo L,2013;Karakounos I,2018)

2. Research object

2.1. NANPING VILLAGE

China constantly devotes to explore new approaches of sustainable development in rural areas, which helps to balance development between urban and rural area. NanPing village is facing the challenges of urbanization and sustainable development. It is located in the northeast of Guangzhou and far from high-density cities.NanPing village has the basic characteristics of ordinary Chinese villages. Majority of the houses in the core area of NanPing Village are traditional brick-walled buildings with 1~2 floor.(Fig. 1)

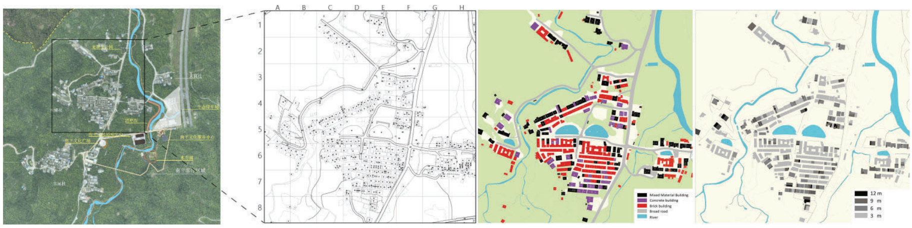


Figure 1. The research scope and surrounding status of NanPing Village.

The average winter temperature in this village is about 17° C.Through questionnaire survey, more than 73% of people feel cold every night because of the Wet and Cold microclimate. they usually keep warm by burning charcoal wood. Due to the young go out for work, the residents in NanPing are mostly children and the older over 50 years old. For the elderly population, it is more sensitive and uncomfortable under the wet and cold microclimate at night.

2.2. URBAN ROUGHNESS GRIDS IN NANPING VILLAGE

Since the study of urban roughness is based on the discussion of urban texture level, the size of the grid still needs to reflect the basic dimensions of the street contour. This experiment uses a simple comparison of 150*150m. (Bottema M, 1998)Common urban roughness research units are used as research units for each grid. This study selected 8*8 small blocks to cut 400*400m for 64 small squares, and each small quare is 50*50m,and each 9 small square block formed a 150*150m grid. Each grid area is 2.25ha, and a total of 36 grids can be obtained.

The urban roughness values of 36 grids were differentiated by depth to obtain four distribution maps. According to the distribution, it is obvious that building density(C), FAR(R), building dispersion ratio(T)are positively correlated. The three are negatively correlated with green rate(D). (Fig. 2)

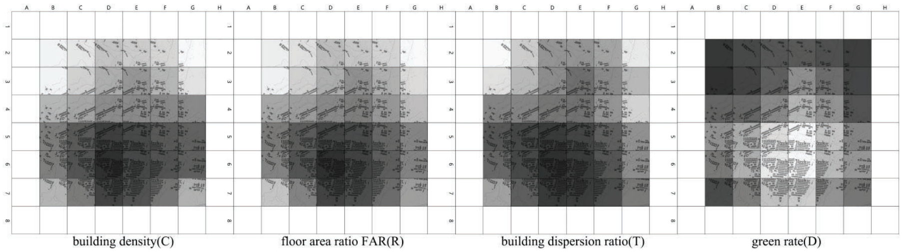


Figure 2. Urban roughness color distribution map of 150*150m grid.

3. Measurement

3.1. MEASUREMENT CONTENT AND POINT DISTRIBUTION

The study uses a fixed-point observation method to set up 7 observation instruments (HD 32.3). The air temperature and relative humidity of the test area at different measuring points were recorded every 15 minutes. The test time is from 14:30 on January 18th(2020) to 8:30 on January 19th(2020).The appropriate air temperature and relative humidity are mainly concentrated in the first half of the night, which is 17:00 to 21:00 on January 18th.

According to the characteristics of the settlement of NanPing Village, the study selects four measuring grid points of B5, C5, D2, and F4 with significantly different urban roughness. Among four indoor points and three outdoor points, the experiments try to eliminate the influence of the underlying surface and water. According to the measurement result, the indoor and outdoor temperature difference is small, changes were not evident. Air temperature at 20:00 starts to a lower stable value and heats the following morning at 6:00. Seven measuring points showed that the relative humidity maintained a high value from 20:00, and the relative humidity began to decrease after 6:00. (Fig.3)

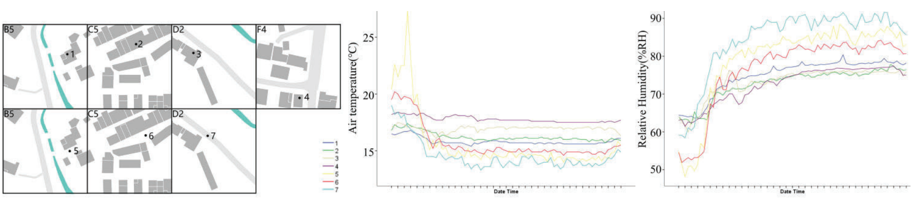


Figure 3. Air temperature and relative humidity change chart (1.4m) .

3.2. RELATIONSHIP BETWEEN URBAN ROUGHNESS AND MICROCLIMATE IN 7 MEASUREMENT POINTS

Other experiments show that the most comfortable indoor temperature and humidity: the winter comfort air temperature is 15.2 ˜ 23.3°C, the appropriate relative humidity limit is 30 to 80% (Li Yaya.2013;Xu Kunlun.2016), Indoor humidity combined with the average humidity value of the night is set to 45 to 75%. The study calculates the proportion of time that the air temperature and relative humidity reached the comfort standard at night. (Table 1).

Table 1. Comparison of measuring point humidity compliance rate and urban roughness.

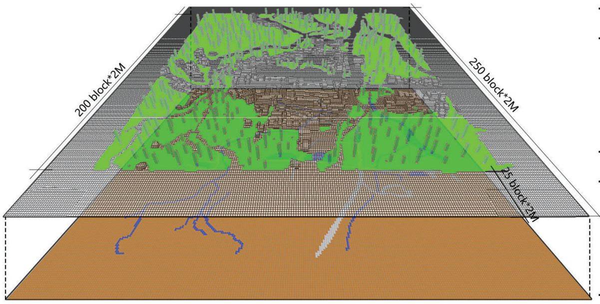
Object	B5（1,5）	C5（2,6）	D2（3,7）	F4（4）
Average indoor air temperature（℃）	15.69	16.07	16.95	17.70
Indoor air temperature comfortable time ratio at 15.2-23.3℃	100%	100%	100%	100%
Average outdoor air temperature（℃）	14.56	15.03	13.99	/
Outdoor air temperature comfortable time ratio at 15.2-23.3℃	12.70%	23.81%	1.59%	/
Average indoor relative humidity（%RH）	76.87	74.38	74.82	74.42
Indoor relative humidity comfortable time ratio at 45~75%	22.64%	58.49%	37.74%	43.40%
Average outdoor relative humidity（%RH）	83.95	80.60	88.28	/
Outdoor relative humidity comfortable time ratio at 30%~80%	9.43%	32.08%	0.00%	/
Building density（C）	0.18	0.25	0.08	0.17
FAR（R）	0.26	0.34	0.13	0.20
Building dispersion ratio（T）	6.77	7.64	4.68	4.65
Green rate（D）	0.46	0.39	0.67	0.46

According to the relationship between urban roughness and time ratio, the urban roughness data has a certain correlation with the temperature and humidity changes in NanPing. However, due to the limited data of the seven measuring points, it is impossible to obtain clear correlation data and related functions. It is necessary to carry out the microclimate simulation of the entire NanPing through ENVI-met. Then coupling analysis with the relationship between microclimate situation and further scientific conclusions in 36 grids.

4. ENVI-met simulation

4.1. COMPUTATIONAL DOMAIN AND BLOCK SIZE

The study uses ENVI-met modeling the core area of NanPing Village (36ha). The overall horizontal modeling block is 250*250 (the horizontal area is 500*500m, core area is 400*400m), the vertical block is 15 equidistant blocks (vertical height is 30m, the highest building in the site is 12 m). (Fig. 4)



Spaces settings	
Block	250*250*15
Block element	X/Y/Z=2.00m/block;
Coordinate	China Standard Time GMT+8
ConfigWizard settings	
Start simulation date	18.01.2020(Winter)
wind speed(10m)	South Wind 0.2m/s
Start simulation time	12：00(5 hours in advance model preheating)

Figure 4. 3D model and settings in ENVI-met.

4.2. COMPARISON BETWEEN MEASURED AND SIMULATED VERIFICATION

To verify the reliability of the simulation, the study uses the simulation data of the same position measurement point to carry ENVI-met simulation and compares the changes of air temperature and relative humidity data of point (5, 6, 7) at 1.4m height on a time-by-time basis. (Fig. 5)

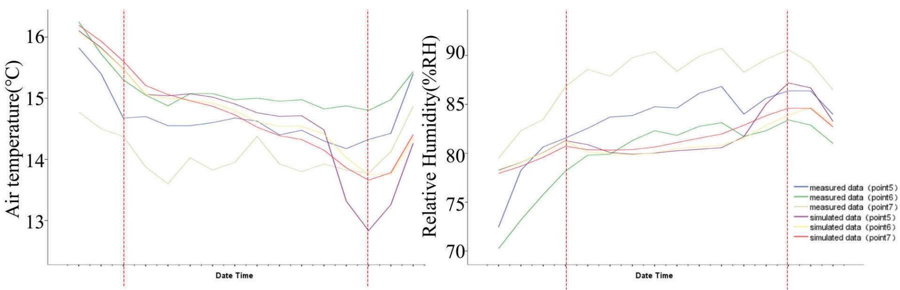


Figure 5. Simulation and measured contrast of Air Temperature and Relative Humidity(1.4m).

After comparison, the simulation is consistent with the actual measurement. More than 90% of simulated and measured values in air temperature are within 1.5 °C, more than 80% of simulated and measured data values in relative humidity differ by 8%. It determines the ENVI-met simulation results can roughly reflect the spatial distribution characteristics and changes of the near-surface thermal environment.

At the same time, according to the data chart, it is determined that NanPing village on the night of 18th, 20:00 is the starting point of the air temperature tends to be stable, and also the critical point of the relative humidity of 80%. Starting from 20:00, the air temperature of several measuring points is lower than 15 °C, and the relative humidity is higher than 80%. At 6:00 on 19th, it is the lowest point of night air temperature and the highest point of relative humidity.

The conclusions show that the subsequent experimental data analysis should focus on the temperature and humidity threshold (20:00,18th) and the temperature and humidity limit (6:00,19th).ENVI-met outputs microclimate simulation data at 20:00 and 6:00.(Fig. 6)

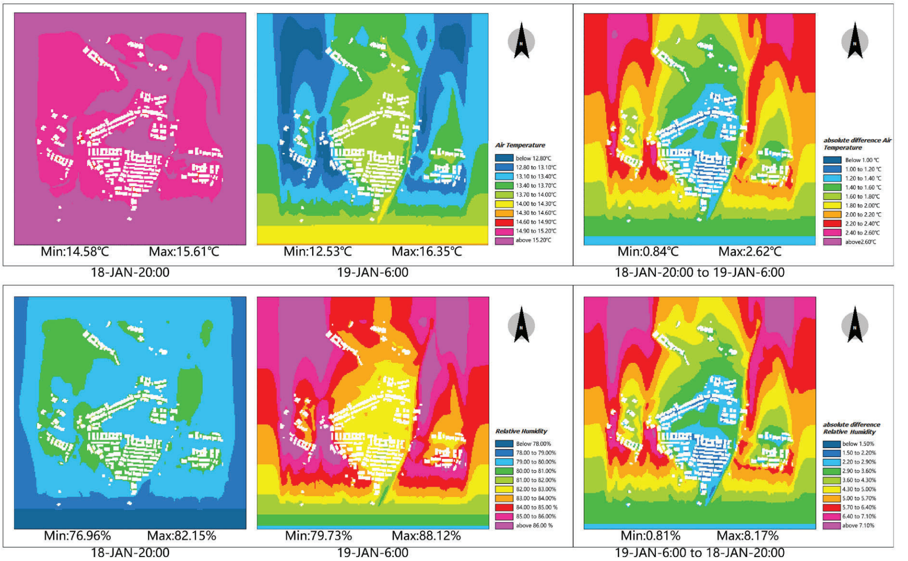


Figure 6. Air temperature and relative humidity simulation result by ENVI-met.

To summarize the improvement of the wet and cold climate in NanPing in winter, it should focus on two points:

(1)Stretch the duration of the comfortable temperature and humidity (comfortable standard time ratio);

(2)Expand the comfortable area of the temperature and humidity(comfortable standard area ratio).

4.3. COMFORTABLE STANDARD TIME RATIO

The hourly microclimate data of 36 girds can be obtained by using the same method in Table.1. It is mainly the comfortable standard of the time-to-standard ratio of 36girds' points. Using SPSS to calculate the Pearson correlation of urban roughness and temperature-to-humidity comfortable standard time ratio. (Fig.8).

(1)There is no obvious coupling relationship between the air temperature comfortable standard time ratio and the urban roughness.

(2)the Pearson between the relative humidity comfortable standard time ratio and urban roughness is more than 0.3 and less than 0.5, which is a low correlation linear correlation. It is determined that the design of the urban roughness can be used to improve the length of the relative humidity comfort interval.

4.4. COMFORTABLE STANDARD AREA RATIO

4.4.1. comfortable area ratio (20:00 ,18th)

The weather conditions of the site at the critical point of night humidity (20:00,18th) were selected. The relative humidity at this time was relatively stable, and the relative humidity range of 77.97 to 83.15% could effectively show a comfortable relative humidity range of 30 to 80%. Data section(20:00,18th) Get the field area within the comfortable relative humidity range of 30 to 80% through photoshop.Using ImageJ to calculate the interval area data can obtain the relative humidity area ratio of each grid at 20:00(Fig.7).In the same way, the air temperature comfortable standard area ratio of each grid at 20:00 was obtained.

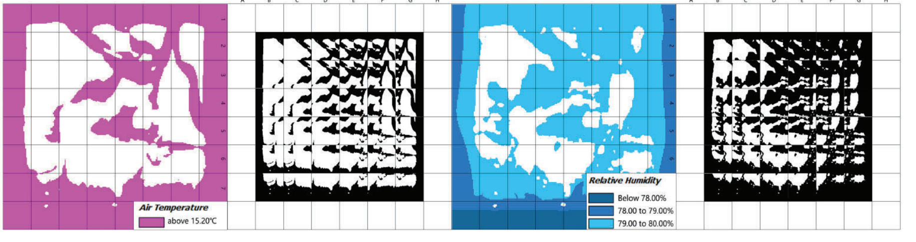


Figure 7. Air temperature and relative humidity comfortable area(1.4m).

Using SPSS to calculate the Pearson between standard area ratio and urban roughness. Except the relationship between building dispersion ratio and air temperature comfortable standard ratio, there is a coupling relationship between other urban roughness and the standard area. It is determined that the design of urban roughness can be used to improve the comfort zone area of temperature and humidity. (Fig.8).

4.4.2. comfortable area ratio (6:00 ,19th)

At 6:00 on January 19th, the minimum humidity of NanPing village on the morning of 6:00 was 80.73%, and the air temperature was low from a comfortable standard. Most areas of the site at 6:00 were unsuitable for temperature and humidity, which does not apply to data research through comfort compliance rates. ENVI-met shows the average PMV was around -1.5(6:00,19th). Under the current climatic conditions, the research on urban roughness can't improve the Relative humidity comfortable area ratio.

4.5. RELATIONSHIP BETWEEN URBAN ROUGHNESS AND MICROCLIMATE IN 36 SIMULATION GRIDS

Pearson correlation values obtain the relationship between urban roughness and winter temperature and humidity by eleven relations, in which blue is negatively correlated, and red is positively correlated (Fig.8). Extending the duration of comfortable humidity can be achieved by increasing building density, FAR, building dispersion ratio, and reducing green rate. Increasing the area of comfortable temperature and humidity can be achieved by reducing building density, FAR, building dispersion ratio, and increasing green rate.

Pearson	Air temperature Comfortable Standard Time Ratio	Relative humidity Comfortable Standard Time Ratio	Air temperature Comfortable Standard Area Ratio	Relative humidity Comfortable Standard Area Ratio
Building density (C)	-0.029	0.453 (>0.3)	-0.309 (<-0.3)	-0.342 (<-0.3)
FAR (R)	-0.03	0.441 (>0.3)	-0.329 (<-0.3)	-0.386 (<-0.3)
Building dispersion ratio (T)	0.129	0.403 (>0.3)	-0.278	-0.325 (<-0.3)
Green rate (D)	-0.037	-0.464 (<-0.3)	0.313 (>0.3)	0.303 (>0.3)

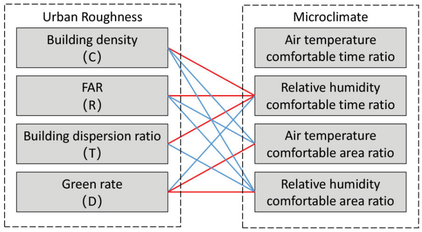


Figure 8. Pearson between urban roughness and microclimate.

There is an opposite relationship between extended comfort time and increased comfort area. The data under 36 grids were coupled to the urban roughness to obtain four scatter trend plots (Fig.9). For building density, the suitable range is 0.05˜0.2; for FAR, the suitable range is 0.1˜0.3; for building dispersion ratio, the suitable range is 6˜8; for the green rate, the appropriate range is 0.6˜0.8.

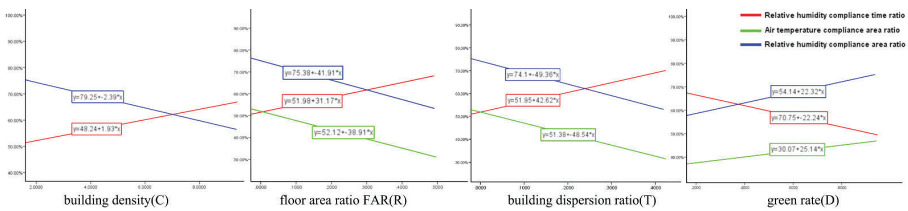


Figure 9. Trend graph of urban roughness and temperature and humidity compliance.

4.6. DESIGN STRATEGIES

For the final range of suitable urban roughness, here are three design strategies for sustainable development of NanPing village:

4.6.1. Suggestions for the renovation of village buildings

Most of the villagers have the idea of renovating their own houses by added height based on the original houses. This change will mainly affect the FAR. It can calculate the FAR data within the 150*150m gird of the building. If the total building FAR after added is guaranteed to be within the appropriate value range(0.1˜0.3), the building height should be allowed added.

4.6.2. Suggestions for new construction of villagers

It is crucial that consider the building density and building dispersion in the surrounding area if the villagers want to build a new house in the surrounding homestead. When the building density can be guaranteed within the appropriate value range(0.05˜0.2), then building a new building can be allowed.

4.6.3. Suggestions for rural planning and urban design

In the plan of rural expansion area, optimizing the environment and improving the quality, the village committee should comprehensively consider the adaptation intervals of the four urban roughness to ensure the basic comfort of the villagers and the sustainable development goals of the village.

5. Discussion and Conclusion

Green design should be promoted not only in cities but also in rural. The concept of sustainable green is mainly reflected in the three aspects of providing a comfortable environment, reducing the burning of bonfires, and reducing the use of heating equipment. Studying the relationship between the winter wet and cold microclimate and urban roughness in NanPing village can effectively solve the contradiction between comfort and energy.

There are two main methods to improve the nighttime wet and cold Microclimate. One is to extend the comfortable temperature and humidity duration, and the quantitative time ratio can be used for quantitative evaluation. The second is to expand the comfortable area of temperature and humidity, and the quantitative area ratio can be used for quantitative evaluation.It is determined that the design of the urban roughness can be used to improve the length of the relative humidity comfort interval and the comfort zone of temperature and humidity.

In summary, the study of the relationship between urban roughness and microclimate can help designers and decision-makers to establish a green concept in rural sustainable planning. The use of some rules of architecture and environment can ensure the best comfort for residents, while also meeting the sustainable development of buildings and cities.

6. Funding

The research was supported by

National Key R&D Program of China (no. 2017YFC0702309)

References

Asadi, S., Amiri, S.S. and Mottahedi, M.: 2014, On the Development of Multi-Linear Regression Analysis to Assess Energy Consumption in the Early Stages of Building Design, *Energy & Buildings*, **85**, 246-255.

Bottema, M. and Mestayer, P.G.: 1998, Urban roughness mapping - validation techniques and some first results, *Journal of Wind Engineering & Industrial Aerodynamics*, **s 74–76**, 163-173.

Bruse, M. and Fleer, H.: 1998, Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model, *Environmental Modelling & Software*, **13**(3-4), 373-384.

Emmanuel, R. and Johansson, E.: 2006, Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka, *Climate Research*, **30**(3), 189-200.

J, Z.H.: 2011, Climatic background of cold and wet winter in southern China: part I

observational analysis, *Climate Dynamics*, **37**, 11-12.
Jendritzky, G. and Nübler, W.: 1981, A model analysing the urban thermal environment in physiologically significant terms, *Meteorology & Atmospheric Physics*, **29(4)**, 313-326..
Johansson, E. and Emmanuel, R.: 2006, The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka, *International Journal of Biometeorology*, **51**(2), 119-133.
Johansson, E., Spangenberg, J., Gouvêa, M.L. and Freitas, E.D.: 2013, Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of So Paulo, Brazil, *Urban Climate*, **6**, 24-43.
Karakounos, I., Dimoudi, A. and Zoras, S.: 2017, The influence of bioclimatic urban redevelopment on outdoor thermal comfort, *Energy & Buildings*, **158**(PT.2), 1266-1274.
Kunlun, X.: 2016, *Experimental study on the effect of low humidity on human comfort*, Ph.D. Thesis, Chongqing University.
Lo, L.J., Banks, D. and Novoselac, A.: 2013, Combined wind tunnel and CFD analysis for indoor airflow prediction of wind-driven cross ventilation, *Building & Environment*, **60**(FEB.), 12-23.
Perini, K. and Magliocco, A.: 2014, Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort, *Urban Forestry & Urban Greening*, **13**(3), 495-506.
Sharmin, T., Steemers, K. and Matzarakis, A.: 2017, Microclimatic modelling in assessing the impact of urban geometry on urban thermal environment, *Sustainable Cities & Society*, **34**, 0.
Ding W, H.Y.: 2012, Study on the correlation between urban morphology and urban microclimate, *Journal of architecture*, **007**, 16-21.
Wiener, J.M. and Franz, G.: 2004, Isovists as a Means to Predict Spatial Experience and Behavior, *International Conference on Spatial Cognition*, 45-47.
Yahia, M.W., Johansson, E., Thorsson, S., Lindberg, F. and Rasmussen, M.I.: 2018, Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania, *International Journal of Biometeorology*, **62**(3), 373-385.
Yaya, L.: 2013, *Study on Indoor Thermal Comfort of Residential Buildings in Summer and Hot Winter Cold Region——Taking Hangzhou and Hefei as Examples*, Ph.D. Thesis, Xi'an University of Architecture and Technology.
Zhang, X., Zhang, Y., Zang, Q., Yu, M. and Tong, Z.: 2016, Comparative cognition of microclimate of different types of open spaces, *International Conference on Geoinformatics*.

ANALYTICAL STUDY OF THE IMPACT OF GREENERY AND PUBLIC SPACE DISTRIBUTION ON LAND SURFACE TEMPERATURE IN MID-SIZE CITIES OF POLAND

ADAM ZWOLIŃSKI[1] and AGNIESZKA WOCHNA[2]
[1] *West Pomeranian University of Technology in Szczecin, Poland*
[1] *azwolinski@zut.edu.pl*
[2] *University of Gdańsk, Poland*
[2] *agnieszka.wochna@ug.edu.pl*

Abstract. The focus of the article is the impact of urban geometry and greenery on the surface temperature in a city and the Urban Heat Islands (UHI) effect. The research problem discussed in the article is to define optimal combination of such parameters as urban geometry, greenery and the LST to enhance the temperature comfort and reduce the UHI effect. The methodology combines CAD and GIS environments. Vector data of 1:10000 scale, from the National Database of Topographic Objects (BDOT10k) is used to analyse urban structure. GIS data include rasters derived from remote sensing: Land Surface Temperature (LST), Digital Surface Model (DSM) and Digital Terrain Model (DTM). The analysis covers areas in Szczecin and Gdynia, two mid-sized cities in Poland. The results indicate a more distinct dependence of LST on greenery parameters than on buildings. The main contribution of the article is the development of a uniform data grid based on CAD and GIS data, allowing for an objective analysis of the city's temperature comfort based on the parameters of buildings, greenery and LST.

Keywords. Urban Heat Islands; Land Surface Temperature; Urban morphology; Greenery in cities.

1. INTRODUCTION

The size, shape and spatial features of urban space evolve due to social, economic, and climate changes. Nowadays, climate plays an increasingly important role in the shape of cities. The interest in examining the phenomenon of urban space warming started already in 1980s. The standard UHI (Urban Heat Island) model, presented by Oke, assumes that the temperature of urban space grows proportionally to the intensity of buildings and population, from rural areas, through suburbs, and towards the city centre (Oke, 1987). The temperature peak appears above the most urbanized area of the city and the magnitude of the UHI is defined as a difference between the temperature in the city and temperature in suburbs. Considering Oke's UHI zones, the article focuses on the urban areas (Fig. 1).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 437-446.

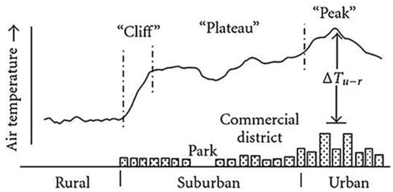


Figure 1. Typical cross section of the Urban Heat Island (UHI) effect vs temperature variations over different land-use areas. Source: Oke, 1987.

The UHI effect has been described in a separate publication by the US EPA (United States Environmental Protection Agency, 2014). The publication indicates, that differences in LST between rural and urban areas can reach about 15°C. Bonan (Bonan, 2002) considers meteorological phenomena and urban space parameters to be the main causes of the UHI effect. Description of UHI factors, such as heat generated from human activities, greenhouse effect, reduced air flow in streets, urban materials, emission and reflected heat can be found in publications in 1991 (Oke et al., 1991). These publications also use the term of 'urban canyon' whose size and proportions determine the UHI effect.

The cooling effect of greenery within streets has been studied in Athens (Tsiros, 2010) and the reduction of the LST is up to 2.2°C in daytime. The review of studies on the impact of trees in urban areas (Bowler et al., 2010) proves that the reduction of the LST is nearly identical regardless the number of trees. Li et al. research touches upon various factors contributing to the UHI effect (Li et al., 2020). Each one of them has a different impact on temperature in city space (Takebayashi and Senoo, 2018) and consequently on the comfort of living. Measurement tests and experiments regarding the impact have been described in the literature (Kaplan, Peeters and Erell, 2016). The extended specification of UHI factors, including those selected for the article, has been studied by Ryu and Baik (Ryu & Baik, 2012).

This article discusses mutual relations and optimal configuration of 3 UHI factors: urban geometry (morphology), greenery and land surface temperature (LST). These are expressed by building coverage, buildings height, greenery coverage, greenery height and LST distribution (Fig. 2). Research questions in the context of the selected parameters are: what and how strong is relationship between buildings and greenery intensity with LST in urban area of the two cities? What combination of buildings and greenery helps to reduce the UHI effect? In terms of data the question is how to combine remote sensing and vector data to get objective information for the UHI effect in the city scale.

UHI SELECTED FACTORS			
MEANS OF EXPRESSION	URBAN PARAMETERS	GREENERY	TEMPERATURE
GENERAL ANALYSIS	URBAN DENSITY AVERAGE BUILDING HEIGHT	% OF GREEN AREA AVERAGE GREENERY HEIGHT	LAND SURFACE TEMPERATURE (LST)
DETAILED ANALYSIS	% OF BUILDING AREA URBAN MORPHOLOGY SCHEME	DISTRIBUTION OF GREENERY	TEMPERATURE DISTRIBUTION
SOURCE DATA	BDOT10k VECTOR DATA	ELEVATION RASTER	LANDSAT 8

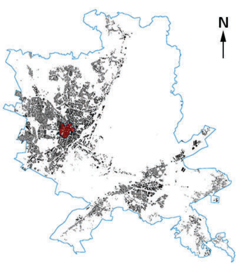
Figure 2. Selected UHI factors with measurement methods and source data. Source: authors.

Based on the combination of CAD and GIS data, the article presents original methodology of analysis and imaging of specific parameters. The methodology has been used in a case study of selected areas in Szczecin and Gdynia, two mid-size cities in Poland. Research findings have been examined from two points of view: general trends and the relationship between parameters and thorough analysis of characteristic areas of cities.

2. METHODOLOGY

2.1. RESEARCH AREA

The research area comprises Gdynia and Szczecin, two mid-sized cities in Poland. The cities were chosen due to similarities in their cityscapes and characteristic urban structure of their city centres. Moreover, both cities share the same cityscape features (location on water body and surrounded by forests). Yet another factor was authors' affiliation and familiarity of urban space from the point of its user. General data range is limited to administrative boundaries of the cities. The detailed analyses focused on two urban units designated SZN_01 and GDY_01 in centres of Szczecin and Gdynia (Fig. 3). The two units are selected based on their homogenous city centre urban structure and diverse configuration of open space (street canyons, squares, interiors).



SZCZECIN	CITY	GDYNIA
SZN_01	URBAN UNIT NAME	GDY_01
129.96	UNIT AREA [ha]	52.02
1444	NUMBER OF RASTER CELLS	578
37.3	BUILDING COVERAGE [%]	34.0
9.26	VEGETATION COVERAGE [%]	6.03
36.7-43.3	TEMPERATURE RANGE [°C]	32.8-36.8
6.7	TEMPERATURE SPREAD [°C]	4.0
40.6	AVERAGE TEMPERATURE [°C]	35.1
2020.08.13	DATE OF SATELLITE IMAGE	2020.08.15

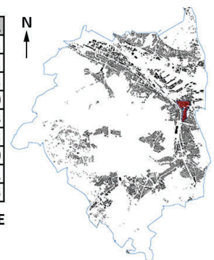


Figure 3. Research area: Urban units SZN_01 and GDY_01 located in the city centers of Szczecin and Gdynia with specification of analytic data (PL) Source: authors.

2.2. URBAN DENSITY

The delimitation of examined urban units has been based on building density. It was determined using BDOT10k vector data and the method of clustering, namely DBSCAN (Density Based Spatial Clustering of Applications with Noise) (Ester et al., 1996). The assumption was to delimit homogeneous areas within city centres in terms of the distance between buildings. In BDOT10k database, buildings are reflected as single features. Building polygons have been converted into points by generating centroids within building envelopes. The layer of points were processed the DBSCAN analysis with search point distance of 20 m. Developed clusters of points indicated areas of homogenous development in terms of density and morphology (distances and scale of buildings). These areas were used to delimit SZN_01 and GDY_01 units for further analysis (Fig. 4). The single-colored dots represent homogeneous urban structures.

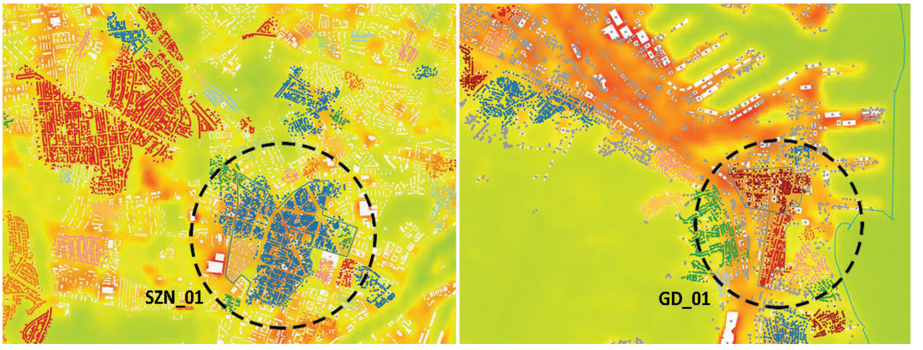


Figure 4. Delimitation of urban units SZN_01 (Szczecin) and GDY_01 (Gdynia) by the density-based clustering methodology. Source: authors.

2.3. DATA PROCESSING

To determine building and greenery intensity, a number of parameters have been calculated for each urban unit (SZN_01 and GDY_01). The diagram of data processing is presented in figure 5. In the first step, the difference between the Digital Surface Model (DSM) and Digital Terrain Model (DTM) was calculated to get the heights of elements above ground level and this was rounded to integers according to mathematical rules. Then heights were assigned to buildings based on BDOT10k vector data, what required combining raster data (1 m cell size) and buildings of several hundred square metres. We decided to assign a median of all pixels with heights within the polygon of a building, since the mean value could have been distorted by pixels of incorrect low (in case of pixels at ground level) or high values (trees above low buildings). Each building with high difference between median and mean was visually checked and frequently divided into several features. Most often, the difference was caused by differences in height of particular parts of buildings, whereas in BDOT10k it was reflected as one feature.

It was assumed that all differences between DSM and DTM above 0.5 (rounded to 1) that were not buildings represent vegetation. As a result it was crucial to investigate the map of differences to find all build-up terrain with heights exceeded 0 m above ground level and treat it as buildings. It helped to identify several hundred objects, most often low utility buildings, such as garages, which previously have not been included in the BDOT10k database and correct any inaccuracies. They all were digitized to vector data and added to the buildings database.

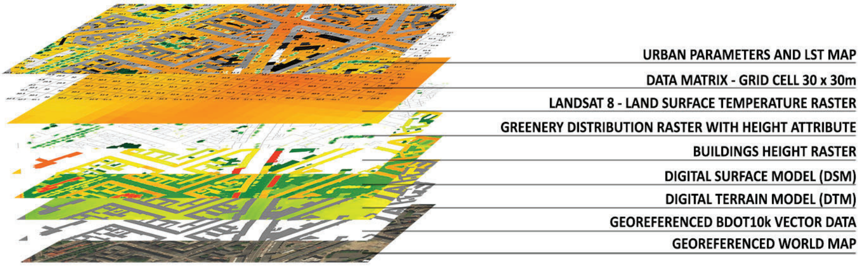


Figure 5. Diagram of data processing. Combination of CAD and GIS data. The final map of the analyzed parameters at the top. Source: authors.

All steps described above helped to develop a raster layer of buildings, including their height, and a raster layer of greenery with height, both with 1 meter spatial resolution. Temperature for UHI studies was downloaded from USGS website as a Landsat 8 Collection 2 level-2 Product - already corrected Earth surface temperature resampled to 30m resolution, and calculated with multiplicative and additive scale factors (Landsat 8 Collection 2 Level 2 Science Product Guide, 2020), then converted to Celsius degrees by subtracting 273.15. In research we used satellite derived LST for summer days - 15.08.2020 for Szczecin and 13.08.2020 for Gdynia. To combine temperature of spatial resolution 30m with building and vegetation data, a square vector mesh was developed overlapping with pixels of a satellite image resulting 1444 cells in Szczecin and 578 cells in Gdynia. Calculations for each cell of the mesh included: coverage with buildings, coverage with greenery, and the average height of buildings and greenery in each cell. The temperature rounded to 0.1°C was added and we obtained a set of parameters describing buildings urban geometry, greenery and temperature.

The relationship between the Land Surface Temperature (LST) and above-mentioned parameters have been examined after averaging values of density and height of buildings and vegetation in all cells of a given temperature.

3. RESULTS

3.1. TRENDS

Temperatures in two analysed cities differ much, as mean temperatures are 35.1°C in Gdynia and 40.6°C in Szczecin. The difference between maximum and minimum temperatures in Szczecin and Gdynia were 4.0°C and 6.7°C, respectively. The percentage of both building and vegetation area is higher in Szczecin (Fig. 3).

We have determined general trends in LST fluctuation depending on the intensity of buildings and vegetation by calculating Spearman correlation coefficients for particular parameters (Tab. 1). In Gdynia, we found outliers of exceptionally low and high temperatures. Outliers are defined as values that differ from the mean value by at least 2 standard deviations. In this case, the outliers included temperatures below 33.7°C and above 36.5°C. In Szczecin, no such outliers were found, most probably due to a different character of the area studied, variety of data and larger standard deviation. Since outliers caused no correlation between parameters, we tried to analyse relationships between selected cells. Table 1 shows correlation values including and excluding outliers.

Table 1. Spearman correlation coefficients, for Gdynia with and without outliers (3 cells of highest and 18 of lowest values). Source: authors.

Urban units	LST vs % of building coverage	LST vs mean buildings height	LST vs % of vegetation coverage	LST vs mean vegetation height
SZN_01	**0.64 *****	**0.68 *****	**-0.83 *****	**-0.80 *****
GDY_01 no outliers	**0.26**	**0.04**	**-0.46****	**-0.08**
GDY_01 all	**0.05**	**-0.12**	**-0.31 ***	**0.26**
****p<0.01; **p<0.05; *p<0.10*				

Both in Szczecin and Gdynia, we can see a relationship between the percentage of vegetation area and the LST, but in Szczecin this relationship is stronger. Moreover, while in Szczecin there is a significant correlation between the buildings (both coverage and height) and temperature, in Gdynia no such trend can be determined. Szczecin shows stronger relationship of temperature with density and height of greenery, than with buildings (Tab. 1).

In cells of a higher vegetation coverage, temperatures are visibly lower (Fig. 6AB) in Szczecin. However, there is a visible concentration of points on the vegetation coverage and LST scatterplot (Fig. 6A) which is characterized by a high drop in temperature with an increasing vegetation coverage. The Spearman correlation just for these points equals -0.89, and the points represent 91% of the area analysed.

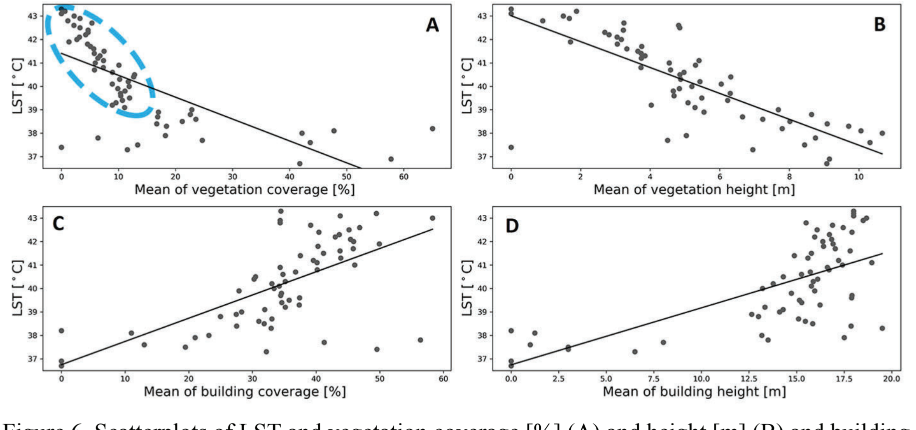


Figure 6. Scatterplots of LST and vegetation coverage [%] (A) and height [m] (B) and building coverage [%] (C) and height [m] (D) in Szczecin. Blue ellipse includes cells of high decrease of temperatures examined more closely. Source: authors.

In the case of three highest temperatures in Szczecin (above 43°C) - area located around crossroads surrounded by high buildings, the density of greenery is 0.2%, building intensity is 42.6% and 18 m height, whereas the two lowest LST values (below 37°C) are in cells located in a park with no buildings and high vegetation coverage (49.7%, 9.1m)

3.2. SPECIAL CASES

Apart from general trends and correlations between specific parameters, the study identified special cases showing the influence of building and greenery coverage on city space temperatures.

The first case involves two typical streets in Szczecin. Both of them are the main arterial roads playing a similar role in the traffic system (Fig. 7). However, they differ in their geometry and greenery coverage. The first arterial road (pixels A and B) is an avenue with double rows of trees and lawn strips. The second one (pixel C) is a densely developed street with single trees. The analysis of temperature in these cells show a significant variation of 3.2°C between the part of the avenue with trees (pixel A), and the second street deprived of greenery (pixel C). The height of greenery is less important in this case. For pixel A, the average height is 9.2 m, and pixel B 7.8 m. The building height for both streets is very similar. Additionally, the width of streets corresponds the general level of temperature (about 2°C difference). In the case of an avenue with trees (pixels A and B), the H/W ratio is 0.33 (18.5m / 55m), whereas in the case of the second street H/W= 0.61 (18.5m / 30m).

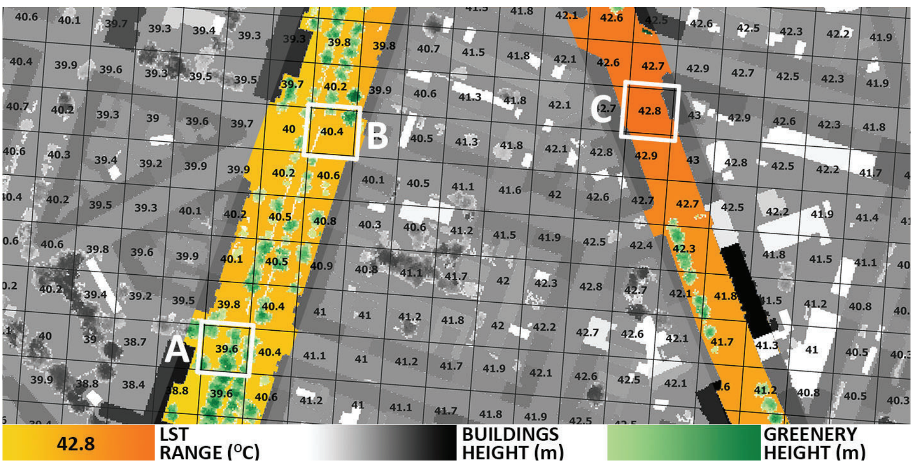


Figure 7. Case 1 – Two street in Szczecin. Values of LST / %greenery / %building coverage for pixels A, B, C: A(39.6 / 58.0 / 0.0), B(40.4 / 19.2 / 0.0), C(42.8 / 0.0 / 11.4). Source: authors.

In the second case, the analysis focused on the character of build-up development and the level of temperatures in city quarters defined as SZN_01 and GDY_01 (Fig.8). A detailed analysis included the level of temperature in areas of 3x3 pixels in interiors of city quarters (SZN_01, areas D and E) and the relationship between the interior of a quarter and the street (GDY_01, area F).

Figure 8. Case 2 – City quarters in SZN_01 (areas D and E) and GDY_01 (area F). Comparison of temperatures in 19th cent. closed residential quarters in Szczecin (area E) and partially open modernist quarters in Gdynia (area D). Source: authors.

Areas D and E show visible differences in LST levels (ca 1.5°C) to the disadvantage of the closed quarters in area E (42.4°C / 29.3%). The partial opening of the city quarters in area D (41.2°C / 43.7%) translates into a better air circulation and lower temperatures. In the case of area F in Gdynia, temperatures in residential quarters are the same as in the street. This is the result of a larger internal space of the modernist quarters in Gdynia and better wind flow.

4. DISCUSSION

Temperatures and ranges of temperatures in two analysed cities differ a lot: mean temperature is almost 5°C lower and ranges is almost 3°C lower in Gdynia (Tab. 1). Moreover, correlations with building and vegetation intensity, as expected (Li et al.,2020, Tsiros, 2010) and clearly visible in Szczecin, in Gdynia is limited to significant correlation with vegetation coverage but below 0.5 Spearman correlation coefficient. Such large differences in temperatures and correlations between examined parameters result from a close distance to the sea and frequent winds in the seafront district (Papanastasiou et al., 2010) of Gdynia. Czarnecka and Nidzgorska-Lencewicz, 2014, analysed the impact of sea breeze in neighbouring city (Gdańsk) on air pollution and UHI and the same phenomenon surely occurs in Gdynia. Frequently appearing sea breeze in summer causes ventilation of the city, daily movement and air exchange causing a drop of temperatures and its amplitudes (Miller et al., 2003).

The relationship between vegetation and its height in Szczecin was expected (Bowler et al., 2010) however on the scatterplot we can see a high drop of LST where vegetation coverages increases from 0 to 13%, what is marked with blue ellipse. Such greenery intensity is typical in that city as this range covers 91% of cells. The decrease of LST is from the highest - 43°C to 39°C- below the average.

The cooling effect of vegetation seems effective - 1°C over each 3% of vegetation coverage what is higher than was noticed in Toronto (Wang et al., 2015). The vegetation in our research includes only above 0.5 meters in height as a result of methodology, so it includes mainly trees and higher bushes.

The grid overlapping pixels in the satellite image allowed for calculations of vegetation and building in each cell and an objective analysis of relations of those parameters with the LST. However, as can be seen from a deeper analysis of special cases, we need to take the neighbourhood into consideration as well. A 3x3 cell window should be taken into consideration as in the city quarters analysis that showed a strong correlation between the formation of heat islands and building height, and consequently size and proportions of open space. This can also be done by the extraction of objects (streets, squares, quarters) for which other properties may be calculated, such as the W/H ratio as in the case of two streets in Szczecin where the temperature difference is about 2.5°C and the W/H ratio difference is about 0.3. Parameters assigned to objects may simplify the interpretation of results.

5. CONCLUSIONS

The article combines vector data with GIS remote sensing data. This allowed for the generation of a uniform objective grid of parameters: building coverage and height, vegetation coverage and height, LST. The application of the method indicated, that for individual cell of the grid it would be important to include infomation about its neighbourhood.

The investigated case of Szczecin emphasized a greater role of greenery than the building parameters for temperature comfort. Within the increase of concentration of the vegetation up to 13% of coverage, the temperature drops by 1°C for every 3%.

The research clearly indicates the role of furnishing street canyons with trees in city centre areas, as well as in poorly ventilated enclosed urban quarters.

The research also confirmed the contribution of other factors on the shaping of UHI effect (air flow, openness of urban geometry, transportation heat etc.). In the case of seaside Gdynia, the breeze significantly affects the temperature. It makes the correlation of LST with greenery and buildings weak. These factors could be added to the data grid in future studies.

In the context of data, the next step would be to increase the accuracy of the data grid (30x30m). This would be possible with drone measurements using a thermal camera. A natural continuation of the method would be to simulate the results in a 3d city model taking into account additional parameters. (Czyńska, 2015).

6. REFERENCE LIST

References

"Landsat 8 Collection 2 (C2) Level 2 Science Product (L2SP) Guide" : 2020. Available from <https://www.usgs.gov/media/files/landsat-8-collection-2-level-2-science-product-guide> (accessed 10.02.2021).

Bonan, G.B.: 2016, *Ecological climatology : concepts and applications*, Cambridge University Press.

Bowler, D.E., Buyung-Ali, L., Knight, T.M. and Pullin, A.S.: 2010, Urban greening to cool towns and cities: A systematic review of the empirical evidence, *Landscape and Urban Planning*, **97**, 147-155.

Czarnecka, M. and Nidzgorska-Lencewicz, J.: 2014, Intensity of Urban Heat Island and Air Quality, *Polish Journal of Environmental Studies*, **23**, 329-340.

Czyńska, K.: 2015, Application of Lidar Data and 3DCity Models in Visual Impact Simulations of Tall Buildings, *ISPRSInternational Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XL7/W3**, 1359-1366.

Geletič, J., Lehnert, M. and Dobrovolný, P.: 2016, Land Surface Temperature Differences within Local Climate Zones, Based on Two Central European Cities, *Remote Sensing*, **8**, 788.

Johnson, G.T., Oke, T.R., Lyons, T.J., Steyn, D.G., Watson, I.D. and Voogt, J.A.: 1991, Simulation of surface urban heat islands under ?IDEAL? conditions at night part 1: Theory and tests against field data, *Boundary-Layer Meteorology*, **56**, 275-294.

Kriegel, H., Kröger, P., Sander, J. and Zimek, A.: 2011, Densitybased clustering, *WIREs Data Mining Knowl Discov*, **1**, 231-240.

Miller, S.T.K., Keim, B.D., Talbot, R.W. and Mao, H.: 2003, Sea breeze: Structure, forecasting, and impacts, *Review of Geophysics*, **41**(3), 1-31.

Mohammed, Y. and Salman, A.: 2018, Effect of urban geometry and green area on the formation of the urban heat island in Baghdad city, *MATEC Web of Conferences*, **162**, 05025.

Muniz-Gäal, L.P., Pezzuto, C.C., Carvalho, M. and Mota, L.T.M.: 2020, Urban geometry and the microclimate of street canyons in tropical climate, *Building and Environment*, **169**, 106547.

Oke, T.R.: 1987, *Boundary layer climates*, Methuen.

Oke, T.R., Johnson, G.T., Steyn, D.G. and Watson, I.D.: 1991, Simulation of surface urban heat islands under ?ideal? conditions at night part 2: Diagnosis of causation, *Boundary-Layer Meteorology*, **56**, 339-358.

Papanastasiou, D.K., Melas, D., Bartzanas, T. and Kittas, C.: 2009, Temperature, comfort and pollution levels during heat waves and the role of sea breeze, *International Journal of Biometeorology*, **54**, 307-317.

Ryu, Y.H. and Baik, J.J.: 2012, Quantitative Analysis of Factors Contributing to Urban Heat Island Intensity, *Journal of Applied Meteorology and Climatology*, **51**, 842-854.

Takebayashi, H. and Senoo, M.: 2018, Analysis of the relationship between urban size and heat island intensity using WRF model, *Urban Climate*, **24**, 287-298.

Tsiros, I.: 2010, Assessment and energy implications of street air temperature cooling by shade tress in Athens (Greece) under extremely hot weather conditions, *Renewable Energy*, **35**, 1866-1869.

Voogt, A.: 2000, Image Representations of Complete Urban Surface Temperatures, *null*, **15**, 21-32.

Wang, Y., Berardi, U. and Akbari, H.: 2015, The urban heat island effect in the city of toronto, *Procedia Engineering*, **118**, 137-144.

TOWARDS WIND-INDUCED ARCHITECTURAL SYSTEMATIZATION

Demonstrating the Collective Behaviour of Urban Blocks as a Design Asset

CHESKA DACLAG NODADO[1], CHRISTINE YOGIAMAN[2] and KENNETH TRACY[3]
[1,2,3]*Singapore University of Technology and Design*
[1]*cheska_nodado@mymail.sutd.edu.sg* [2,3]*{christine_yogiaman| kenneth_tracy}@sutd.edu.sg*

Abstract. This paper presents the premise of collective behaviour of singular units as a design asset in an urban environment. The collaborative effect of building shapes, surface texture and the order of buildings on wind patterns in the urban were explored and analysed. The results revealed that these three factors are imperative to effectively design airflow and air velocity to create cooling effects in warm urban environments. This study intends to solve the problem of compact building blocks which create stagnant air in outdoor urban spaces that worsens outdoor urban thermal comfort. As the study involves a large scale urban area which requires tremendous simulation time, this paper would also demonstrate an attempt for an alternative workflow in studying computational fluid dynamic (CFD) through utilizing Houdini, which is an animation software to predict wind flow patterns in an urban context in a faster way which is highly beneficial for conceptual design stage. The paper explains the setup of Houdini working interface which enables the researcher to compare simulation results of varying models with ease via the switch button, and further improve simulation speed by disabling the need of remeshing the original model.

Keywords. Collaborative behaviour; urban blocks; wind pattern; computational fluid dynamics (CFD).

1. Introduction

Urbanization has increased rapidly in the world and is creating profound effects. The high rate of urbanization in cities has largely affected low-level airflow and high heat island intensity. Compact building blocks create stagnant air in outdoor urban spaces that worsens outdoor urban thermal comfort (Li, 2018). Surface materials and canyon urban structure are the main factors that contribute poor airflow. The impact of the city design over the urban microclimate has been raising concerns about the development of too urban areas. In view of this, the relationship between buildings and their surroundings has become an interdisciplinary challenge for architects and urban engineers. A research group led by Professor Li Yuguo found that it was not enough to solely focus on individual buildings, but that it is important to broaden the analysis to groups of buildings or urban blocks to better analyse the penetration and distribution of air. There is a distinct wind pattern differences when studying the effects of buildings individually and in groups. Individually, buildings cause the downdraught effect which makes the encompassing roads and walkways windier. In groups, buildings can form street canyons which are the roads that have numerous tall buildings on each side and the resulting wind patterns depend on the angle at which the wind reaches the street canyons. Wind behaviours such as channelization, venturi and row effects can only be detected when buildings are studied in groups. As such, once the buildings are laid in clusters, the wind flow pattern of buildings starts to alter. This leads to the idea that studying urban city blocks would further demonstrate a collective behaviour.

2. Literature Review

2.1. SYNCHRONIZATION AND COLLECTIVE MOTION IN NATURE

Collaborative behaviour of urban blocks refers to the relationship between buildings and their surroundings. The main feature of collective behaviour is that tiny movements of an individual unit can add up to an enormous scope. This interesting ordering phenomena can be found in nature where animals in groups have to move in the appropriate formations with an exact spacing between individuals to achieve significant energy savings benefit, create vorticity in their wake or distort the flow patterns (Fish, 1999). For instance, fish school adopts the diamond lattice formation to enable each member to exploit the flow patterns generated by fish ahead of them. In figure 1, the fish used the vortices produced by the leading fish to improve their own thrust performance, lift generation, increase efficiency and reduce drag. The closer the fish to the vortex core generated by its neighbouring fish, the higher the velocity it will experience and the greater momentum it can extract from the moving fluid. However, if the fish follows directly behind the leading fish, it would have to utilize a greater amount of energy instead (Weihs, 1973). Similarly, birds fly in V pattern have the ability to organize the airflow around them and the creation of field around these living beings would be impossible unless they worked together (Fish, 1999). Indeed, a simple set of rules governing the space between each individual and its immediate neighbours could result in changing environmental condition that is interesting to study.

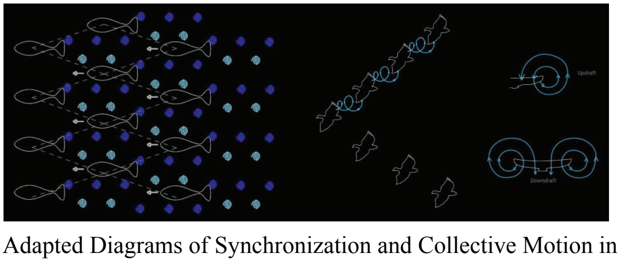


Figure 1. Adapted Diagrams of Synchronization and Collective Motion in Nature.

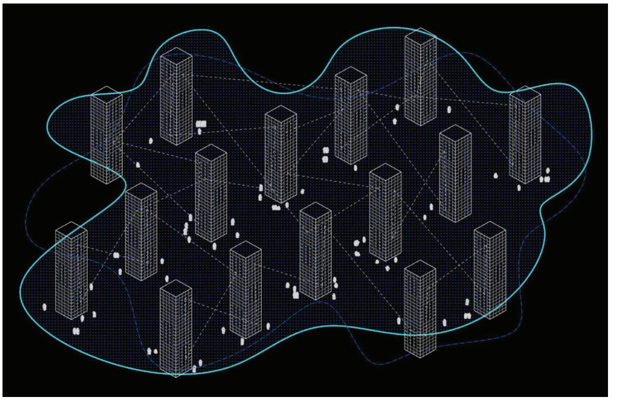


Figure 2. Reimagining cities exhibiting a collective behaviour.

As the air flow patterns around buildings are considerably influenced by buildings around them, the premise of collaborative behaviour of singular units can be applied in the urban environment where there is potential that buildings can work together to build an ambient environment that is good for the collective urban blocks as conceptualize in figure 2.

2.2. URBAN MORPHOLOGY

The air movement within the city depends on its morphology, its street design and orientation, and its form. In the same manner, the shape of the cities is significantly influenced by its local climate to create spaces that are thermally comfortable. For instance, in the town of Harran in Southern Turkey, houses are shaped like beehives. The dome shape design is set up to be resistant to heat and cold. On the other hand, windcatchers in Iran are integrated with building design to trap the wind from high above the building and designs can vary from hexagonal to octagonal depending on the location of different cities. At a street level, aspect ratio is a key parameter that determines the canyon geometry. It pertains to the average height (H) over the canyon width (W). Likewise, different climatic types in the world would have a different ideal aspect ratio or the street design. In a temperate climate, the ideal aspect ratio ranges from 0.4 to 0.6 (Oke, 1988). But in tropical climate, a high asymmetrical aspect ratio of 2-0.8 asymmetrical street aspect ratio was more beneficial (Qaid et al., 2014). In the context of increasing of urbanization especially in Central Business District (CBD) area, these ideal aspect ratios on streets and city morphology are less likely to be followed as streets tend to be skinnier and buildings more compact.

3. Design Methodology

3.1. PROJECT BACKGROUND

The research was carried out during the development of the author's architectural thesis project, which aimed to improve pedestrian-level air flow performance in urban streets. The study will focus on hot-humid regions such as Philippines, which is facing rapid urbanization as well as climatic problems. In Philippines, the leading financial and central business district is located in Makati City. Generally, Makati City has a high humidity level with an average annual percentage of humidity of 75.0% and average wind speed of 3m/s. Throughout the day, it is generally hot and warm. The site study area is highlighted in red in figure 3. The site was chosen as the streets are oriented in parallel with the prevailing wind directions and it is an ideal location to test design strategies at a 3x3 regular street grid. This will allow a way to understand the urban ventilation of the city for decisions related to air paths, urban permeability and site porosity.

Figure 3. CBD Area at Makati City, Philippines.

3.2. WIND SIMULATION TOOLS

In the context of assessment of natural ventilation in urban areas, a large number of investigations have been conducted in recent years, and CFD method has been introduced as an appropriate approach. CFD is a tool with stunning flexibility, accuracy and broadness of use. The technique has a high consistency with experimental outputs which in turn is the indication of its high accuracy. The most significant imported data for benefiting the CFD method is the amount of wind speed and direction.

3.2.1. Forecasting Wind Behaviour with Ansys Fluent

In any case, the CFD results that provide insights to help optimize designs can be out of reach unless the software is carefully chosen. Ansys Fluent is capable of performing complex CFD simulations, produce reliable technical research and simulation results that are internationally industrial accepted quality standard. Ansys Fluent utilizes a single-window workflow, helping streamline the process from CAD to mesh to accurate results. The workflow in Ansys begins with task-based meshing, continues to a streamlines physics setup and concludes with interactive post-processing.

For a successful CFD simulation, a 3D model must be well developed to maximize its accuracy. Rhino (ver. 6) was selected in this study to develop the 3D model because Rhino is highly compatible with ANSYS (ver. 2021 R1). The models developed in Rhino were exported as Parasolid to ANSYS for CFD study. After which, the boundary conditions of the model were set based on AIJ guidelines, where the lateral and the top boundary should be set 5H or more away from the building and the outflow boundary should be set at least 10H behind the building, where H is the height of the target building (Tominaga et al., 2008).

3.2.2. Visualisation of Results using an Animation Software

CFD simulations of detailed design in an urban scale using Ansys are accurate, however, it is time consuming. To obtain a fast and informative solution to designers during early conceptual design, this study introduces Houdini (ver. 18.0.391) as animation software for simulating windflow. As the paper is studying buildings in an urban context which involves heavy data, it is essential to have an alternative workflow to streamline and amplify the research work by allowing a researcher to consider tens to hundreds of design variations in an urban scale. The Houdini animation software is capable of giving quick and close to accurate CFD results. The wind flow animation in three-dimension in Houdini can be obtained in 1-5 minutes (Kaushik et al., 2015).

Figure 4 shows the details of the components used in the proposed Houdini Working Interface set-up which is an improvement of Kaushik et al. research work. The proposed settings allow the results to stabilize with increasing animation frame instead of spotting the best animation frame. The setup also allows the researcher to only load the mesh model without the need of remeshing or simplifying the original mesh model. This advantage is beneficial as remeshing or finding the correct cell size for the model takes considerable amount of time even before running a CFD simulation. The setup also allows a researcher to have a reusable workflow. At “01 Components in buildings”, users are allowed to load the model at Model_version_1 and another model at Model_version_2 for comparison. This setup allows the user to have as many Model_version_n for comparison just by copying the components and connecting it to the switch button. The switch button allows the researcher to view the CFD simulation results of various 3D models in a single interface and similar settings (ie. incoming wind velocity, boundary conditions, viscous model etc). This reusable workflow in Houdini would definitely help to amplify the research work and output many design variations. Components in 02 are to set up the boundary conditions for the simulation and the incoming wind velocity, where the wind is set as laminar flow. Components in 03 allows the researcher to visualize the output in two options, either via trails or particles. The recommended visualisation output is by particles as the setup allows colour-graded arrows to be attached in each particle for a clear and informative visualisation of varying wind speed and direction. Lastly, components in 04 allows for a recorded flythrough animation of the result.

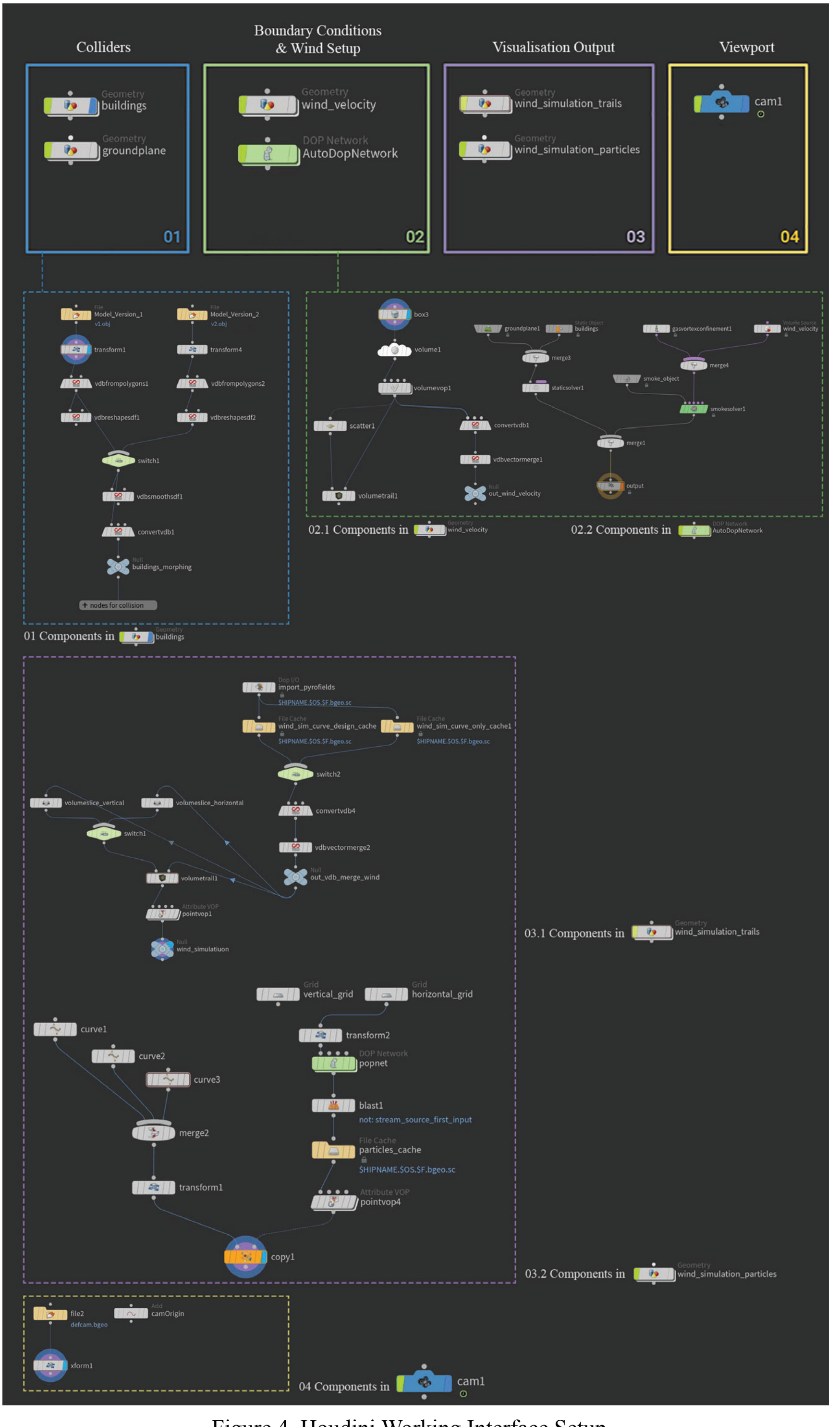


Figure 4. Houdini Working Interface Setup.

4. Design Exploration and Proposal

The project started from investigating the unit behaviour of various forms and surface textures which have the ability to design airflow and air velocity to create cooling effects in warm urban environments (Yogiaman et al.,2018). CFD simulations were conducted to study the shape of the buildings, the texture, and the order of the blocks in the urban setting.

4.1. SHAPE STUDY

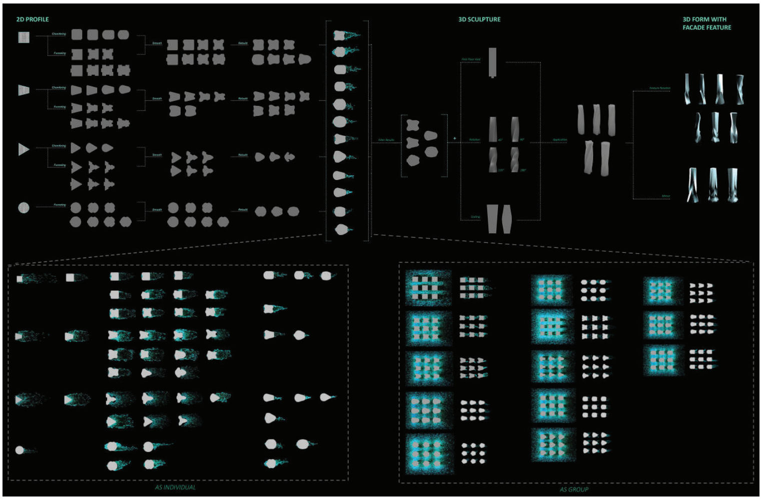


Figure 5. Summary of Shape Exploration and Design Evolution.

Figure 5 shows how the shape has evolved starting from 2D Profile until it was sculptured in 3D. Basic geometries were used as a starting point of the experiment such as square, triangle, trapezoid and circle. Strategies were then applied such as chamfering and funnelling at the first stage. The resulting profiles were then smoothen and rebuilt for second and third stage respectively. At fourth stage, the 2D profiles were filtered based on their performance in the CFD simulation. The results were ranked based on the average wind velocity and percentage of stagnant air for each 2D profile, as individual and as a group. These filtering methods were used until the results were filtered to the best five 2D profiles, which were then used as a basis for 3D sculpturing.

The 3D models were sculptured using the strategies of rotation, scaling and inserting voids. In the same way, the results were ranked and filtered based on the CFD performance by looking at the average wind velocity and the percentage of stagnant air. The results showed that 3D forms which have a twisting character between 135° to 180° displayed the best performance. Subsequently, the forms were then sculpted to have a façade feature that is rotated directly towards the stagnant area to guide the wind and eventually disperse at stagnant areas. This technique would minimize the percentage of stagnant air as the façade helps to direct the wind at areas where wind shadows were prominent. Design variations of 3D form with façade features which demonstrated best performance are displayed at the last stage of figure 5.

4.2. TEXTURE STUDY

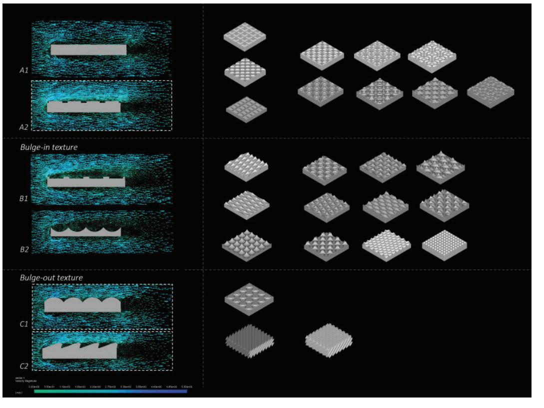


Figure 6. Exploration of Texture CFD Performance.

A total of 25 tiles of different textures were tested for CFD simulation to understand each unit behaviour in relation with the incoming wind of 3m/s. The goal for this exploration is to apply the texture to the geometric form derived from the shape study in the desire that it would amplify the performance of the 3D form and minimize the area with stagnant air in the urban. In figure 6, A1 is the control shape which is a flat texture. From the CFD simulation, the results show that bulging out textures have the ability to let the air stick to the texture closer and maintain the wind velocity as seen from the simulations C1 and C2. This effect is in contrast with the carving in or bulging in textures, which creates turbulence instead and causes the wind to move away as displayed in image B1 and B2. In view of this, bulging out textures are more preferred as it is able to let the wind stick to the geometric form and maintain the original wind velocity, which is highly desirable when combined with the strategy to guide the wind towards the stagnant areas as shown in figure 7.

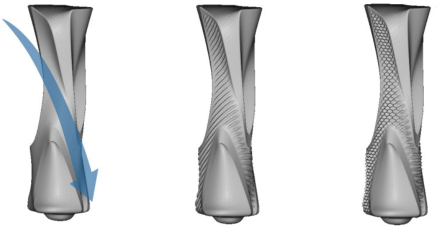


Figure 7. Texture applied on 3D Geometry.

4.3. ORDER AND PLACEMENT OF VOIDS

The form was further developed by creating voids at buildings to allow penetration of air and dispersion to stagnant areas and effectively improve the surrounding wind environment. The voids enabled the wind distribution to be more even around the buildings and eventually lessen the areas of wind shadow at pedestrian level. Figure 8 shows the visualisation of voids at 3D form with integrated façade features. The voids are generally placed at the ground floor level. This creates variations of building core placement at the site area which can be properly arranged and ordered to respond and pattern the incoming wind.

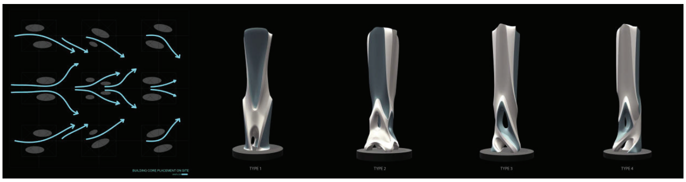


Figure 8. Design Variations of 3D forms with voids .

4.4. PROPOSED DESIGN

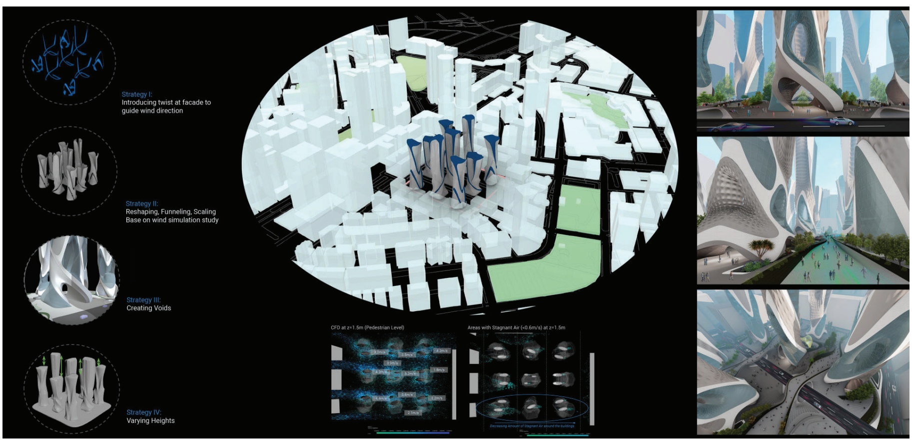


Figure 9. Application of Design Strategies and Design Proposal.

The project explored how urban blocks could display a collective wind behaviour as a design asset in urban environment as shown in figure 9. It utilized the building shape, texture and placement of voids as a way to create a design collaboration of urban blocks as a sustainable approach to improving urban ventilation in between buildings in the CBD Area and, eventually, thermal comfort as compared to individual architectural strategies. The project understood that the design ability and capacity of an individual building to control outdoor airflow movement will not suffice in a large-scale urban setting, and hence, made use of the compact buildings in CBD area to create a coordinated design of building blocks to design an ambient environment.

5. Conclusion

After research and analysis, it can be observed that the shape, texture and arrangement of building cores can be modelled carefully to design wind pattern in the urban. Through an accurate and conscious architectural design that reinforce the design goals of neighbouring buildings, it would be possible to improve outdoor thermal comfort significantly in between buildings. Effective shaping strategies are softening sharp corners, creating openings in the building for the wind to bleed through, funnelling and facade features are essential in the design process. However, shaping strategies should be backed with texture strategies and arrangement of voids to effectively reinforce the design goals and performance of the final form. More advanced simulation should be conducted to test design strategies which include building disposition and various building heights to reveal more insights in the research. Furthermore, the proposed workflow in this research appears to be encouraging with respect to the two key issues of visualizing the wind flow in animation and simulation speed. Although further calibration of Houdini software settings are still required to match with the results from Ansys Fluent, this paper explores the ability of using animation software to aid researchers in the early conceptual design stage and even perform CFD simulations in a large scale urban setting in just a matter of minutes. It should be noted that this workflow is still on its early stage of development and only recommended if the researcher intends to see the general wind flow direction of the design. In-depth calculations and analysis of CFD simulations should still be carried out in internationally industrial accepted quality standard software such as Ansys Fluent.

References

Fish, F.: 1999, Energetics of Swimming and Flying in Formation, *Comments on Theoretical Biology*, **5**, 283-304.

Kaushik, V. and Janssen, P.: 2015, Urban Windflow: Investigating the use of animation software for simulating windflow around buildings, *Proceedings of the 33rd eCAADe Conference*, Vienna, Austria.

Li, Y.: 2018, The Physics in Natural Ventilation of Cities and Buildings, *International Building Physics Conference*, Syracuse, NY.

Oke, T.R.: 1988, Street design and urban canopy layer climate, *Energy and Buildings*, **11(1–3)**, 103–113.

Qaid, A. and Ossen, D.R.: 2014, Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions, *International Journal of Biometeorology*, **59(6)**, 657–677.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M. and Shirasawa, T.: 2008, AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, *Journal of Wind Engineering and Industrial Aerodynamics*, **96(10-11)**, 1749-1761.

Weihs, D.: 1973, Hydromechanics of Fish Schooling, *Nature*, **241(5387)**, 290–291.

Yogiaman, C., Tracy, K., Ghosh, O. and Valdivia y Alvarado, P.: 2018, Aerodynamic articulation: Re-calibrating micro airflow patterns for thermal comfort, *Texas Society of Architects 79th Annual Convention and Design Expo*, Fort Worth, TX.

3D SPACE RESILIENCE ANALYSIS OF COMMERCIAL COMPLEX

Beijing APM as an Example

SHAOJI WU
[1]*Tianjin University*
[1]*wsjarchitecture@tju.edu.cn*

Abstract. Commercial complexes have played an increasingly important role in contemporary cities. Due to the occurrence of crowded people or equipment overhauls, some paths in a commercial complex may become impassable, which can be seen as disruptions to its spatial system. This paper provides a practical method to quantify the spatial resilience of a commercial complex taking Beijing APM as an example. This study can be divided into the following three steps. First, transforming the realistic spatial path system to a directed network model. Second, using topological, metric, and angular distance as edge weight to calculate the centrality and present its distribution. Third, using two disruption processes, randomized and attractor-guided strategy, evaluates the spatial network's resilience. There are three conclusions from this study. The first one is the process of disruption is non-linear, and there is a phase transition process when it reaches the critical threshold. The second one is the most efficient disruption method is the topological BC attractor-guided strategy. The last one is the resilience of a commercial complex, whose 3D spatial network's resilience is lower than the 2D spatial network's resilience by comparison with Duan and Lu's (2013) study.

Keywords. Resilience; Robustness; Network Secience; Commercial Complex.

1. Introduction

Spatial resilience characterizes the ability of a building to maintain its essential functions when facing disruptions. In the field of network science, a robust network is more stable and harder to change. This paper uses the concept of robustness in network science to measure commercial complex's spatial resilience.

In recent years, commercial complexes have played an increasingly important role in cities worldwide and are considered as the prototype of the future vertical city. This paper aims to fill the research gap by proposing a method to quantify the spatial resilience of the commercial complex's 3D space structure.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 457-466.

1.1. RESEARCH REVIEW

Most current research on spatial resilience within buildings has focused on their spatial forms and construction techniques (Phillips, Troup, Fannon, & Eckelman, 2017). However, few research has been done from the perspective of network science. This section analyses three streams of researches.

Network science studies network, which regards a complex system's main element as nodes and their relationships as edges that can be assigned weights. A holistic understanding of complex systems can be obtained by performing mathematical and statistical studies on the network. In the field of architecture, spatial syntax is a theory based on network science in which the connecting relationship between spaces of a building or a city, and was developed by Bill Hillier et al.(1989).

Robustness is the measure of resilience in network science. Albert, Jeong, and Barabási(2000) showed a method to calculate a network's robustness by using external disruptions. Based on the methods proposed by Barabási et al., the resilience of some complex systems has been investigated in power grid systems(Albert & Nakarado, 2004), metro systems(Angeloudis & Fisk, 2006), and urban water supply systems(Yazdani & Jeffrey, 2011). These works have also demonstrated the generalizability of Barabási's method.

Recently, researchers introduced the concept of robustness into the field of urban research. Duan and Lu (2013) studied the robustness of urban road networks in six cities, including Beijing, Paris, San Francisco, Toronto, Singapore, London, and find out that the variation of road networks' robustness is non-linearity in the process of disruption. Kermanshah and Derrible(2017) used the concept of robustness in their study to evaluate the effects of flooding on urban road networks. Casali and Heinimann(2020) studied the changes in Zurich's urban road network's robustness between 1955 and 2012 and concluded that Zurich's urban robustness increased because of the increasing road density during this period.

1.2. STUDY AREA

Our case study is Beijing APM, one of the most prosperous commercial complexes in Beijing, located in the Wangfujing business district in Beijing's central area. The total area of the building is 220,000 square meters, of which the commercial complex area is 140,000 square meters, and the daily passenger flow is about 150,000. The commercial complex is divided into seven floors (one underground and six above ground).

2. Methodology

The occurrence of crowded people or equipment overhauls can corrupt a building's spatial structure: an impassable path in a building might prevent users from reaching their destination. This phenomenon can be seen as disruptions to a building. Figure 1 illustrates the technology roadmap of this study. The first step is to decide how to build a network and the second one is to transform the spatial path system into a network model. The third step is to calculate the robustness of the network model by simulate disruptions. This study uses Rhino/Grasshopper as the research platform, and the core analysis batteries are programmed on C Sharp.

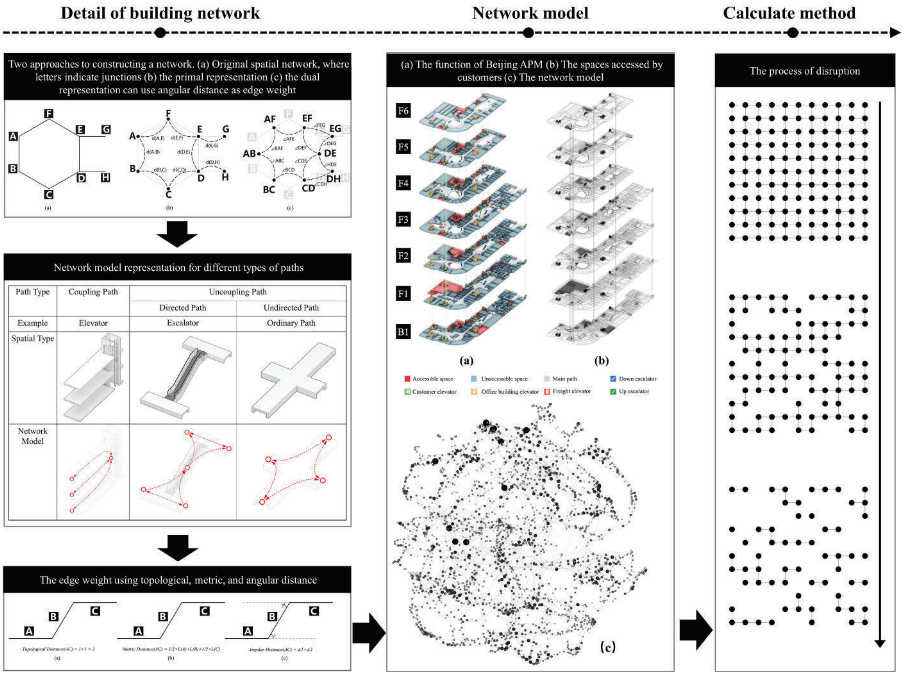


Figure 1. Technology Roadmap.

2.1. NETWORK MODELING

In a commercial complex, the path system connects all other systems, such as the sale system, service system, firefighting system, etc. All the pedestrians' movement depends on the path system, and other systems only provide space for people to stay. Therefore, the path system is chosen to be transformed into a network model.

There are two questions when using network models to represent the path system. The first one is although the undirected network has proven to be a useful way to describe the real world in previous studies. It could be errors when treating a directed path as an undirected path. As a result, we use directed networks to represent the path system of the building. The other is we have to decide which element in the path system as nodes and which as edges when constructing a network. There are two modeling ways: The first one is primal representation, which is the simplest. In this representation, we use junctions as nodes and the path between them as edges, which can use the topological distance and metric distance between two paths as edge weight. On the contrary, the other way is dual representation. This representation uses junctions as edges and the path between them as nodes, which can use the topological distance, metric distance, and the angular distance between two paths as edge weight. Because this study needs to use the angular distance as edge weight to calculate the centrality, we choose the dual representation as the modeling method.

There are two main path types inside the commercial complex. The first type is the coupling path, which contains multiple paths, and if one of them impassable, other coupled paths cannot be used simultaneously, typically elevators. We use a node to represent the coupling path. The other is the uncoupling path, which can be subdivided into two types: one is the directed path, such as escalators, and the other is the undirected path.

2.2. NETWORK CHARACTERISTICS

Centrality is a concept to evaluate the importance of a node in a network, and there are several definitions of centrality in network science. In this paper, closeness centrality and betweenness centrality are used to measure the network.

The closeness centrality(CC) of a node measures its average farness (inverse distance) to all other nodes in a network. Nodes with a high closeness centrality have the shortest distances to all other nodes. Alex Bavelas(1950) introduced the method using the shortest path length to measure closeness centrality, which is formally defined as:

$$CC(s) = \frac{1}{\sum_t d(s,t)} \tag{1}$$

where both s and t are two nodes in the network, and $d(s,t)$ is the length of the shortest path between s and t.

Proposed by Freeman (1977), the betweenness centrality(BC) of a node in a network quantifies the number of times a node acts as a bridge along the shortest path between two other nodes, which is mathematically defined as follows:

$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{2}$$

where σ_{st} is the total number of shortest paths from node s to node t, and $\sigma_{st}(v)$ is the number of those paths that pass through v.

We used Dijkstra's algorithm to find the shortest path between two nodes in a network. Following the convention for analyzing segment models introduced by Hillier and Hanson (1989), we use three ways to assign weights to edges: topological distance, metric distance, and angular distance between two neighboring segments.

2.3. NETWORK RESILIENCE

In a commercial complex, path closures or breakdowns make it difficult for users to move between two places. With the increase of impassable paths, the commercial complex's space system will gradually become unusable, which is the idea behind the approach described in this section. We call this process disruption. There are two main issues in this section:

In this study, there are two approaches to disrupt an existing network: the first is to remove a node in the network each time, and the second is to remove an edge in the network each time. Since we use dual representation to construct the network model, one path blocked corresponds to the network's one node deletion. Therefore, the first disruption method is chosen.

Another issue is what rules are used to remove nodes, called disruption strategies. There are two disruption strategies in this paper. One is the randomized strategy (i.e., randomly deleting a node each time in the process). The other is the attacker-guided strategy (i.e., deleting nodes in order of their centrality in the process). After each disruption frame, we use the giant component scale, which is the largest part that any two nodes are connected after disruption, to evaluate its impact. The calculated data are used to draw a plot to visualize the commercial complex's spatial network's resilience. After calculating the size of the giant component $S(f, q)$, there is a indicator: the ratio $R(f)$ of $S(f, q)$ to the number of nodes N. Barabási(2016) proposes that the Molloy-Reed criterion can determine when a network loses its giant component and calculates the critical threshold. The Molloy-Reed criterion is based on an observation that if there is a giant component in a network, then each node should have at least two neighboring nodes on average, which is calculated as follows.

$$\kappa = \frac{\langle k^2 \rangle}{\langle k \rangle} > 2 \tag{3}$$

where $\langle k \rangle$ is the average degree of the network, and the degree of a node is the number of edges it connects.The $R(f)$ measures are defined in the randomized strategy as:

$$R(f) = \frac{1}{Q}\sum_{q=1}^{Q}\frac{S(f, q)}{N} \tag{4}$$

where Q is the total number of iterations, which is 500 in this study, and N is the original number of nodes. When using attacker-guided strategy, the value of $R(f)$ only need to be calculated once.

3. Analysis and result

Figure 2 shows the analysis process in Grasshopper. After transforming its path system into a network model, the closeness centrality(CC) and betweenness centrality(BC) distributions are firstly calculated at three edge weight: topological, metric, and angular distance. The network is then disrupted using randomized and attacker-guided strategies when calculating the giant component's size after each disruption. The third step compares the similarities and differences of the network's resilience under the two disruption strategies.

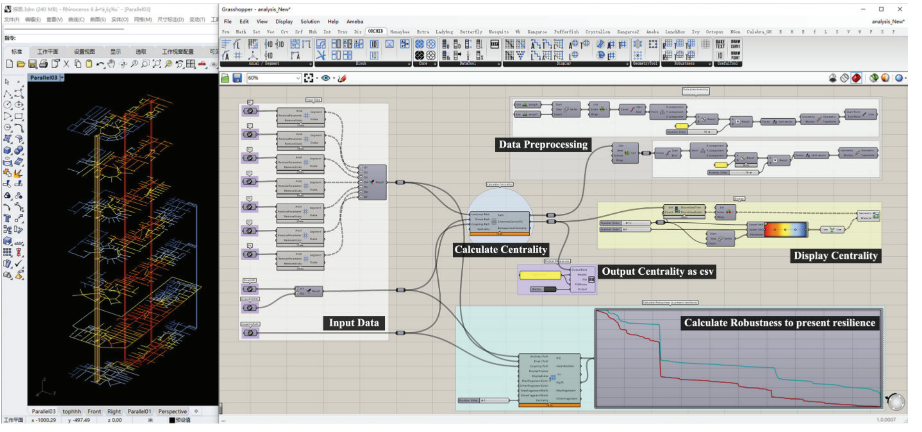


Figure 2. The analysis process in Grasshopper.

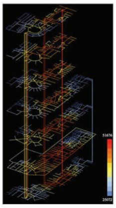
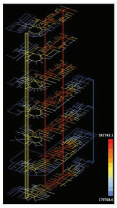
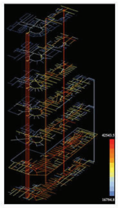
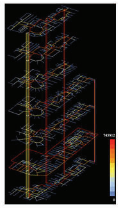
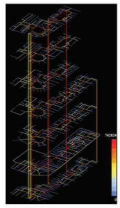
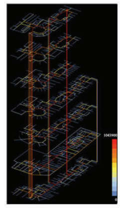
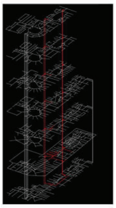
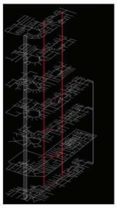
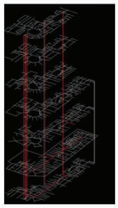
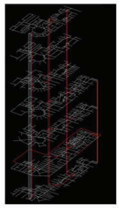
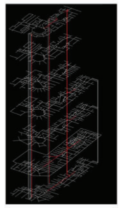
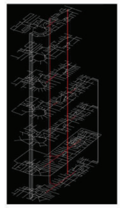
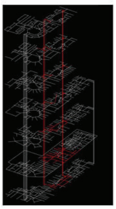
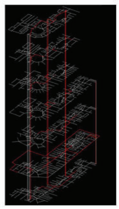
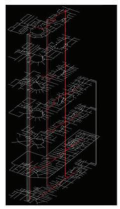
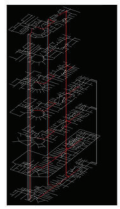
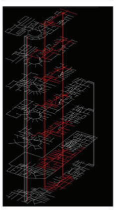
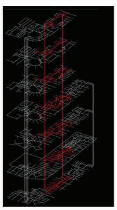
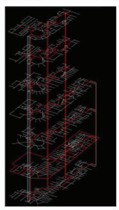
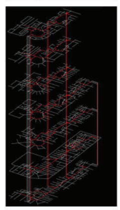
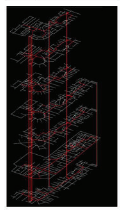
3.1. SPATIAL NETWORK CHARACTERISTICS

Some places in Beijing APM are inaccessible to customers, such as the staff area, firefighting stairway, office building service facilities, etc. This study building a network model base on the spaces accessed and used by customers. The volume of the Beijing APM is L-shaped, and its horizontal customer path consists of one main street connecting four atriums, which are numbered sequentially in one to four. And the vertical paths are composed of escalators and elevators located around the four atriums. This section characterizes spatial networks by using closeness centrality(CC) and betweenness centrality(BC)(Table 1). The top 5%, top 10%, and the top 25% values of CC and BC are selected as quantiles to visualize the spatially distributed features.

Horizontally, three CC are distributed unevenly in Beijing APM. The topological CC and metric CC show a decreasing radial distribution around Atrium No.3. The angular CC is centered on the north-south main street, connecting Atrium No.2 and Atrium No.4, which is different from the topological CC and metric CC. Vertically, the closer a floor is to the ground, the more possibility of paths with the high CC value the floor has. The angular CC distribution showed the most significant vertical variation, and the distribution of topological CC also had this trend. The metric CC shows almost no such tendency.

The segments with high BC coincide with the main public paths, such as elevators, paths around the atriums, the main street in the building, etc. Among the three BC distributions, topological BC has the best ability to identify paths because it can accurately identify both indoor and outdoor public paths. Metric BC has the second strongest ability to identify pathways, and it has difficulty identifying outdoor public pathways. Angular BC is the worst one.

Table 1. The distribution of centrality.

	Topological CC	Metric CC	Angular CC	Topological BC	Metric BC	Angular BC
Centrality						
Top 5% Segment						
Top 10% Segment						
Top 25% Segment						

3.2. DISRUPTION ANALYSIS

3.2.1. Randomized strategy

The first disruption process, randomized strategy, set all network nodes to have equal importance. And during the process, we delete the nodes of the network randomly one by one. Figure 3(a) illustrate the average $R(f)$ after 500 times random disruptions.

The figure shows the $R(f)$ decreased non-linearly by following three phases. Firstly, $R(f)$ almost unchangeable when from 0 to 10% of nodes are removed, and it means that the whole network remained mostly connected. Then, between 10% and 30% of nodes are removed, $R(f)$ declines rapidly, and the network's intactness is disrupted. The phase transition occurs when 16% of the nodes are removed. In the third stage, $R(f)$ is extremely small when more than 30% of the nodes are removed.

3.2.2. Attractor-guided strategy

Attractor-guided disruptions on the network based on CC can simulate that important destinations in a commercial complex, such as essential stores, cannot be reached. And based on BC can simulate that essential paths in a commercial complex cannot be passed. Firstly, we calculate CC and BC of Beijing APM's spatial network with three edge weights: the topological, metric, and angular distance. Then, nodes are deleted based on each node's centrality from largest to smallest (i.e., the more important the node is, the more chances it will be deleted). Figure 3(b-c) shows the result.

There are three phases with the decrease of $R(f)$ using attractor-guided strategy. $R(f)$ keeps stable when 22%(topological CC), 38%(metric CC), 5%(angular CC), 2%(topological BC), 4%(metric BC) and 6%(angular BC) of nodes are removed. Then a dramatic fall of $R(f)$ occurs in these critical thresholds, and it means the size of the giant component decreases rapidly at this point. After the phase transition process, the network is destroyed to pieces, and the spatial system became unusable.

3.3. COMPARISON

Figures 3(d) provide an intuitive illustration of the $R(f)$ of all seven processes. Based on it, we compare the similarities and differences between them.

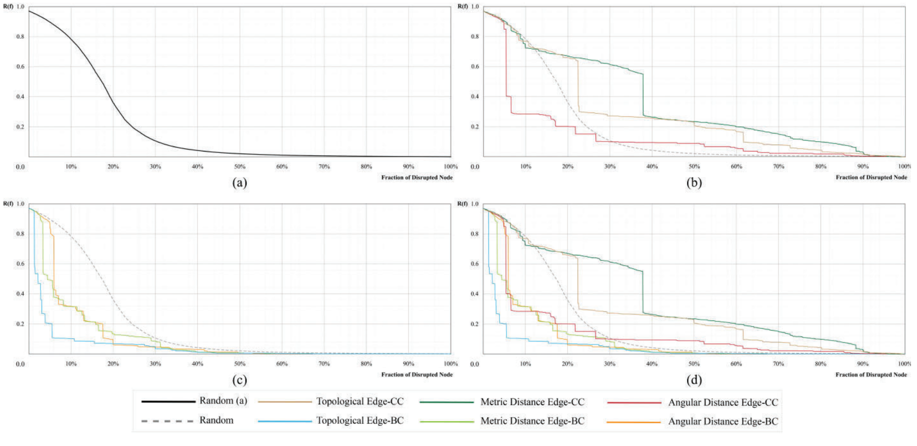


Figure 3. (a) R(f) of randomized strategy (b) R(f) of CC attractor-guided strategy (c) R(f) of BC attractor-guided strategy (d) R(f) of all seven processes.

The line chart of the robustness distribution function $R(f)$ with randomized strategy showed a steady decline during the whole disruption process. And the value of $R(f)$ do not change drastically around the critical threshold as well. It is different from all six other processes using attractor-guided strategy.

There are two common points between the three attractor-guided strategy distribution functions using closeness centrality(CC) as edge weight. One is more nodes than randomized strategy's function need to be removed to reach the critical threshold. And the other is that the size of the giant component is larger after the phase transition. There are also significant differences between the three process. The node number that needs to be removed to reach the critical threshold is different, which is 22%(topological CC),38%(metric CC), and 5%(angular CC). The first two number is larger than 16%, the critical threshold of randomized strategy. The size of the three giant components after phase transition is also different. After the phase transition, the giant component's size with metric CC and topological CC are similar, and two of them are larger than the size with angular CC. The comparison shows that the topological CC and metric CC attractor-guided strategy delayed the network's collapse. In contrast, the angular CC attractor-guided strategy accelerated the process.

There are also two common points between the distribution function's strategy distribution function using the betweenness centrality(BC) as edge weight. Not only do the fewer nodes need to be deleted to reach the critical threshold, but the giant component size is also smaller after the phase transition. The difference between the three is the number of nodes that need to be deleted to reach the critical threshold, which is 2%(topological BC), 4%(metric BC), and 6%(angular BC). The result of the comparison shows that all three processes accelerate the collapse of the network.

Duan and Lu (2013) show a two-dimensional spatial network would malfunctions when more than 50% of the nodes are randomly removed, or 20% of the nodes are removed by order of topological or metric BC. Comparing their findings with this study, we found that the commercial complex path network's resilience is worse than a two-dimensional road spatial network's resilience, which means three-dimensional spatial networks are less resistant to disruption.

4. Discussion

Resilience analysis from network science perspective can effectively quantify the impact of disruption in commercial complexes. However, there are three factors that might affect the analysis, and we hope to overcome these issues in future research.

First, in this paper, we assumed that each node deletion is an independent event. In fact, in a network of a commercial complex's path system, a node's error might cause the error of its neighboring nodes, and we call it cascading failures. This may cause this paper's simulation results to deviate from the actual situation and affect the results' accuracy.

Second, This study building a three-dimensional spatial network model without including the Beijing APM's surrounding paths. However, the surrounding space also affects people's understanding of its inside space.

Third, This study only experiments on one commercial complex, Beijing APM. Therefore we can not verify the generalizability of the conclusions. In the future, we hope to use the same approach to study more spatial network to draw more generalizable conclusions.

5. Conclusions

This paper proposes a method to quantify the resilience of a 3D spatial structure and provide a perspective for architects to understand it. This study has three findings as follows.

First, the spatial resilience of 3D spatial networks under disruption is non-linear. Specifically, it can be divided into three phases: the first stage is that the giant component's size remains basically unchanged. Then, the phase transition happened, and the giant component vanishes. Many tiny components exist after the critical threshold during the third stage.

Second, among the strategies used in this study, The most efficient one is the topological BC attractor-guided strategy, where the spatial network undergoes a phase transition when 2% of the nodes are removed. While the least efficient way is the metric CC attractor-guided strategy, and its critical threshold is 38%.

Third, by comparison with the discussion of Duan and Lu (2013), we can conclude that the resilience of 3D spatial networks in the commercial complex, such as Beijing APM, is lower than the 2D road network's resilience. As the vertical city moves from theory to reality, architects should understand that while the 3D spatial path network is highly efficient, it is also has a low spatial resilience when facing disruptions.

References

Albert, R., Albert, I. and Nakarado, G.L.: 2004, Structural vulnerability of the North American power grid, *Physical review E*, **69(2)**, 025103.

Albert, R., Jeong, H. and Barabási, A.L.: 2000, Error and attack tolerance of complex networks, *Nature*, **406**, 378-382.

Angeloudis, P. and Fisk, D.: 2006, Large subway systems as complex networks, *Physica A: Statistical Mechanics and its Applications*, **367**, 553-558.

Barabási, A.L.: 2016, *Network science*, Cambridge university press.

Bavelas, A.: 1950, Communication patterns in task□oriented groups, *The journal of the acoustical society of America*, **22(6)**, 725-730.

Casali, Y. and Heinimann, H.R.: 2020, Robustness response of the Zurich road network under different disruption processes, *Computers, Environment and Urban Systems*, **81**, 101460.

Duan, Y. and Lu, F.: 2013, Structural robustness of city road networks based on community., *Computers, Environment and Urban Systems*, **41**, 75-87.

Freeman, L.C.: 1977, A set of measures of centrality based on betweenness, *Sociometry*, **1977(01)**, 35-41.

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

Kermanshah, A. and Derrible, S.: 2017, Robustness of road systems to extreme flooding: using elements of GIS, travel demand, and network science, *Natural Hazards*, **86(1)**, 151-164.

Philips, R., Troup, L. and Fannon, D.: 2017, Do resilient and sustainable design strategies conflict in commercial buildings? A critical analysis of existing resilient building frameworks and their sustainability implications, *Energy and Buildings*, **146**, 295-311.

Yazdani, A. and Jeffrey, P.: 2011, Complex network analysis of water distribution systems., *Chaos: An Interdisciplinary Journal of Nonlinear Science*, **21(1)**, 016111.

‘TEAR DOWN’ THE FENCES: DEVELOPING ABM INFORMED DESIGN STRATEGIES FOR UNGATING CLOSED RESIDENTIAL COMMUNITIES

Developing ABM informed design strategies for ungating closed residential communities

WENZHAO XU[1], XIAORAN HUANG[2] and GEOFF KIMM[3]
[1]*University of Pennsylvania*
[1]*wenzhao@alumni.upenn.edu*
[2]*North China University of Technology, Swinburne University of Technology*
[2]*xiaoran.huang@ncut.edu.cn*
[3]*Swinburne University of Technology*
[3]*gkimm@swin.edu.au*

Abstract. Embedded in China’s urbanization process, the growth of gated residential estates has gradually induced severance of urban spaces, resulting in an underutilization of public amenities, a lack of walkable permeability, and congestion of traffic. Responding to these negative effects on urban development, the CPC has released a guideline in February 2016 to prohibit the development of any new closed residential areas in principle and to advocate ungated communities. In this paper, we utilized ABM simulation analysis to test different degrees of openness, the position of new entrances/openness, and pedestrian network typologies, aiming to explore feasible strategies to accommodate the new urban design agenda. A series of typical gated compounds in Beijing were selected for comparative case studies, conducted under different degrees of openness of each case and under diverse ungating modes between cases. On the basis of these analyses, we summarized a sequence of pedestrian-centric design strategies, seeking to increase the communities’ permeability and walkability by suggesting alternative internal and external road network design options for Beijing urban renewal. By integrating quantified simulation into the empirical method of urban design, our research can positively assist and inform urban practitioners to propose a more sustainable urbanity in the future.

Keywords. Gated community; agent-based modeling; pedestrian simulation; computer-aided urban design; road network optimization.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 467-477.

1. Introduction

The growth of gated communities and compounds is ubiquitous in China's urbanization process, with a history traced back to the introspective courtyard archetype of the feudal monarchy period of China (Miao et al., 2009). Earlier this century, Chinese urban planners and researchers noticed that multiple urban problems induced by gated compounds have gradually emerged. The closedness and segregation of gated communities tended to fragment urban spaces, exacerbating the disconnected traffic networks, underutilization of public amenities and social-geographical inequality. Responding to these negative effects on urban development, the CPC (Central Committee and State Council) has released a guideline in February 2016 to gradually prohibit the development of any new closed residential areas in principle, and to advocate ungated communities with denser and more public road networks. Preceding studies provide supporting evidence for the central government's wish to ungate China's superblocks: small blocks mostly produce a highly interconnected pedestrian network (Jacobs, 1961) and a more highly connected and walkable built environment is associated with better sustainability and physical health (Alfonzo et al., 2014). As prior gated community researches have commonly concentrated on empirical sociological studies (Low, 2001; Le Goix, 2005) and regional analysis of urban morphology, much less effort has been given to community-scale ungating strategy analysis. It is of great significance to develop an effective ungating strategy from a neighborhood's perspective, seeking to promote a better city form with permeable spatial patterns facilitating accessibility and maximising connectivity (Lynch, 1981; Talen, 2002).

Agent-based models (ABM) are widely used for the dynamic simulation of the simultaneous operations and interactions of multiple agents (Grimm et al., 2005). In the field of urban design, ABM is a useful tool for circulation simulation, as a person can be identified and traced as an individual entity (Ronald et al., 2007). The specificity and fine-grain analysis of ABM makes it suitable for neighborhood-scale investigation and studies of walkability and its essential dimensions. One such crucial dimension, permeability, is utilized in this research to investigate efficacious opening strategies to prosecute the objectives of the new urban design agenda of the CPC through improved walkability. We define permeability in this work as two complementary metrics of *through-movement* and *to-movement* (Hiller et al., 1993) to construct a two-tier system in the simulation process. Beijing, with widespread private secured residential compounds in its metropolitan area, is an apposite site of investigation. In our experiment, comparative ABM simulation analysis case studies of permeability with or without gating were undertaken for compounds around the Beijing CBD area. The research utilized PedSim, a free Grasshopper plug-in to model the movement and circulation of pedestrians (www.food4rhino.com/app/pedsim). Based on the existing population density and the location of public amenities, we proposed different strategies of opening with new entrances/openness, and simulated pedestrian patterns accordingly. We subsequently summarized diverse pedestrian-centric design strategies of each community type, suggesting an optimized alternative road network structure with shortened walking distances and provision of more travel options. This digital design approach could extensively explore effective and diversified developments of open communities in the future instead of coercive removal of restricted gates.

2. Background

2.1. GATED COMMUNITIES AND PERMEABLE WALKING SYSTEM

As discussed above, gated communities have been widespread in contemporary China's urbanization process as an effective residential unit for governance and management. Generally, enclosing walls and guarded gates are typical elements presented ubiquitously in gated compounds as barriers for through-traffic (Glasze et al., 2004; Xu and Yang, 2009), physically segregating the internal road systems of closed residential communities from the public road network of the city. Such isolation has induced impermeability of pedestrian travel between residential neighborhoods and greater car-driving behavior, which has sequentially given rise to the ineffective use of public facilities inside the community and traffic jams outside the compound (Normile, 2016; Wu, 2005).

The accessible level of to-movement and through-movement for pedestrians are two significant aspects of a compound's walking permeability. Previous studies have shown that the hypothetical removal of gated community barriers could strikingly increase accessibility and permeability for pedestrians (Sun et al., 2017). Guarded barriers may address safety and governing issues; strategies for ungating closed compounds therefore need to be prudent instead of advocating their complete removal. In this study, we simulated pedestrian networks under different degrees of openness, and compare effective ungating strategies for various types of closed residential communities.

2.2. ABM AND PEDESTRIAN SIMULATION IN ARCHITECTURAL AND URBAN DESIGN

In general, the agent-based model (ABM) is an approach to examining complex systems of the autonomous operations and interactions of multiple agents (Grimm et al., 2005; Macal and North, 2010). By modeling agents individually, the agent-based simulation focuses on modeling agents' heterogeneity across a population and the emergence of self-organization (Macal and North, 2010). Since the 1940s, ABM has become largely implemented for modeling complex adaptive systems (CAS), ranging from modeling agent behavior in the stock market (Arthur et al., 1997) to investigating the fall of ancient civilizations (Kohler et al., 2005).

In urban design, ABM has been increasingly developed and applied to simulating human movement over the past two decades. As a single person can be marked as an individual agent, diverse results can be observed from the collective behavioral patterns emerging from the interaction of micro-level agents (Ronald et al., 2007; Osaragi 2004; Kitazawa and Batty 2001;). In 1996, Turner first introduced ABM in micro-level studies of urban scenarios, realizing the application of ABM in the urban design domain. To date, most ABMs are integrated with other modeling strategies to develop more synthetic simulations. In 2D, a space syntax base ABM was developed by Turner and Penn (2001) in the early time of this century. In 2008, procedural modeling and ABM were aggregated by Aschwanden (2014) as a synthetic tool. To realize ABM in the 3D digital dimension, Huang, White and Burry integrated Virtual Reality with ABM in 2018, simulating and visualizing pedestrian behaviors in urban environments with immersive design experience (Huang et al., 2018). Instead of conducting highly detailed ABM simulation in building scale analysis, this research utilized PedSim to investigate walkable permeability in the neighborhood scale and proposes future strategies for modifying neighborhood walkability.

3. Methodology

3.1. PERMEABILITY AND ASSESSMENT

Generally defined as the degree to which an urban form permeates the publicly accessible space, permeability has been identified as one of the essential aspects of walkability, together with safety, footpath quality, land use mix, density, and climate (Marshall 2005; Ewing and Handy 2009; Pafka and Dovey 2016). Its measurements relate to the ease of movement through a targeted urban area and the diversity of travel choices. Therefore, this research selected two types of movements to assess permeability in the neighborhood's scale. The first is named through-movement, representing the potential for pedestrians outside the neighborhood to travel through the community and to access the public facilities and landscape resources inside and surrounding the neighborhood. Second, the type of movement by which pedestrians living inside the neighborhood can access directly to public amenities around the community can be defined as to-movement. In this mixed measurement system, convenient and diversified through-movement and to-movement for pedestrians represent a neighborhood with good permeability.

3.2. ABM PEDESTRIAN SIMULATION

As described above, we have proposed a two-tier pedestrian simulation through PedSim. The location of public transit nodes, public facilities around the targeted closed compound, and the gates of surrounding communities were firstly set as the start-points and end-points for the simulation of through-movement. Public amenities and green space resources within the gated compound were marked as the targets that could be shared for pedestrians traveling through the community. Following a similar logic, we then set the location of each residential building's entrance as the start-point and set the surrounding public amenities as the end-point for the simulation of to-movement.

To evaluate the permeable pedestrian network under different degrees of gatedness, we use the cumulative density of agent path trajectories as an indication of travel choice. Summarizing travel choice tendencies, we correspondingly revised the position of new gates and the extent of boundary walls for further testing the next scenario. As additional indicators for optimizing pedestrian networks, the average travel time and distance of agents were calculated to measure the convenience and ease of movement. These two indications facilitated us to conduct comparative studies under various gatedness degrees within one case, suggesting a series of optimized opening strategies accordingly. Based on the differentiation of optimized patterns among these cases, ungating strategies were summarized for a taxonomy of gated communities.

Table 1. Simulation settings of the ABM system.

INDIVIDUAL AGENT SETTINGS	
AGENT NUMBER	The number of agents is assumed to be 200.
MAX SPEED	The agent moves towards targets and gates with this speed.
MAX FORCE	The magnitude of attracting force that makes a person move towards targets, which is set as 30 in this research.
LIFESPAN	Number of time steps an agent can survive
GOAL POINT SETTINGS	
GATE	Surrounding public facilities, the location of public transits, and the entrances for internal residential buildings
TARGET	Internal public facilities that can be shared, green spaces, schools and commercial buildings

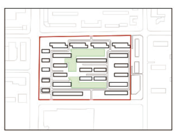
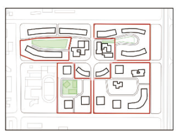
4. Comparative Case Study

As one of the pilot cities for China’s rapid urbanization, gated compounds have developed rapidly in the Beijing metropolitan area in the past few decades. In total, approximately 10300 privately secured gated communities were built up to February 2020 (The Beijing News, 2020.2.22). Borrowing theories from community openness evaluation, current gated communities in the Beijing metropolitan area can be classified into four categories on a continuum from closed to open: *enclosed community*, *semi-enclosed community*, *semi-open community*, and *open community* (Liu, 2016; Liu et al., 2020). Enclosed communities with guarding gates were widely constructed from the 1950s to the 1990s. The block length of these communities is relatively long, ranging from 60 to 400 meters; however, the number of gates on each side of the block is often limited to three. Compared to the enclosed community type, the other three types have smaller blocks with more gates and higher openness.

Although the development of open communities is only in an early stage, the *Jianwai SOHO* neighborhood is a successful attempt in Beijing. Designed by Riken Yamamoto and Field Shop, the site’s existing superblock was subdivided into nine smaller groups while arterial roads and secondary streets were introduced into the site. The mixed road system and compound building type provide possibilities for the pedestrian that endow a high degree of liveliness of the community (Rowe and Kan). Despite the fact that a complete ungating strategy like Jianwai SOHO cannot be applied to every compound, this research proposes to maximise the openness degree while retaining the safety and privacy of each residential model.

Figure 1. Distribution of gated communities in the Beijing metropolitan area and the position of selected cases.

Table 2. Existing site conditions of selected cases.

GATEDNESS/OPENNESS	FULLY ENCLOSED GATED COMMUNITY	SEMI-ENCLOSED GATED COMMUNITY	SEMI-OPEN GATED COMMUNITY	OPEN COMMUNITY
GATING/OPENING MODES	Gated residential community & Gated residential cluster	Open residential community & Gated residential cluster	Open residential community & Partially open residential cluster	Open residential community & Open residential cluster
BOUNDARY MANAGEMENT MODES	Continuous enclosing walls & Guarding Gates	Continuous enclosing walls & Guarding Gates	Partial enclosing walls & Guarding Gates	Guarding Gates
CASE	Fudishoufu Community	Houxiandaicheng Community	Sailuocheng Community-North Block	Jianwai SOHO
GATE NUMBER	3	7	14	
WALL MAPPING				

4.1. CASE 1 FUDISHOUFU COMMUNITY

As a typical fully enclosed residential community, *Fudishoufu Community* has relatively low existing permeability that inhibits through-travel and poses an inconvenience for movements to surrounding public facilities. It occupies a huge block covering a total area of 91937 square metres by 24 residential buildings. The largest block length measures up to 400 metres, with only four guarding gates in total. The existing permeability level is relatively low, inhibiting through-travel and posing inconvenience for movements to surrounding public facilities.

The simulation of the Fudishoufu Community was conducted under various degrees of openness from completely open to partially open: the selected procedures are listed below. As mentioned above, the existing gates and the location of surrounding public transits and infrastructures were defined as the "gate" in simulations, while the internal green spaces and public amenities were set as the "target". According to the cumulative density of agent path trajectories under 100% open simulation, the tendency for travel choice was captured and analyzed, and correspondingly, the position of new community gates and the extent of new boundaries were designated for further simulation. Following the same procedure, the pedestrian simulation was iteratively conducted until the optimized pedestrian network was determined and integrated with the existing road system.

Findings: The results illustrated denser and more connected pedestrian networks after the removal of the gates. However, as the enclosed community has few shared facilities and amenities, it’s not meaningful to divide the block into small clusters. Furthermore, the building type in such communities is residential, which requires a high level of privacy and safety. Therefore, the optimized ungating strategy is to maximize the number of guarding gates at minimum private cost. (Figure 2)

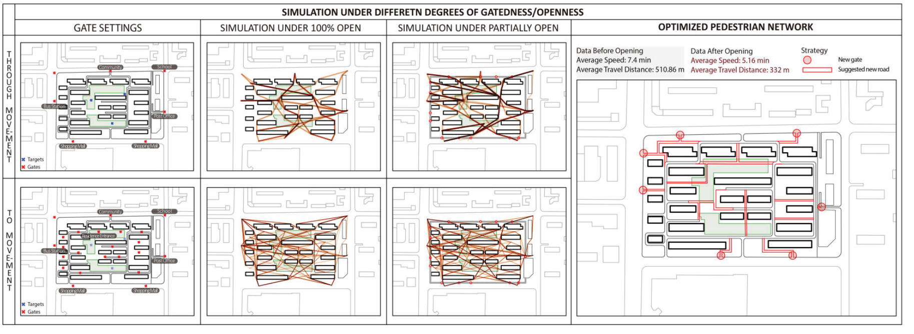


Figure 2. Simulation results of Fudishoufu Community and proposed new pedestrian network.

4.2. CASE 2 HOUXIANDAICHENG COMMUNITY

The *Houxiandaicheng Community* is located on Baiziwan Road in Chaoyang District, covering 206300 square metres. Different from Fudishoufu Community, it contains diverse building types, including residential, office, and commercial. The neighborhood is divided into four groups with separating roads that are open and connected to the city network. Compared with the traditional airtight enclosed residential areas around, the Houxiandaicheng Community is a progressive step towards openness in the design of Chinese urban communities.

Findings: The existing permeable level of Houxiandaicheng Community is better than case 1, which is consistent with the research results by Jane Jacobs that short blocks relate to a better interconnected pedestrian network (Jacobs 1961, pp.178-186). However, the simulation indicates the need to increase walkable connection between four residential groups. Specifically, a viable ungating approach for semi-enclosed communities is to improve permeability between groups by setting more gates and adding potential connecting pedestrian access above or below ground. (Figure 3)

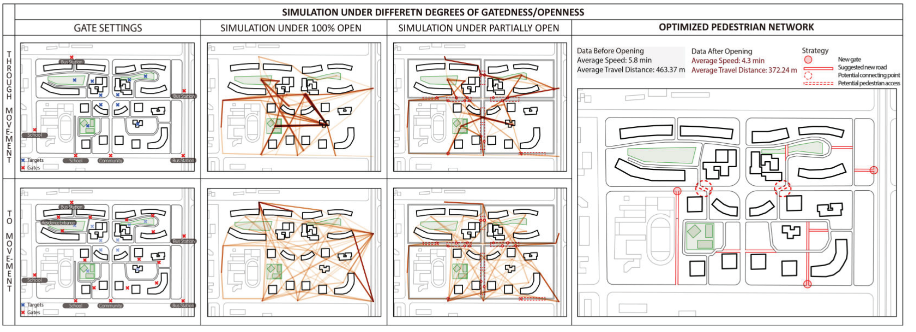


Figure 3. Simulation results of Houxiandaicheng and proposed new pedestrian network.

4.3. CASE 3 SAILUOCHENG COMMUNITY-NORTH BLOCK

Located at a distance of 1.2km from the Houxiandaicheng Community, *Sailuocheng Community* has a higher degree of openness with block-oriented planning. The division of the internal clusters of the Sailuocheng Community can be regarded as a model of the "small blocks, dense road network" promoted by the CPC. The entire residential area consists of four rectangular areas arranged in a north-south direction, and each area is divided into three to five groups of mixed-use buildings with underlying commercial facilities. Under that condition, the simulation of this case focused on the optimization of existing pedestrian networks and the selective relocation of enclosing walls.

Findings: The planning modes of the Sailuocheng Community are close to a completely open community. Correspondingly, its existing permeability is the best among the three cases, which send a positive signal that a reasonable opening of gated communities can indeed have positive impacts on the urban pedestrian system. According to our simulation results, only a small number of guarding gates and enclosing walls need to be removed or relocated. (Figure 4)

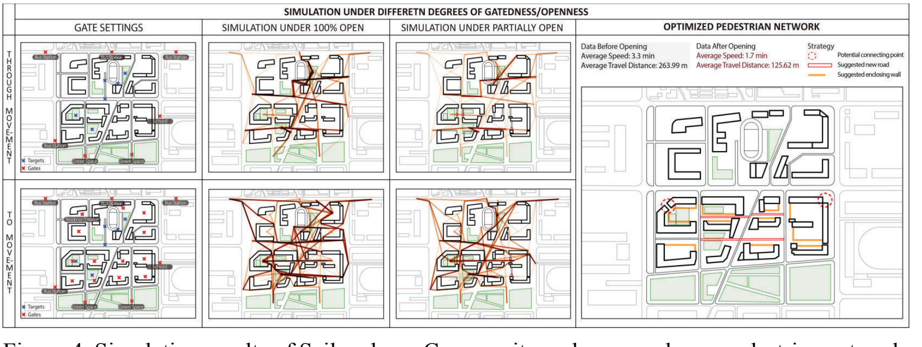


Figure 4. Simulation results of Sailuocheng Community and proposed new pedestrian network.

According to simulation results of three ungating scenarios, the ease of movement has been improved to varying degrees with various opening strategies, indicating the potential and significance to develop specific opening approaches for different types of private secured neighborhoods.

5. Discussion and Conclusion

As discussed above, there is a striking difference in walking accessibility after compound gates have been completely opened and the enclosing walls have been removed. This is a positive indication that opening communities’ internal road networks to the city can promote sharing public service facilities and green space resources, building a harmonious and unified neighborhood environment. However, wholescale and arbitrary removal of guarding gates and enclosures is unacceptable, which may give rise to a new urban conflict of property rights and safety issues. Thus, it is prudent to determine the ungating strategy for different types of gated communities at minimum political and legal cost.

Compared with conventional studies on the walkability of gated communities, this paper presents a novel research approach by establishing the two-tier pedestrian movement modeling through ABM, investigating changes in permeability among multiple opening scenarios, and informing corresponding patterns for Beijing’s ungating urbanity. According to our research findings, different types of gated communities have obvious differentiations in the degree and mode of opening.

For the fully enclosed gated community type, building types inside the compounds are mostly residential buildings, which in and of themselves are inappropriate to be opened or shared with the outside of the community. Resources in these communities that may be of interest to the general public are limited and mostly green space resources. Specifically, our research has shown that the impactful ungating strategy for these gated compounds is to have more gates and more dynamic pedestrian networks, so as to facilitate walkability for pedestrians living in- and outside the compound.

Necessitating a different approach, the extant morphology of semi-enclosed and semi-open gated community types is division into smaller clusters than enclosed communities. Their internal road networks have correspondingly multiple layers and are partially connected with the urban road network system. Building types in these communities are more diverse and vertically compound, including community schools, local centers, surrounding community shops, and underlying commercial facilities. Ungating tactics for these compounds concentrated more on optimizing the pedestrian networks between sub-clusters to enhance the public utilization of shared amenities.

With the aid of computational simulation, this research demonstrates that road network typologies with varying degrees of openness have an influence on pedestrian travel choice. In investigating the potential pedestrian access of ungated compounds, we seek to increase the communities’ permeability and walkability by suggesting alternative internal and external road network design options. However, this study has the potential for future extensions in both diversity and accuracy. For example, the neighborhood-level permeability study concentrated more on investigating walking patterns and road networks without including spatial design at the building scale. Moreover, a more delicate road network could be developed, separating the cycling network from the pedestrian network. Considering that, we are now proposing a finer pedestrian network of micro permeability based on this research, offering a more pragmatic opening scenario for Beijing urban renewal.

References

Alfonzo, M., Guo, Z., Lin, L. and Day, K.: 2014, Walking, obesity and urban design in Chinese neighborhoods, *Preventive medicine*, **69**, S79-S85.

Arthur, W.B.: 2018, *The economy as an evolving complex system II*, CRC Press.

Aschwanden, G.: 2014, *Health and Place: an analysis of the built environment's impact on walking behavior and health*, Ph.D. Thesis, ETH Zurich.

Ewing, R. and Handy, S.: 2009, Measuring the unmeasurable: Urban design qualities related to walkability, *Journal of Urban design*, **14**(1), 65-84.

Glasze, G., Webster, C. and Frantz, K.: 2004, *Private cities: Global and local perspectives*, Routledge.

Le Goix, R.: 2005, Gated communities: Sprawl and social segregation in Southern California, *Housing studies*, **20**(2), 323-343.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K. and Huse, G.: 2006, A standard protocol for describing individual-based and agent-based models, *Ecological modelling*, **198**(1-2), 115-126.

Hillier, B., Penn, A., Hanson, J., Grajewski, T. and Xu, J.: 1993, Natural movement: or, configuration and attraction in urban pedestrian movement, *Environment and Planning B: planning and design*, **20**(1), 29-66.

Huang, X., White, M. and Burry, M.: 2018, Design Globally, Immerse Locally, *Learning, Adapting and Prototyping–CAADRIA, Beijing*, **1**, 473-482.

Jacobs, J.: 2016, *The death and life of great American cities*, Vintage.

Kitazawa, K. and Batty, M.: 2001, Pedestrian behaviour modelling, *Environment and Planning B: Planning and Design 2001*, **28**, 321-326.

Kohler, T.A., Gumerman, G.J. and Reynolds, R.G.: 2005, Simulating ancient societies, *Scientific American*, **293**(1), 76-84.

Liu, X.: 2016, A Study on the Opening Mode of Open Residential Districts in Beijing and the Feedback, *2016 China Urban Planning Annual Conference Proceedings*, Shenyang, China.

Low, S.M.: 2001, The edge and the center: Gated communities and the discourse of urban fear, *American anthropologist*, **103**(1), 45-58.

Lynch, K.: 1984, *Good city form*, MIT press.

Macal, C.M. and North, M.J.: 2005, Tutorial on agent-based modeling and simulation, *Proceedings of the Winter Simulation Conference, 2005.*, 14-pp.

Osaragi, T.: 2004, Modeling of pedestrian behavior and its applications to spatial evaluation, *Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems-Volume 2*, 836-843.

Pafka, E. and Dovey, K.: 2017, Permeability and interface catchment: measuring and mapping walkable access, *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, **10**(2), 150-162.

Penn, A. and Turner, A. 2002, Space syntax based agent simulation, *in* M. Schreckenberg and S.D. Sharma (eds.), *Pedestrian and Evacuation Dynamics*, Springer-Verlag.

Porta, S. and Renne, J.L.: 2005, Linking urban design to sustainability: formal indicators of social urban sustainability field research in Perth, Western Australia, *Urban Design International*, **10**(1), 51-64.

Ronald, N., Sterling, L. and Kirley, M.: 2007, An agent-based approach to modelling pedestrian behaviour, *International Journal of Simulation*, **8**(1), 25-38.

Sun, G., Webster, C. and Chiaradia, A.: 2018, Ungating the city: A permeability perspective, *Urban studies*, **55**(12), 2586-2602.
Talen, E.: 2002, Pedestrian access as a measure of urban quality, *Planning Practice and Research*, **17**(3), 257-278.
Wu, F.: 2005, Rediscovering the ‘gate’ under market transition: from work-unit compounds to commodity housing enclaves, *Housing studies*, **20**(2), 235-254.
Xu, M. and Yang, Z.: 2009, Design history of China’s gated cities and neighbourhoods: Prototype and evolution, *Urban Design International*, **14**(2), 99-117.

URBAN SPACE SIMULATION SYSTEM FOR TOWNSCAPE ORDINANCE

YASUO KAWAI
[1]*Bunkyo University*
[1]*kawai@bunkyo.ac.jp*

Abstract. In this study, a game engine-based urban space simulation system for townscape ordinance was developed and evaluated. For accurate evaluation of a townscape, it is important for the townscape simulation to be as close to reality as possible from various perspectives. The proposed system employs a freely moving first-person viewpoint with different height and origin variations; the building height and exterior wall color can also be changed. To evaluate the system, the simulation and photographic images were compared. The photographic images exhibited a higher gaze rate on spatial components; high gaze rates were also observed for vehicle and pedestrian in the photographic images. Therefore, we recreated dynamic spatial components such as vehicles and pedestrians. Additionally, we successfully reproduced the night townscape via a switchable light source and enabled the control of the numbers of poles and signs. The townscape reproduced by the proposed system could contribute to townscape planning. In the future, a more versatile urban space simulation system that combines various sources of urban information can be developed.

Keywords. Landscape Simulation; Game Engine; Urban Planning; Gaze Elements; Sequence.

1. Introduction

We developed an urban space simulation system for townscape ordinance using a game engine. The urban space comprises various spatial components, such as buildings, facilities, and signs, which can be controlled to create the desired townscape. In a townscape, humans recognize environmental information and evaluate it sensitively; consequently, formulating a townscape plan based on objective evaluation is not easy. However, with the promulgation of the Japanese Landscape Act in 2004, the townscape has become an essential element in urban planning. Local governments have established various townscape ordinances to create a pleasant urban space.

While the interest in townscapes is increasing, it is difficult for citizens and developers to imagine the urban space characteristics and changes affected by townscape planning. To create an urban space image, models and composite photographs have been used. Models have been widely used to share townscape images during the planning stage; they are still being used because they enable

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 479-488.

the study from multiple angles (Bosselman, 1987; Feimer, 1984). However, modeling requires considerable time and cost, and design changes are difficult to reflect immediately. Composite photographs and montages have been used for a long time to evaluate the impact of new architectural plans on the townscape (Lange, 2001; Rekittke and Paar, 2008). In recent years, digital image processing has enabled the generation of realistic predictive images (Rohrmann and Bishop, 2002; Wergles and Muhar, 2009). However, the output of a still image is limited to a fixed viewpoint. In particular, it is possible to minimize the effects on the surrounding environment, and therefore, it is necessary to be careful when planning and evaluating the townscape. Recently, a computer visualization system using 3D shape data created during the design stage was also observed (Portman, Natapov and Fisher, 2015; Azhar et al., 2008). However, these systems were often developed as dedicated systems that require specific systems to be developed for each project, thereby making them expensive and lack versatility.

In this study, we developed a general-purpose urban space simulation system for a townscape using a game engine, which is used as a development environment for digital content, such as games, to experience a reproduced townscape at a low cost. There are various types of game engines, but Unity was used for the development environment in this study. Unity has a lighter editor than those of other game engines, and it can be programmed directly in C sharp script, making it suitable for developing complicated systems with large-scale models. Although previous studies have been conducted on urban space simulations using game engines that have exhibited their potential, they focused on a small limited area, such as a single building and so on, and did not simulate an entire city. (Herwig and Paar, 2002). Only a few dedicated systems can examine the townscape of a real city in a large-scale model at the city block level owing to the large amount of data to be handled (Lim, Honjo and Umeki, 2006; Santosa, Ikaruga and Kobayashi, 2014). We developed an urban space simulation system for townscape planning in which a large-scale urban model can be displayed in a light-weight game development environment, and the elements necessary for townscape planning, such as the building height, exterior wall color, nighttime views, and number of signs, can be changed accordingly in real time.

2. Method

2.1. SIMULATION SYSTEM THAT ALLOWS FOR CHANGES IN BUILDING CONDITIONS

2.1.1. Development

We developed an urban space simulation system that allows users to change the architectural conditions. The Shonandai Townscape Formation Area in Fujisawa City, Kanagawa Prefecture, Japan, was selected as the study site (Figure 1). The Shonandai Townscape Formation Area, which is the urban hub of the northern part of the city, comprises a terminal station connected by three railway lines, a commercial area around the station, a neighborhood residential area, and a traffic terminal for the nearby industrial and educational districts. Target areas and townscape control standards are defined as part of the city's townscape plan, which has been in operation since 2012. The area imposes restrictions on wall location, architectural form and design, color standards, outdoor advertising, planting, and nighttime views. In accordance with Article 16, paragraph 1 of the Japanese Landscape Act, developers are required to notify any new construction, extension, renovation, or relocation, repairs, redecoration, or color change of a building or structure that can change its appearance.

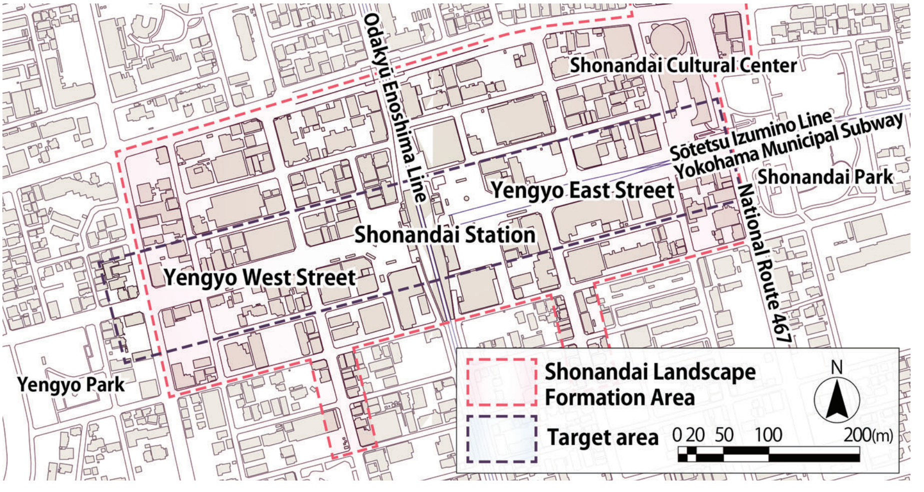


Figure 1. Shonandai Landscape Formation Area.

Three-dimensional shape models were created for the spatial components of buildings and urban facilities in the study area. An entire city, owing to the excessive number of polygons, is difficult to model; therefore, we created a model for each building site, imported it into the game engine, prefabbed it, and then accurately placed it on a mapped model with geographic information data. Furthermore, we created a first-person walkthrough on the game engine that allows the user to move freely. The initial viewpoint height was set at 1500 mm, which was changed to simulate views from not only the street level but also from the interiors of the middle and upper floors of a building (Figure 2). Changing the viewpoint height enables the user to view the townscape from both the public street level and from each private residential unit.

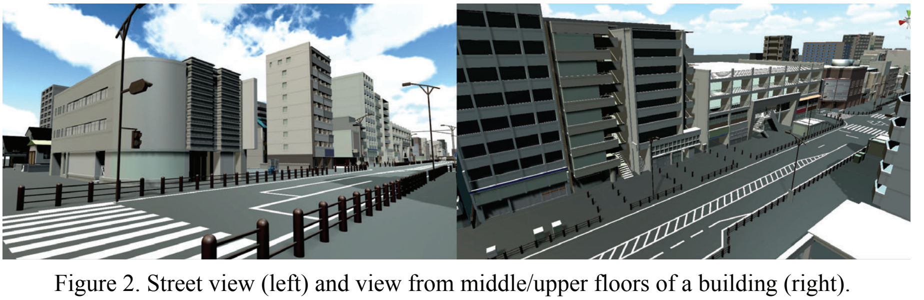


Figure 2. Street view (left) and view from middle/upper floors of a building (right).

Various spatial parameters, including building height and setback, can be changed (Figure 3); building wall material and color can also be changed (Figure 4). A touch-screen display enables the real-time study of building heights and setbacks using an intuitive drag-and-drop operation.

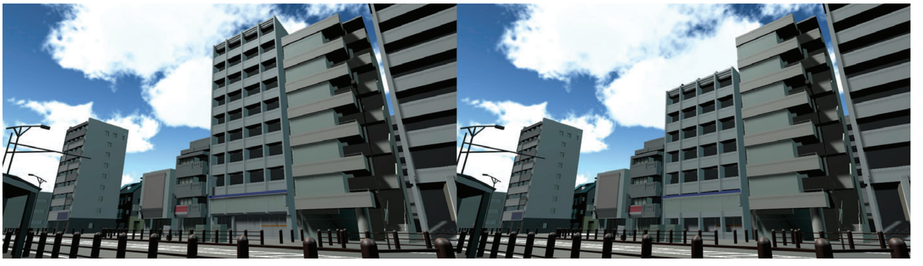


Figure 3. Changes in building height and setback.

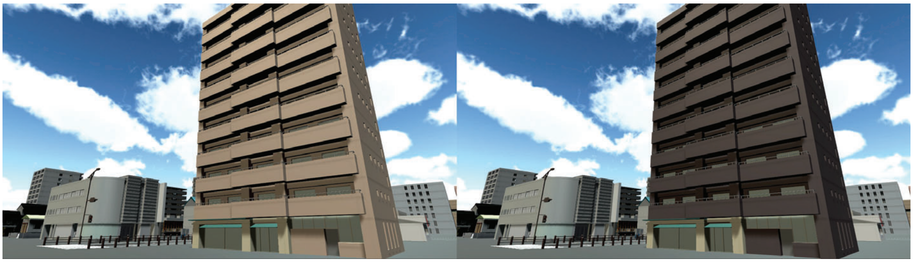


Figure 4. Changes in building external wall material and color.

Input interfaces for free movement in the virtual urban space are designed to be operated by a gamepad, along with a keyboard and a mouse. The left-handed analog pad is used for viewpoint movement, whereas the right-handed analog pad is used for viewpoint rotation to enable intuitive operation. As an output interface, a head-mounted display could be used to enhance the immersion experience.

2.1.2. Evaluation

Methods such as subjective psychological measurement have been used to evaluate townscapes (Reeve, Goodey and Shipley, 2007). However, these are evaluations of the overall impression of the townscape, and the specific spatial components that are affected by these evaluations are not clear. Vision directs the attention by illuminating a specific area of the visual field such as with a spotlight (Posner, Snyder and Davidson, 1980). Here, we pay attention to specific objects in the visual field rather than the entire visual field area (Cave and Bichot, 1999). There have been studies that use eye tracking to analyze the gazing behavior of real townscapes (Simpson et al., 2019; Spanjar and Suurenbroek, 2020). We developed a simple evaluation system to measure gazing objects without using special equipment, such as eye tracking, to determine what is being gazed at in the reproduced townscape and images.

The developed urban space simulation system was evaluated by comparing system images with photographic images (i.e., Street View images from Google Maps). Yengyo West Street was selected as the evaluation area. In Google Maps, 23 points were identified at 10-m intervals from Street View in the evaluation area. The same viewpoint field as the shooting point of each Street View was used in the game engine. In this experiment, a 1280 × 720 image was used. The image was divided into 100 segments, and HTML files for each segmented image were prepared. In this study, the access analysis of each HTML file was used to identify the segmented images that were clicked. The subjects were instructed to click on any number of points of interest on the image displayed on a monitor. This evaluation method is a way to make a conscious choice among the objects in the line of vision. A total of 115 subjects, who frequently visit the places around this area, participated in this experiment.

2.1.3. Results and Discussion

The results indicate that the gaze frequency of the photographic images was higher than that of the system images for each viewpoint field (Figure 5). To evaluate the townscape, we classified images used in the experiments into five spatial components: sky, building and facility, commercial sign, traffic sign, and road.

Gaze rates for each spatial component were measured and compared. The gaze rate was calculated by dividing the total number of gazes clicked on each image by the number of participants; the click rate per image was used. In the case of multiple spatial component species coexisting in the same segmented image, the spatial components are classified based on the percentage of the screen occupied by each spatial component. The results show similar trends for the sky, buildings, and facilities. In contrast, the gaze rates for commercial signs in system images are lower than those in photographic images. It was found that commercial signs, which are small but require attention in the townscape, require more detailed representations (e.g., the preparation of high-resolution textured material). A similarly low gaze rate was observed for roads in the system images. Roads are a background element of the townscape, and they are a spatial component with a high level of screen share.

In photographic images, a high gaze rate was observed for plants, vehicles, and pedestrians, which were not represented in the system. Plants are visually informative elements with complex edges. Vehicles and people are temporary and dynamic elements, and typically, these elements are noisy during townscape evaluation, and our system could remove them. However, these elements were found to be spatial components that were the focus of many gazing behaviors in townscape evaluation. The actual townscape is composed of vehicles and pedestrians, and therefore, these elements are essential in townscape evaluation in the actual urban space.

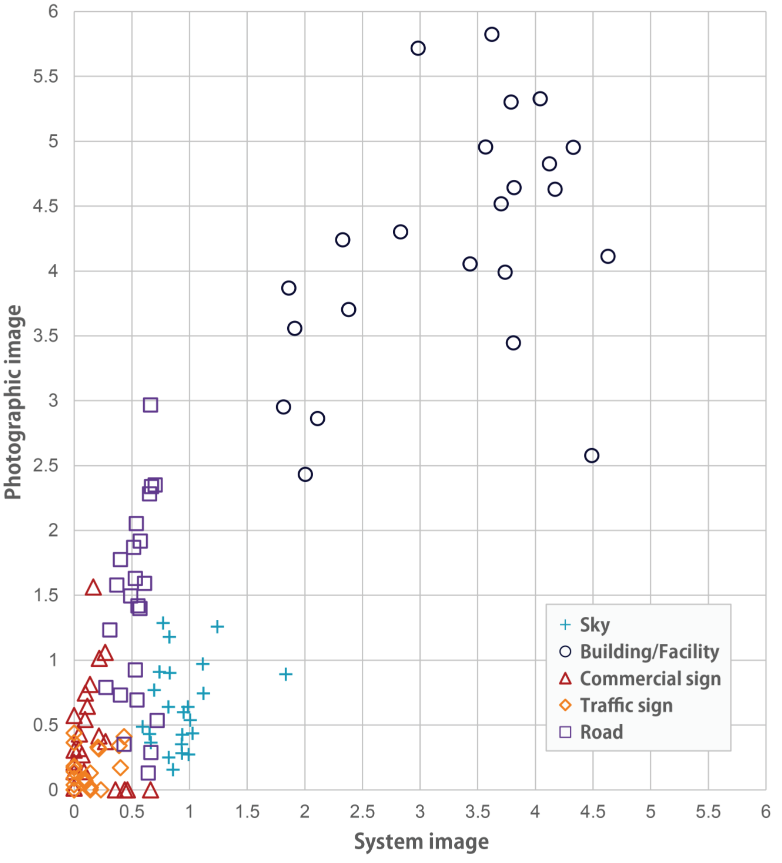


Figure 5. Gaze rates for photographic and system images.

2.2. SIMULATION SYSTEM THAT ALLOWS FOR CHANGES IN DAYTIME AND NIGHTTIME VIEWS

2.2.1. Development

We developed an urban space simulation system that represented day and night townscapes and dynamic elements such as vehicles and pedestrians. A light source is embedded in an object that emits light at night. These point light sources can be switched to light sources representing sunlight to reproduce daytime and nighttime townscapes. The agent models of vehicles and pedestrians acting autonomously were also prepared.

The Special Townscape Community Planning around the North Exit of Chigasaki Station Area in Chigasaki City, Kanagawa Prefecture, Japan, was selected as the study site. The area around the north exit of Chigasaki Station is the urban center of Chigasaki City. It is composed of three characteristic districts: a commercial district with commercial buildings, a governmental district with public buildings, and the Tokaido district along the national road. Chigasaki City has been devoting efforts to create a pleasant townscape even before the enforcement of the Japanese Landscape Law. These efforts include the formulation of the Chigasaki City Townscape Basic Plan in 1998 and enactment of the Chigasaki City Townscape Ordinance in 2000. In 2001, the Special Townscape Community Planning around the North Exit of Chigasaki Station Area was designated as an area that focuses on townscape development. Any new construction, extension, relocation, repair, redecoration, color change, or other development activity that results in the construction of a new building or structure within this area will change the appearance of the building or structure that will be planned to conform to the townscape control standards and must be notified to that effect. Further, it is necessary to evaluate the impact on the surrounding environment and the building size that will appear as a result of the development by creating a simulated scenario using composite photographs, models, and balloons, prior to implementation subject to notification.

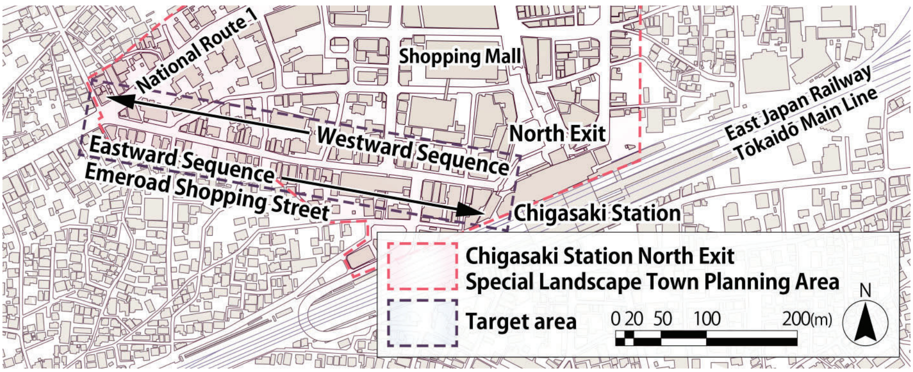


Figure 6. Chigasaki Station North Exit Special Landscape Town Planning Area.

Figure 7. Day and nighttime views of system image.

In this study, the Emeroad shopping street located northwest of Chigasaki Station was selected as the target area (Figure 6). In addition to the detailed modeling of the existing 76 buildings and their related facilities facing north and south, point light sources were inserted into spatial components, such as commercial signs, shop eaves, and streetlights that emit light autonomously. These light sources can be switched between daytime and nighttime townscapes (Figure 7). In this system, planting was reproduced, and models of autonomous vehicles and pedestrians were prepared.

2.2.2. Evaluation

An identifier was assigned to each model placed on the game engine. The 76 buildings were divided into 'walls,' which represent the outer building walls; 'openings' such as windows; and 'temporary structures,' such as storefront products and vending machines, with 228 identifiers as buildings. In addition, there were 194 identifiers for 'traffic signs' including road traffic signs; 'commercial signs' such as permanent signs; and 'temporary signs' such as flag- and stand-type signs. Moreover, 'street trees,' including trees along the road, and 'plants,' including plants or planters, were designed as 96 identifiers of 'planting'; 'street lamps,' 'utility poles,' 'electric wires,' 'car stops,' and 'manholes' were designed as 210 identifiers of 'urban facilities.' They were made to be a model with 728 identifiers in total.

This urban space simulation system has two functions: townscape mode and evaluation mode. In the townscape mode, reconstruction and large-scale repairs were simulated for existing buildings by replacing the building model and changing the outer wall texture, respectively, via mouse clicks. In addition, changes to urban properties related to the townscape, such as the undergrounding of wires and poles and signage control, are possible. In the evaluation mode, the object on the marker displayed in the center of the screen is recorded by clicking the mouse. When the marker is clicked, it acquires the identifier of the object to which the polygon on the line of the marker belongs and stores it in a log file. Using this evaluation mode, the gaze tendencies in the daytime and nighttime townscapes are used to determine spatial component characteristics in the urban space represented in the system.

A total of 404 subjects participated in this evaluation experiment. In the evaluation experiment using the evaluation mode of this system, the participants were instructed to click on an interesting spatial component, and their gazing elements were analyzed in the log. To recognize the townscape as a continuous sequential scene, two routes are prepared: a westward sequence from the station to the shopping street and an eastward sequence from the shopping street to the station.

2.2.3. Results and Discussion

The gaze rate in the westward sequence was plotted in a scatter plot of spatial components, with daytime and nighttime on the horizontal and vertical axes, respectively (Figure 8). The gaze rate is the number of times a spatial component is clicked divided by the number of participants. When the slope of the line connecting each point and the origin is less than 1, the tendency to gaze during the daytime is high; when the slope is greater than 1, the tendency to gaze during the nighttime is high. For example, the commercial sign located in the upper right corner on the westward figure has high gaze rates in both daytime and nighttime; however, because it is an autonomous light-emitting sign, its gaze rates at nighttime and daytime are 2.09 and 1.10, respectively. The average gaze rates of all the spatial components are higher at nighttime than at daytime. With regard to the types of spatial components, the gaze rates of signs and plantings were high, especially at nighttime.

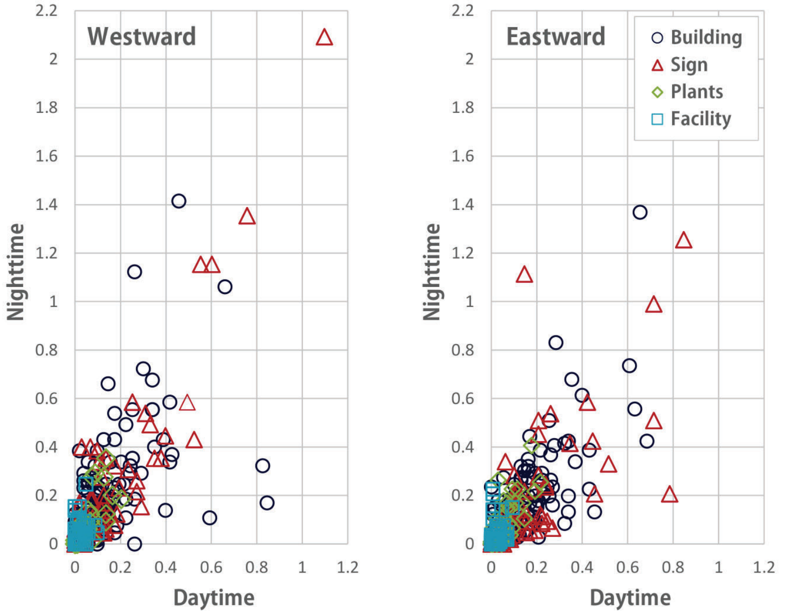


Figure 8. Day and nighttime gaze rates in westward (left) and eastward (right) sequences.

Spatial components with high gaze rates at nighttime were commercial signs that emit light autonomously, openings that allow interior light to leak out, and architectural elements that are illuminated by streetlights. In contrast, spatial components with high gaze rates during daytime were the exterior walls of characteristic buildings and storefronts. These are spatial components that do not emit light at night, and therefore, objects that are figures in daylight become the ground at night and background for other spatial components.

The scatter plot for the gaze rate in the eastward sequence is also shown. The average gaze rates for all spatial components tended to be higher at nighttime than at daytime in the westward moving sequence; however, the slope was relatively low. Spatial components with high gaze rates at nighttime were slightly more modest in comparison to the westward sequence. The westward sequence goes from the station to the shopping street, whereas the eastward sequence goes in the opposite direction. Because commercial signs and shops are spatial components that encourage pedestrians to gaze from the station, nighttime townscapes of the eastward sequence tend to have low gaze rates. Thus, westward and eastward sequences showed different gaze-rate trends during daytime and nighttime.

3. Conclusion

In this study, we developed and evaluated an urban space simulation system for townscape evaluation. These systems, which use a game engine, are easy to operate and represent a useful tool for townscape planning. Using the game engine as a development environment enables the development of high-quality simulation systems at low cost without the need to develop an expensive dedicated system. Further, it is possible to consider environmental condition changes from the private space of the residence and from a public space at the street level, which have been the centers of evaluation in past townscape planning. The evaluation results indicate that vehicles and pedestrians were spatial components that were lacking in the system. Therefore, we recreated the dynamic spatial components. In addition, the townscape impression changes significantly with time. Therefore, we decided to create a system that can switch between the daytime and nighttime. The urban space simulation system using the game engine developed in this study is relatively inexpensive and easy to operate, and it can be used by various organizations and local governments. In the future, we will develop a more versatile urban space simulation system by combining various sources of urban information.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP 19K12665, and the foundation for the fusion of science and technology.

References

Azhar, S., Nadeem, A., Mok, J.Y. and Leung, B.H.: 2008, Building Information Modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects, *First International Conference on Construction in Developing Countries*, 435-446.

Bosselman, P.: 1987, Times Square, *Places*, **4**(2), 55-63.

Feimer, N.R.: 1984, Environmental perception: The effects of media, evaluative context, and observer sample, *Journal of Environmental Psychology*, **4**(1), 61-80.

Herwig, A. and Paar, P.: 2002, Game engines: tools for landscape visualization and planning, *Trends in GIS and Virtualization in Environmental Planning and Design*, 161-172.

Lange, E.: 2001, The limits of realism: perceptions of virtual landscapes, *Landscape and Urban Planning*, **54**, 163-182.

Lim, E.M., Honjo, T. and Umeki, K.: 2006, The validity of VRML images as a stimulus for landscape assessment, *Landscape and Urban Planning*, **77**(1), 80-93.

Portman, M.E., Natapov, A. and Fisher-Gewirtzman, D.: 2015, To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning, *Computers, Environment and Urban Systems*, **54**, 376-384.

Rekittke, J. and Paar, D.P.: 2008, Real-time collage in landscape architecture, *Digital Design in Landscape Architecture*, Dessau, 88-95.

Rohrmann, B. and Bishop, I.: 2002, Subjective responses to computer simulations of urban environments, *Journal of Environmental Psychology*, **22**(4), 319-331.

Santosa, H., Ikaruga, S. and Kobayashi, T.: 2014, Development of Landscape Planning Support System using Interactive 3d Visualization: A case study in Malang, Indonesia, *Journal of Architecture and Planning*, **79**(706), 2699-2709.

Wergles, N. and Muhar, A.: 2009, The role of computer visualization in the communication of urban design—A comparison of viewer responses to visualizations versus on-site visits, *Landscape and Urban Planning*, **91**(4), 171-182.

DEVELOPMENT OF A LANDSCAPE SIMULATION SYSTEM FOR HISTORICAL AND CULTURAL HERITAGE OF THE REGION

YASUO KAWAI
[1]*Bunkyo University*
[1]*kawai@bunkyo.ac.jp*

Abstract. In this study, we developed a historical and cultural landscape simulation system for Fujisawa-juku, a post town of the old Tokaido road. A game engine was used to recreate the landscape of the past by referring to old documents to inherit the history and culture of the region. Subsequently, an enhanced system was developed for changing the representation of time, season, and weather, and another system was developed for recreating the landscape using Ukiyo-e-style rendering. The developed system was exhibited at permanent installations in public facilities and at community events, and feedback from users led to major updates to the system. With the new information, we reviewed the shape of the model of the spatial components of the system and updated it to be more accurate. The digital model of this system can be updated with information that is not possible in a real model, such as a diorama. We will generalize this system through the unitization of spatial components to create a platform for historical cultural landscape simulation systems that can be used in other regions.

Keywords. Landscape Simulation; Historical Landscape; Local Cultural Inheritance; Ukiyoe; Game Engine.

1. Introduction

In recent years, the preservation of local history and culture has become a challenge for many ordinary towns in Japan because of rapid urbanization and depopulation, declining birthrates, and aging population (Yamauchi, 2009). Measures based on the Law for the Protection of Cultural Properties (1950) have been undertaken for each category including tangible cultural property, intangible cultural property, folk cultural property, historical sites, important cultural scenery, and areas for the preservation of traditional buildings, according to the characteristics of each category. However, the general historical culture of the region, which has cultivated in the lives of the locals over a long period of time, has been buried and lost to society without being designated as a cultural asset and without its value being discovered.

In 2007, the Agency for Cultural Affairs of Japan proposed the "Basic Concept of History and Culture," which provides a policy for the comprehensive inheritance and utilization of cultural properties, whether designated or undesignated, that exist widely in the region, including the surrounding

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 489-498.

environment, within the society as a whole. In this project, a self-sustaining and continuous regional design that exploits the characteristics of the region is required in terms of history and culture; it is expected that the historical and cultural resources of the region will be strategically used to revitalize the region and disseminate information as regional tourism resources. We focused on the general historical and cultural landscape of the region and developed a landscape simulation system for inheriting the historical and cultural landscape of the region by visualizing it in an easily understandable approach.

The digital reproduction of historical cultural landscapes has been attempted in various places in the past. Sundstedt et al. (2004) recreated the ancient Egyptian temple of Kalabsha, which was dismantled, on a computer. El-Hakim et al. (2007) used a combination of 3D digitizing and laser scanner modeling, photogrammetry, and computer-aided architectural design to recreate a castle in northern Italy. Although these studies are based on detailed recreations of buildings, they are limited in their scope to famous temples and castles and to the level of buildings. Further, there is a problem with the massive amount of data required to create a 3D model at the town scale; however, there have been a few prior attempts at large-scale landscape simulation. Virtual city reconstruction using procedural modeling methods was performed by Dylla et al. (2008) in the Rome reborn project. Yano et al. (2008) developed a virtual Kyoto using geographic information data and virtual reality to reconstruct past and present urban landscapes. In addition, Fukuda et al. (2015) studied the level of detail and representation of natural objects in a digital recreation project of Azuchi Castle and the Old Castle Town. These are city-level simulations of past landscapes with interactive elements. However, owing to the need for a dedicated and expensive system, it is a large-scale project for a famous historical heritage site. In this study, a system that can recreate the townscape of the past was developed using a low-cost development environment based on a game development system. By using this system, it is possible to create and manage the landscape of each ordinary town in the past that is not a famous heritage or tourist attraction at the local government level.

2. Method

We developed a system that recreated the landscape of a post town in the late Edo period. Post towns were developed along major national roads during the Edo period in Japan, and were places where transportation of goods occurred and where travelers could rest on their journey across the country. In this study, Fujisawa-juku, a post town on the old Tokaido route (Fujisawa City, Kanagawa Prefecture, Japan) was selected as the target area. Fujisawa-juku is the sixth post town, which is about 50 km away from Edo-Nihonbashi (located in Tokyo), which is the starting point of Old Tokaido. Originally, Fujisawa-juku developed as a town for the Yugyo-ji Temple, the head temple of the Jishu Buddhist sect, which was founded in 1325; in 1601, it was developed as one of the first post towns. However, in 1887, when the railway network was built in the southern part of Fujisawa-juku, the center of the city was shifted to the station area. Currently, there are no buildings from the Edo period. This system simulates Fujisawa-juku at the end of the Edo period-in the vicinity of the Daigiri Bridge over the Sakai River-which was the central part of Fujisawa-juku from the Yugyo-ji Temple, which is the northeastern part of the town, to Maita Honjin, which is the western part (Figure 1).

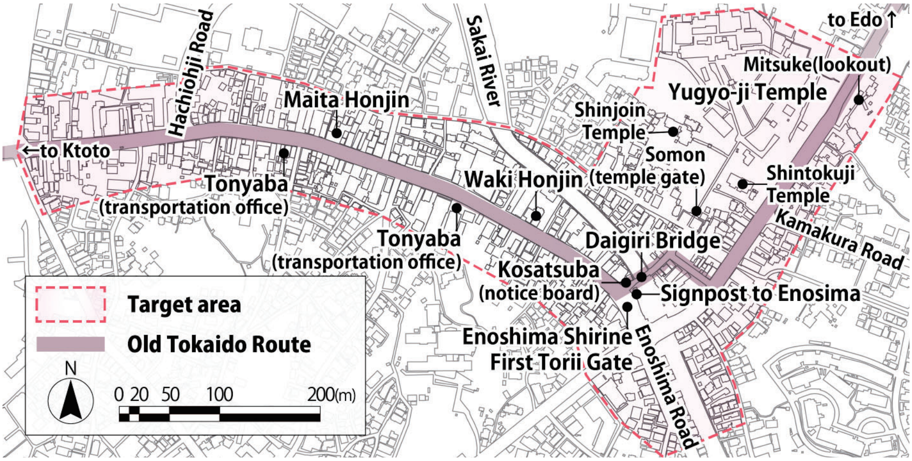


Figure 1. Fujisawa-juku, a post town on old Tokaido.

In 1843, the population of the post town was 4,089 and the number of houses was 919: with one main-Honjin (Maita Honjin) as an inn officially designated as a lodging for a daimyo in the Edo period; one sub-Honjin (Waki Honjin); and 45 inns (Kodama 1970).The Unreal Engine was used as the development environment, and materials such as three-dimensional models, material maps, and sound data were consolidated on the game engine. We modeled buildings such as shops, inns, and temples, urban installations such as tori (gateway), guideposts, and notice boards, trees, and small household items based on ancient documents (Figure 2). The modeling was based on Ukiyo-e, and the types and shapes of spatial components were studied (Utagawa 1832, 1840, 1847). Ukiyo-e is a picture (color print) of everyday life in the Edo period. The spatial components of Ukiyo-e, such as signposts and plantings, are deformed; therefore, the shapes of signposts, tree species, and bridge girders were studied separately, referring to historical documents and other literature (Hirano and Ichikawa, 2017).

Figure 2. View of the Fujisawa post town in the past: a) inn, b) shop, and c) notice board.

In addition to static spatial components, the human model is placed as a nonplayer character (dynamic spatial component) that encourages gazing. We arranged human models on the streets of the town based on the behaviors of the people who lived in Fujisawa-juku, such as townspeople and monks, and the people who visited the post town, such as samurai and travelers. In addition, as an auditory element, natural sounds such as birds and insects were included in the objects as sound effects to create soundscapes that differed according to their positions.

This system is a walkthrough that allows users to move freely in the post town. The system can be operated using a gamepad as well as a keyboard and mouse. The input to the system is based on viewpoint and gaze control with an analog pad, and various actions are operated by buttons. Actions, such as talking, horse riding, and money offering, are based on the relative distance from other objects in the system. In addition, a head-mounted display is used as an output interface to enable an immersive experience.

This system is permanently displayed in a public facility in Fujisawa City. In the exhibition, the system is projected onto a 40-inch monitor and controlled by a gamepad. In addition, the system is not network dependent, and is a PC startup program that automatically starts when the power is turned on, enabling the system to be operated without any special operations.

3. Enhancements to the Historical and Cultural Landscape Simulation System

3.1. DEVELOPMENT OF A HISTORICAL AND CULTURAL LANDSCAPE SIMULATION SYSTEM THAT REPRODUCES THE TIME, SEASON, AND WEATHER

Based on the development of these systems, time and weather designing systems have been developed. The impression of a landscape changes considerably depending on the time of day, whether it is morning, noon, or night, even in the same place (Kawai and Furuyama, 2001). In addition, the image of the landscape changes with the intensity of sunlight and changes in plantings, depending on the season. Furthermore, the landscape looks different even at the same time depending on whether it is sunny, cloudy, rainy, or snowy. Therefore, we decided to develop a system to represent changes in landscape images according to time of day, season, and weather conditions. The target area was Fujisawa-juku, which is similar to that in a previous study. By referring to the records provided by local temples of weather conditions at that time, we could recreate the weather at a specific date and time in the Edo period. In this system, we recreated the weather conditions for one year, 1862.

The location of Fujisawa-juku is at latitude 35°20 min north and longitude 139°30 min east; therefore, the location of the solar source was used to reproduce the time (Figure 3). In the night-time landscape, a light source using the moon was prepared to reproduce the variation in brightness during the night such as at the time of the new moon and full moon. The position of the sun and the moon varies with the seasons. Therefore, the position of the light source was set in conjunction with the time data of the sun and the moon. In addition, four weather patterns were prepared: sunny, cloudy, rainy, and snowy. When it was raining and snowing, we created particles to indicate raining or snowing, and when it was snowing, we modified the surface layer of the model with a material by shaders to represent snowfall (Figure 4). The number of the human models of nonplayer characters varied according to the environment, such as time of day and weather. In addition, as the behavioral pattern of the human model, we added actions such as holding an umbrella when it rains and snows, and carrying a lantern at night.

This system is designed to change the time of day, season, and weather by changing light sources, effects, and materials. It was found that the impression of the landscape was greatly affected by these changing elements.

Figure 3. Changes in time: a) day, b) evening, and c) night.

Figure 4. Changes in weather: a) sunny, b) rainy, and c) snowy.

3.2. DEVELOPMENT OF A HISTORICAL AND CULTURAL LANDSCAPE SIMULATION SYSTEM USING UKIYO-E STYLE RENDERING

In addition, a system was developed with Ukiyo-e style rendering (Figure 5). This system provides not only realistic rendering, but also Ukiyo-e style rendering, thereby allowing users to experience the old landscape in the world of Ukiyo-e in three dimensions. As a base for Ukiyo-e style rendering, we used the style of Hiroshige Utagawa as the basis for the rendering of buildings and other structures. Hiroshige was a Ukiyo-e artist who excelled in the painting of landscapes; his representative work includes the “Fifty-three Stages of the Tokaido.” People painted by Hiroshige are depicted as supplementary landscapes, and therefore, they are not suitable for human models. Therefore, the human models are designed based on the style of Kunisada Utagawa. Hiroshige and Kunisada collaborated on Fifty-three stations by Two Brushes, a collaboration of their Ukiyo-e works (Utagawa and Utagawa 1854). The figures and background are painted by different artists, and we decided to use the same method for this system.

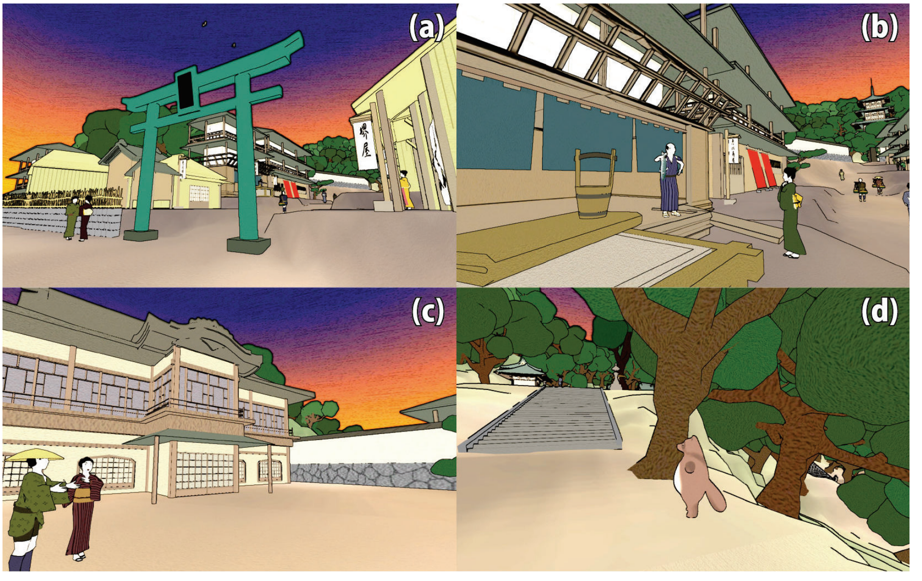


Figure 5. View with Ukiyo-e style reading: a) torii gate, b) shop, c) inn and d) yōkai.

Ukiyo-e style rendering was represented by detecting the edges of objects in the spatial components and by emphasizing the borders of the objects. Edge rendering was added to the objects using edge detection in Unity, the game engine. The values of depth sensitivity, normal sensitivity, and sampling distance were set by the mode filter. A script that automatically adjusts the width of the edges of the foreground and background based on the distance from the viewpoint was created. The adjustments of the edge line segments were introduced through a comparative evaluation of Ukiyo-e style renderings by subjects to make them more Ukiyo-e like. The objects are given the texture of Japanese traditional paper in terms of the material. We prepared an image with a screen size of 1024 × 1024 pixels on an image processing software, filled it with the color of the object on a layer, and we created a paper-quality black-and-white image with a filter on another layer; then, we set the opacity of the layer to 50%. The material was colored with a color gradient, and background elements such as the sky were created.

In Ukiyo-e style rendering, as dynamic elements, we prepared human models, and several yōkai as traditional Japanese ghosts. In the late Edo period, many Ukiyo-e prints depicting yōkai were published. We added a monster cat to the shopping mall, a raccoon dog and a giant snake to the temples and shrines, and a fox to the woods as yōkai. Based on the data from the stories in which the yōkai are said to have appeared, we made the yōkai appear only in the world of Ukiyo-e style rendering of the place where the yōkai are said to have appeared. Further, we made them a characteristic element of the world of Ukiyo-e.

This system uses the Ukiyo-e style to recreate the landscape of the past. In Japan, there is a traditional expression of depth painting called Yamato-e, which is represented by an oblique projection from a bird's-eye view (Suguhara 2011).

It is said that geometric perspective was introduced in the mid-18th century, but the use of perfect perspective was not widespread in Japan. In Ukiyo-e, imperfect perspective projection, orthographic projection, and traditional overhead oblique projection were used (Kishi 1994). Although Ukiyo-e is deformed in terms of depth representation and the arrangement of spatial components, this system provides accurate depth representation using a three-dimensional perspective based on geographic information data. Therefore, even if the location is the same as that depicted in Ukiyo-e, the system image shows a different landscape. Because of this difference in the way of viewing, it is not possible to simply compare the scene reproduced by the system with the original Ukiyo-e, but we have created the Ukiyo-e style rendering system based on user evaluation.

This system was designed for viewing of images on a head-mounted display; however, many cases of virtual reality sickness were observed. Flat materials such as Ukiyo-e may cause confusion in spatial cognition because of the loss of depth cues other than the binocular parallax. In addition, it was found that the movement method, which is the main cause of virtual reality sickness, needs to be considered.

4. Major Update to the Historic and Cultural Landscape Simulation System

These historical and cultural landscape simulation systems were opened to the public and received considerable feedback from the public. In addition, various local materials were provided by nearby temples and regional historians, and we referred to the records of houses in those days. Based on this new information and materials, a major system update was introduced (Figure 6).

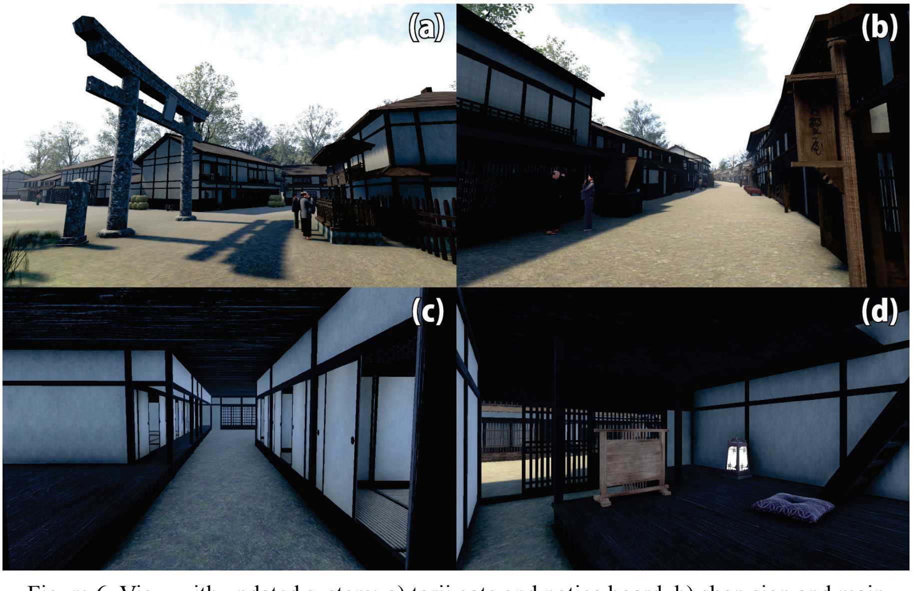


Figure 6. View with updated system: a) torii gate and notice board, b) shop sign and main street, c) inside the Honjin, and d) inside the inn.

The building model was reviewed and remodeled. For the modeling of the townhouse, the building was unitized with walls, entrances, openings, and other components, and these components were combined to reproduce various facades. The buildings were assembled based on the frontage and depth of the buildings from the archives, and these were arranged against the old maps. In addition, there were records of shop names for inns and shops. Therefore, signboards of the shops were reproduced, and interior spaces were recreated to enter the ground floor of the building including earthen floors within a certain range. Further, the road width was changed because it various data indicated that the road was considerably narrow. The depth of the river was also reexamined, as it was used for logistics by boat at that time. For the trees, some species were newly identified in the data, and changes were introduced to more reproduce the landscape of the time faithfully. The trees in this system were based on photogrammetric models generated from photographs. This tree model has a massive number of polygons, and therefore, the level of detail is set up to control the accuracy of the tree model and depict only the range of view. In particular, if the frames per second value falls during the display with the head-mounted display, virtual reality sickness may occur.

This system obtains the time from the clock in the computer and reflects it in real time in the recreated landscape. The position of the sun, which is the main light source of the system, is calculated in terms of longitude and latitude, and the brightness of the sun and the speed of sunset are accurately implemented by referring to the total solar radiation measured by the Japan Meteorological Agency. The cloud cover was measured and divided into finer, cloudless, scattered, partly cloudy, moderately cloudy, and all-sky cloudy. In addition, rainfall depiction in rainy weather is slow in processing if rainfall effects are placed in all locations. Therefore, rainfall is depicted only in the area near the player, and it is possible to represent the rainfall with light processing. Moreover, as a ground system, we simulated changes that the ground undergoes because of weather conditions such as when walking in the rain, the ground is muddy, when it is snowing, and when footprints are marked on the snow.

Further, we used a method of instantaneous movement of the viewpoints by a blackout at the moment of movement, instead of continuous walking. Using this movement method, we suppressed the phenomenon of the difference in the feeling of virtual reality sickness when the user does not move but the screen moves. The input interface allows the user to move by simply pressing and releasing a button, and we checked that even first-time users have no problem using it.

5. Result and Discussion

We developed a historical and cultural landscape simulation system for Fujisawa-juku, a post town in old Tokaido, using Ukiyo-e, old documents, and maps to recreate a past landscape with a game engine for inheriting the historical culture of the region. Further, we developed a system that can change the expression of time (e.g., day and night), seasons (e.g., spring, summer, fall, winter), and weather (e.g., sunny, cloudy, rainy, snowy). Additionally, we studied the reproduction of the landscape using Ukiyo-e style rendering. The developed system has been open to the public through permanent exhibitions in public facilities and local events. There is no major operational problem, and the operation is stable. We received feedback from users about these exhibits, and it motivated us to create major system updates. Specifically, we examined and updated the shapes of the models of the spatial components to be more accurate.

The updated system was also made open to the public, and we received feedback from various regional information reflected in a more accurate post-town model. The digital model was updated to reflect new information, which is not possible with models such as dioramas. In addition, this system is an interactive system, which differs from animations, as it allows users to roam the streets of the past freely. The digital models are not suitable for long-term exhibitions because the execution environment changes rapidly. It also took much work to create many digital detailed models accurately. We hope to reduce the modeling costs by unitizing the model so that it can be used in the production of past landscapes in other areas. We will continue to update the system periodically and develop a general-purpose system that can be used in other regions.

6. Conclusion

In this study, we developed a historical and cultural landscape simulation system using a game engine and made it available to the public; the system considers elements such as time and weather and rendering methods. Further, it can reflect the information collected after publication. However, we found that creating various models to reflect the past landscape accurately requires much time. Previous studies have attempted to digitally recreate the landscape of the past, but most of them were limited in scope to few buildings, famous heritage sites, or tourist sites and used specialized systems. Based on these studies, we attempted to recreate the past landscape of a general ordinary town using an open and inexpensive development environment such as a game engine. In addition, by collecting and referencing materials provided by local archives and temples, we were able to recreate past townscapes and create a system that visually conveys the historical culture of the region. By making this system open to local citizens, the community of citizens discussed how to reproduce the past landscape more accurately. With the new materials provided by the citizens who experienced the system, the system could be easily updated for accurate recreation of the past townscape by this system because this is digital content. Based on this effort, we will rediscover materials related to local history, and connect them to each other to link local history to the next generation in various regions by generalizing the system. In the future, as an extension of the system to the exhibition environment, we will add functions to explain various urban elements and compare them with the current landscape. Further, based on the findings from the recreation of the historical cultural landscape in the target area, we will generalize this system through the unitization of buildings and urban installations, and we plan to create a platform for a historical cultural landscape simulation system that can be used in other areas.

Acknowledgments

This work was supported by JSPS KAKENHI, Grant Number JP19K12665, and the Foundation for the Fusion of Science and Technology. I would like to thank Naoshige Togashi, Kohki Dote, Ryuta Suzuki, Yuta Terayama, Kazuma Numata, Ken Fujii, Youhei Obuchi, Yurika Tsuchiya, Shoko Nihei, Natsumi Kobayashi, Masumi Kiyokawa, Ayaka Enzaka, Sae Itoh, Kie Tsuchiya, and Shusei Yoshida, graduates of our laboratory, for assistance with this study.

References

Dylla, K., Frischer, B., Müller, P., Ulmer, A. and Haegler, S.: 2008, Rome reborn 2.0: A case study of virtual city reconstruction using procedural modeling techniques, *Computer Graphics World*, **16**(6), 62-66.

El-Hakim, S., Gonzo, L., Voltolini, F., Girardi, S., Rizzi, A., Remondino, F. and Whiting, E.: 2007, Detailed 3D modelling of castles, *International Journal of Architectural Computing*, **5**(2), 199-220.

Fukuda, T., Ban, H., Yagi, K. and Nishiie, J.: 2015, Development of high-definition virtual reality for historical architectural and urban digital reconstruction: A case study of Azuchi castle and old castle town in 1581, *International Conference on Computer-Aided Architectural Design Futures*, 75-89.

Hirano, M. and Ichikawa, K.: 2017, *Reconstruction Map of the Tokaido Fujisawa Post Town 1862*, Fujisawa Post Town Exchange Center.

Kawai, Y. and Furuyama, M.: 2001, The space constituent elements of stimulated gazing on sequential street in the daytime and nighttime at Gion Area in Kyoto, *Journal of the City Planning Institute of Japan*, **36**, 757-762.

Kishi, F.: 1994, *Perspective in Edo: The Vision of Ukiyoe*, Keiso shobo.

K. Kodama (ed.): 1970, *Tokaido Syukuson Taigai-cho [Tokokaido Post Town Abstract Book], Kinsei Kotsu Shiryo-shu [Traffical Materials in Early Modern Japan], 4*, Yoshikawa Kobunkan.

Suguhara, F.: 2011, Visual dynamics in the illustrated tale of Genji-"Equivalent Statics" and "Organized Dynamics", *Journal of Human Environmental Studies*, **2**, 117-142.

Sundstedt, V., Chalmers, A. and Martinez, P.: 2004, High fidelity reconstruction of the ancient Egyptian temple of Kalabsha, *Proceedings of the 3rd International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa*, 107-113.

Utagawa, H.: 1832, *Fujisawa in the Fifty-three Stations of the Tokaido (Hoeido edition)*, Hoeido.

Utagawa, H.: 1840, *Fujisawa in the Fifty-three Stations of the Tokaido (Tokaido with Kyoka edition)*, Kikakudo.

Utagawa, H.: 1847, *Fujisawa in the Fifty-three Stations of the Tokaido (Clerical script Tokaido edition)*, Jyukakudo.

Utagawa, H. and Utagawa, K.: 1854, *Fifty-three Stations by Two Brushes*, Marukyu.

Yamauchi, K.: 2009, The role of communities in the era of low fertility and aging: Reviving local communities, *Legislation and Investigation*, **288**, 189-195.

Yano, K., Nakaya, T., Isoda, Y., Takase, Y., Kawasumi, T., Matsuoka, K., Seto, T., Kawahara, D., Tsukamoto, A., Inoue, M. and Kirimura, T.: 2008, Virtual Kyoto: 4DGIS comprising spatial and temporal dimensions, *Journal of Geography*, **117**(2), 464-478.

DEVELOPMENT OF A TSUNAMI EVACUATION BEHAVIOR SIMULATION SYSTEM FOR SELECTION OF EVACUATION SITES

YASUO KAWAI
[1]*Bunkyo University*
[1]*kawai@bunkyo.ac.jp*

Abstract. In this study, a tsunami evacuation simulation system was developed using a game engine and open data to reflect the conditions of a local emergency situation at low cost. Chigasaki City, which is a heavily populated urban area and tourist destination along the coast of Japan, was selected as the target area for this study. A total of 20 simulations were conducted using 20,000 evacuation agents categorized as child, adult, or elderly residents or visitors randomly placed on the road surface in the target area. The simulation results indicate that a 10.60% agent damage rate may occur for a tsunami of height 10 m. In lowland areas where the river flows inland, tsunamis were observed to move up the estuary, trapping agents between the river and the coast. In such inland areas, several areas with no tsunami evacuation buildings were observed. Thus, the low-cost simulations provided by the proposed system can provide necessary support for planning and designating appropriate tsunami evacuation buildings in disaster-prone areas.

Keywords. Tsunami; Evacuation; Agent; Simulation; Game Engine.

1. Introduction

Tsunamis are generated during underwater earthquakes via the impact of seismic waves on the seafloor, thereby causing rapid deformation of the seafloor topography over a short period of time. A tsunami produces significantly high water pressures even at low wave heights and can cause extensive damage over large areas along the coast (Matsutomi and Okamoto, 2010). Many studies have reported on the use of tsunami simulations, mainly to numerically simulate tsunami waves, tsunami arrival times, and tsunami concentrations due to topographic effects (Shimazaki and Somerville, 1978; Shuto and Fujima, 2009). These studies have focused on the relationships between tsunamis and topographies at wavelengths of several kilometers, which is important for disaster management planning at the national level.

However, local governments are the main bodies responsible for providing disaster prevention information, such as tsunami hazard maps, to local residents. Disaster management plans, including evacuation routes and tsunami evacuation buildings on individual streets, are developed by local governments by referring to the inundation areas, tsunami arrival times, and maximum tsunami heights from

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 499-508.

simulation data provided by the national government. Thus, any changes in the simulation data will result in major revisions to local disaster management plans. In many areas of Japan, risk reviews and large-scale data updates were conducted before and after the 2011 Great East Japan Earthquake of 2011, forcing local governments to recreate hazard maps (Koshimura and Shuto, 2015). However, it is not possible for local governments to construct and operate their own tsunami simulation systems owing to their high cost and complex technical aspects; hence, it is difficult to conduct detailed in-city simulations of disaster management plans under various conditions, such as the numbers and types of evacuees and available evacuation sites.

In this study, we accordingly used a game engine and open data to develop a low-cost system able to reflect the disaster management realities of a region. This system was designed to visualize the predicted disaster locations, with particular focus on evacuation behaviors, and to acquire data that may contribute to disaster prevention planning. Agent-based model simulations of tsunami, typhoon, and tornado evacuations have been conducted in the past. Mas et al. conducted numerical tsunami and evacuation simulations using multi-agent programming for the Great East Japan Earthquake of 2011 (Mas et al., 2012). Wang et al. conducted an agent-based evacuation simulation for Seaside, Oregon, and found that decision-making time and variability, provision of vertical evacuation, percentage of car use, and walking speed were strongly correlated with mortality (Wang et al., 2016). Mostafizi et al. presented an agent-based model to evaluate vertical evacuation behavior and evacuation sites for near-field tsunamis (Mostafizi et al., 2019). These studies were conducted at relatively low cost using geographic information system (GIS) data, but their operation and any discussion of their results require specialized knowledge. In this study, we therefore used a game engine to visualize the tsunami inundation and evacuation situation from any viewpoint in the virtual three-dimensional space of a case study city. By relying on open data, the proposed system can be developed at low cost and display easy-to-understand results with simple operations. This approach allows for small organizations such as local governments to evaluate disaster mitigation by designating tsunami evacuation buildings under various conditions.

2. Method

2.1. GEOGRAPHIC MODEL

The proposed simulation system uses the Basic Map Information Download Service of the Geospatial Information Authority of Japan to obtain the requisite geographical information. This service allows users to retrieve various types of basic map information in a mesh of an arbitrary region from the internet in the extensible markup language (XML) data format. In this study, we used data from the range of secondary mesh number 523973 (updated in 2020). Once downloaded, the XML data are imported into the Basic Map Information Viewer, which is dedicated display software for basic data and numerical elevation models, for conversion to shape format data (see figure 1).

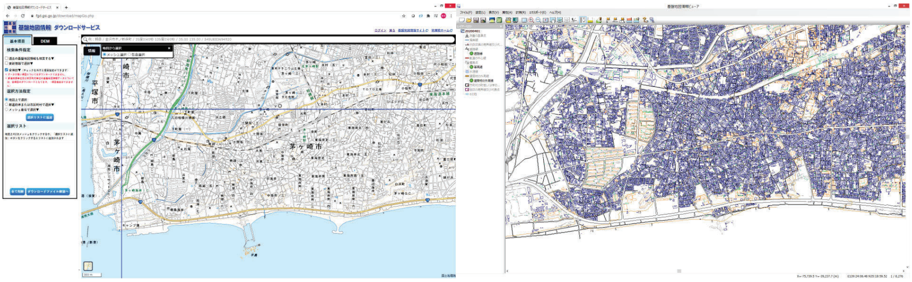


Figure 1. Display of geographic information with the Basic Map Information Service (left), and display with the Basic Map Information Viewer (right).

Next, QGIS, which is a free and open-source geographic information system, is used to import the converted shape files and display them as a new vector layer. Several previous attempts to turn open data into 3D terrain using GIS software were consulted accordingly (Herman, Russnák and Řezník, 2017; Endalew, Shiferaw and Kindie, 2019). In QGIS, a plugin is used to add a tile map to the map canvas (Akagi, 2016), and a three-dimensional (3D) visualization plugin (Akagi, 2020) is used to create the 3D geographic data with height information (see figure 2). Aerial photos of the study area are then projected as texture data onto a geographic model using the Map and Aerial Photo Viewing Service of Geospatial Information Authority. The 3D data processed in QGIS are then exported in standard triangulated language (STL) format as three layers: topography, road edges, and building perimeter lines.

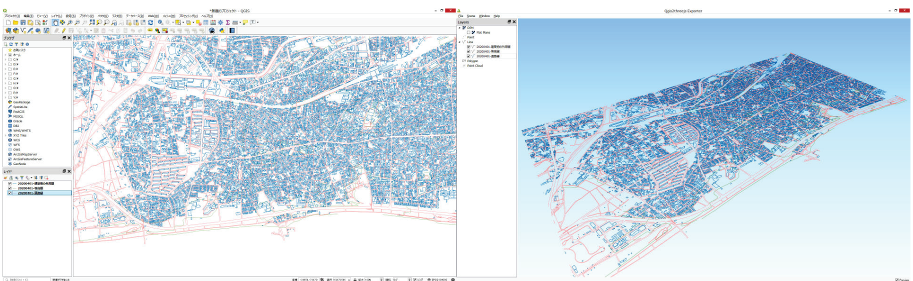


Figure 2. Display of geographic information with QGIS (left), and display of 3D geographic information with plugin (right).

In addition, these STL data are imported into Blender, an integrated 3D computer graphics environment. Based on the road-edge data, polygons are generated on the topographical surface corresponding to the roads to create a detailed urban road surface. The polygons representing the road surface are placed along the topographical model using the cloth modifier in Blender because the measured values will inevitably differ from the height information of the topographical model at certain points. Based on the building perimeter lines, buildings are created by referring to the zoning districts of the target area's city planning map and entering the expected building heights from the floor-area ratio.

However, for tsunami evacuation buildings that can be evacuated vertically, the exact height of each building is entered. Next, these 3D model data generated in Blender are exported as 3D shape data in the filmbox (FBX) format after cleaning up the polygons and reducing the data sizes of the models. These model data are then imported into the UNITY game engine, which is an integrated development environment. The resulting 3D model incorporates three elements as separate layers in the FBX format: a topographical model with height information, a building model, and a 3D road model along the elevation of the terrain (see figure 3).

Figure 3. Geographical model overlaid with topographic, building, and road models of Chigasaki City, Japan.

2.2. TSUNAMI MODEL

According to the Manual of Tsunami and Storm Surge Hazard Mapping provided by the Japanese government, the inundation forecasting method should be accurate according to the purpose and objective of the evaluation. Herein, a numerical simulation based on the time-series approach is proposed to predict and provide accurate data describing the time course of inundation and inundation depth for each point; however, it is typically difficult for local governments to obtain accurate data for the creation of hazard maps because of the required technical skills and high cost of simulation. As a result, a simplified method based on setting the inundation according to the ground level is employed, as this provides a lower cost prediction, but does not predict the exact velocity, inundation start time, or time-series effect of the tsunami run-up based on the topography.

The system proposed in this study uses a tsunami and storm surge hazard map method based on the ground level, with a tsunami model that moves at a constant rate to partially account for the time series of inundation. Thus, a tilted plane rotated by 0.1 degrees was prepared as the tsunami model and inserted within the 3D topographical model to simulate the time-series inundation according to elevation. The tsunami model moved inland at a speed of 40 km/h and then reversed after reaching the deepest point to represent the inundation of the urban area. Note that the proposed system adopts a lightweight tsunami model because it can be represented by simple calculations; however, this model includes no conditions for changes in the flow velocity due to the topography and buildings (see figure 4).

Figure 4. Maximum inundation areas for tsunami heights of 5 m (left) and 10 m (right).

2.3. EVACUATION AGENTS

In the proposed system, agents are used to simulate autonomous evacuation during a tsunami. By improving the evacuation behavior algorithm to reduce the weights of each agent, we developed a system capable of simulating a few tens of thousands of agents operating simultaneously. The evacuation agents are assumed to have two evacuation behavior patterns and are classified into three age groups.

The two types of evacuation behaviors considered are residents and visitors. Residents are established as agents who know the locations of their refuge in advance. The resident agents move at a predetermined speed to the nearest high ground or tsunami evacuation building from their current coordinates in the event of a tsunami. These tsunami evacuation buildings have predetermined capacities; therefore, if these buildings are filled beyond capacity, newly evacuated agents arriving thereafter cannot enter the building. As a result, after confirming that the capacity of a building is exceeded, the agents search for the next evacuation site nearest their current coordinates to recommence evacuation measures. In contrast, visitors are established as agents who are unaware of the evacuation sites, and are expected to follow evacuation measures according to the agents nearest their current coordinates in the event of a tsunami.

The three age groups considered for the agents are adults, children, and the elderly. The adult agents are assumed to move at a speed of 1.5 m/s up to an allowable tsunami inundation depth of 0.6 m, the child agents were assumed to move at a speed of 1.2 m/s up to an allowable tsunami inundation depth of 0.3

m, and the elderly agents were estimated to move at a speed of 1.0 m/s up to an allowable tsunami inundation depth of 0.6 m (Okamoto, 2007). As agents are assumed to have different movement speeds and disaster judgments depending on their age and different evacuation behaviors according to their status as residents or visitors, a total of six different agents are included and color coded according to their characteristics as shown in figures 5 and 6.

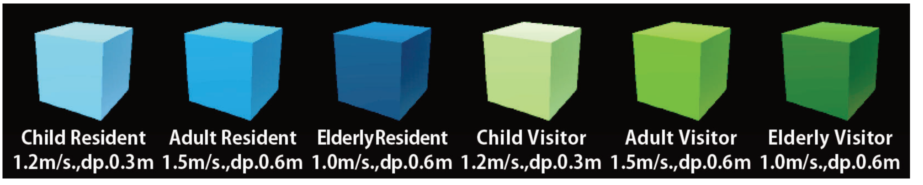


Figure 5. Six types of evacuation agents described in the system.

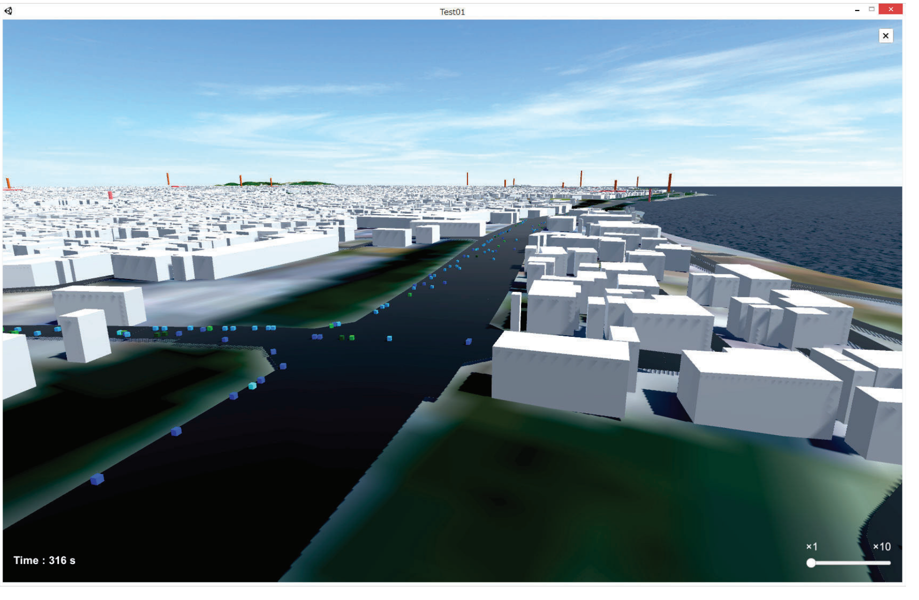


Figure 6. Resident agents (blue cubes) and visitor agents (green cubes) performing evacuation moves.

In the proposed simulation system, agents with the numbers and characteristics registered in the configuration screen are randomly placed on road surfaces within the city limits upon commencement of the simulation. The resident agents move toward the high ground or tsunami evacuation buildings (represented in red) nearest their coordinates, and the visitor agents follow their nearest resident agents. Agents housed in the high ground above the set tsunami height or in tsunami evacuation buildings are represented in orange as evacuees who have completed evacuation, as is their tsunami evacuation building. However, agents were considered damaged and determined to be a casualty if the tilt plane representing the tsunami was greater than or equal to the allowable tsunami inundation height corresponding to each type of agent. The damaged agent is then represented as a pink block at that spot, where they remain in their current position until the end of the simulation. The areas with high concentrations of pink blocks are considered to be the locations with the most victims (see figure 7). After the simulation, the results screen is displayed showing the number of residents and visitors by age group with the system outputs in a comma separated value (CSV) format file.

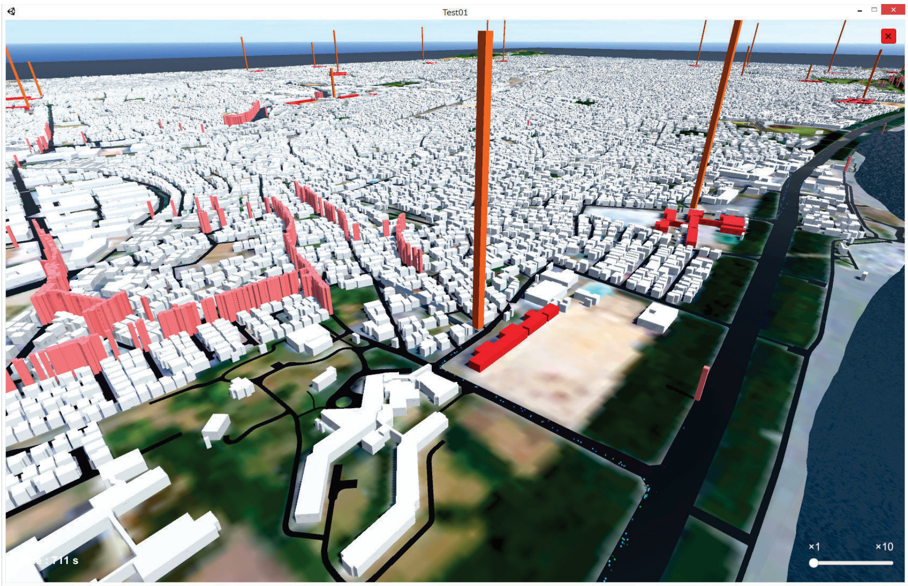


Figure 7. Simulation screen: tsunami evacuation buildings (red), number of evacuees (orange), and damaged agents (pink).

3. Results and Discussion

Chigasaki city, which is located along the coast of Sagami Bay in Kanagawa Prefecture, Japan, was selected as the study area. This area is urbanized, densely populated along the coast, and a tourist destination that requires appropriate evacuation plans in the event of a tsunami. In each simulation using the proposed system, approximately 20,000 agents were randomly placed on a road surface in the area representing Chigasaki City. The percentage of each type of agent was established from the city's age demographic data and tourist count surveys. Note that as the agents are randomly placed on the road, the results may vary depending on the initial conditions of the simulation. Therefore, after setting the initial conditions, we collected and analyzed data from repeated trials. A total of twenty simulations were performed with the results of shown in figure 8.

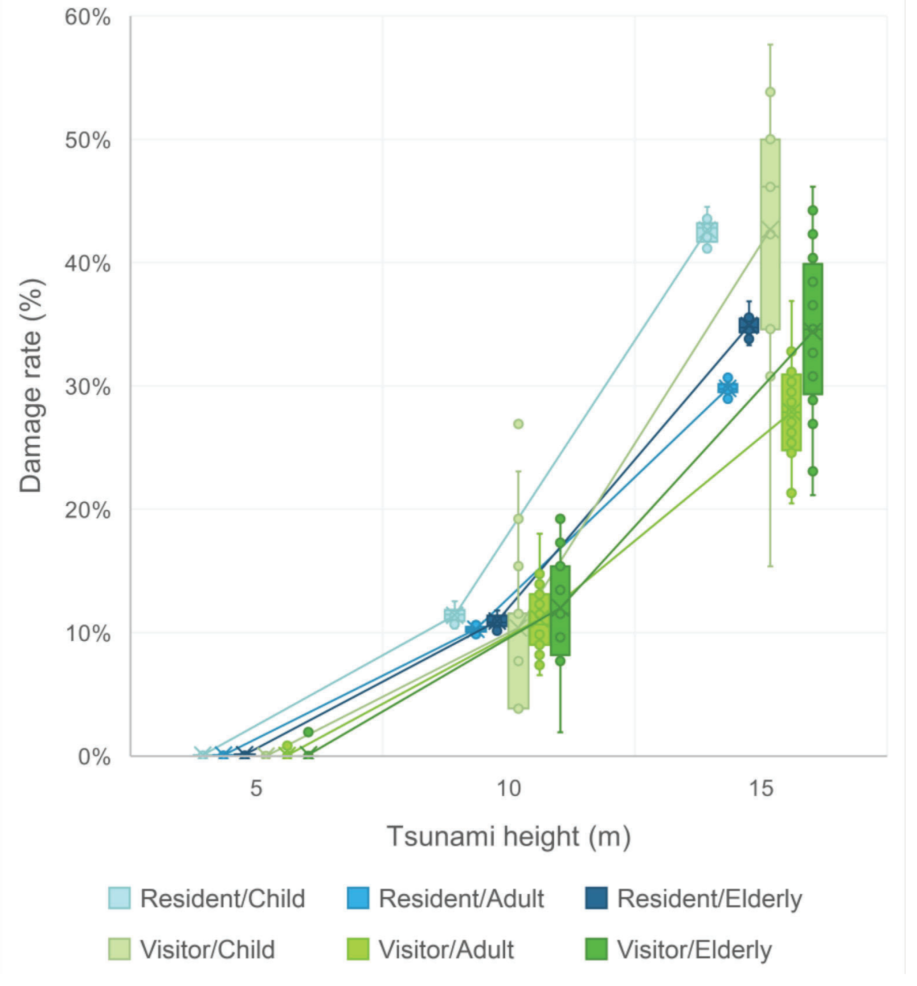


Figure 8. Simulation results of damage rates by tsunami heights and agent types.

At a 5 m tsunami height, the total damage rate was 0.07% in the coverage area. The average damage rate for residents was 0.07% for children, 0.06% for adults, and 0.09% for the elderly, and the average damage rate for visitors was 0.01% for children, 0.04% for adults, and 0.10% for the elderly. Thus, the damage was slight, but agents whose evacuations were delayed were the most affected. Child agents, with lower allowable depths of inundation than adult agents, and elderly agents who moved at lower speeds were affected the most.

At a 10 m tsunami height, the total damage rate was 10.60%. The average damage rate for residents was 11.40% for children, 10.28% for adults, and 10.93% for the elderly, and the average damage rate for visitors was 10.38% for children, 11.11% for adults, and 12.02% for the elderly. The differences in the damage rates between agents types were similar to those at the 5 m height, but the number of victims increased significantly. The largest predicted tsunami height in the Chigasaki hazard map was approximately 8 m for the Genroku-type Kanto earthquake and the Kannawa-Kouzu-Matsuda fault zone earthquake. Thus, a 10 m tsunami is higher than the maximum expected tsunami in the study area, but still represents an important case to consider in order to identify specific area trends. In particular, there were many cases of flooding deep in the urban area owing to the movement of the tsunami upriver. Thus, regardless of the specific height of the tsunami, it is necessary to plan appropriate evacuation sites in inland areas where flat terrain extends into the city.

Finally, for a 15-m high tsunami, the total damage rate was 32.78%. In particular, the damage rates for resident and visitor child agents were 42.64% and 42.69%, respectively. Note that while this class of tsunami is not designed for or expected to occur in the disaster prevention plans of the target region, if such a tsunami did occur, the proposed simulation method indicated that the results could be devastating.

The simulation results show the agents all commenced their evacuation behaviors after the tsunami occurred, and some agents were affected inland, where there were no appropriate evacuation buildings. Especially, some inland areas along the river were found to have high concentrations of victims. In these lowland areas, the tsunamis moved up from the estuary, trapping agents between the river and the coast. Thus, the results obtained using the proposed simulation method indicate that it is necessary for local governments and residents to plan and designate appropriate tsunami evacuation buildings in these areas.

4. Conclusion

In this study, a simulation of tsunami evacuation behavior was developed using open data and the UNITY game engine, then demonstrated for Chigasaki City, Kanagawa Prefecture, Japan. Notably, a low-cost environment was used to develop the simulation system based on free and open-source software, such as the game engine, along with open data, such as geographical information from the Geographical Survey Institute, population data, and tourist count data from local governments. Thus, the proposed system can be easily and cost-effectively operated by local governments to plan for disasters.

The simulation results for Chigasaki City showed that the damage rate for a tsunami height of 5 m was 0.07%; however, for a tsunami height of 10 m, this damage rate could be as high as 10.60%. The assumed maximum tsunami height in the study area is 8 m. However, attention should be paid to the fact that the damage rate exhibits an exponential increase according to the tsunami height. In particular, many inland areas were observed to be damaged as the tsunami travelled up the rivers into low-lying urban areas, indicating that it is also necessary to develop disaster prevention plans for such areas.

As the proposed system is currently limited in its ability to reproduce tsunami motion, future research will focus on accurately reproducing the time-series changes of the tsunami motions. In addition, the algorithms governing the evacuation agents may need to be improved by examining the evacuation speeds according to various conditions such as evacuation distance, evacuee density, and road gradient, and by modeling information exchange among the agents. Furthermore, in the proposed simulation, the agents were initially placed randomly, but this condition should be modified by considering the population/activity density maps according to time of day and season. Finally, the evacuation and inundation due to typhoons and flood as well as tsunamis could be simulated for real-time use by improving the inundation time axis and evacuation algorithm.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP 19K12665 and the foundation for the fusion of science and technology.

References

Akagi, M.: 2016, "TileLayer Plugin" . Available from <https://plugins.qgis.org/plugins/TileLayerPlugin/> (accessed 25th January 2021).

Akagi, M.: 2020, "Qgis2threejs" . Available from <https://plugins.qgis.org/plugins/Qgis2threejs/> (accessed 25th January 2021).

Endalew, M., Shiferaw, W. and Kindie, A.: 2019, Development of web mapping application for spatial ecotourism information using QGIS plugin and freely available web platforms in north west highlands of Ethiopia a case study: Chokie Mountain watersheds, *Advances in Internet of Things*, **9**(3), 50–61.

Herman, L., Russnák, J. and Řezník, T.: 2017, Flood modelling and visualizations of floods through 3D open data, *International Symposium on Environmental Software Systems*, 139–149.

Koshimura, S. and Shuto, N.: 2015, Response to the 2011 great East Japan earthquake and tsunami disaster, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373**, 1-15.

Mas, E., Suppasri, A., Imamura, F. and Koshimura, S.: 2012, Agent-based simulation of the 2011 great east japan earthquake/tsunami evacuation: An integrated model of tsunami inundation and evacuation, *Journal of Natural Disaster Science*, **34**(1), 41–57.

Matsutomi, H. and Okamoto, K.: 2010, Inundation flow velocity of tsunami on land, *Island Arc*, **19**(3), 443-457.

Mostafizi, A., Wang, H., Cox, D. and Dong, S.: 2019, An agent-based vertical evacuation model for a near-field tsunami: Choice behavior, logical shelter locations, and life safety, *International Journal of Disaster Risk Reduction*, **34**, 467–479.

Okamoto, A. and Meguro, K.: 2007, Development of mapping system of tsunami disaster evacuation difficulty based on human evacuation simulation, *Seisan-kenkyu*, **59**(3), 295-298.

Shimazaki, K. and Somerville, P.: 1978, Summary of the static and dynamic parameters of the Izu-Oshima-Kinkai earthquake of January 14, 1978, *Bulletin of the Earthquake Research Institute*, **53**, 613-628.

Shuto, N. and Fujima, K.: 2009, A short history of tsunami research and countermeasures in Japan, *Proceedings of the Japan Academy, Series B*, **85**(8), 267-275.

Wang, H., Mostafizi, A., Cramer, L.A., Cox, D. and Park, H.: 2016, An agent-based model of a multimodal near-field tsunami evacuation: Decision-making and life safety, *Transportation Research Part C: Emerging Technologies*, **64**, 86–100.

HYPERLINKING MECHANISMS IN COMMERCIAL COMPLEX

An Example of The Spatial Network in Taikoo Li Sanlitun, Beijing

SHAOJI WU
[1] *Tianjin University*
[1] *wsjarchitecture@tju.edu.cn*

Abstract. Commercial complexes play an important role in contemporary cities, with elevators, escalators, and other paths on which people do not take natural movement in it. We consider them as spatial hyperlinking paths, which is originated from the web's hyperlinking technology. This paper studies the path network system in Taikoo Li, Sanlitun, Beijing, in three steps. Firstly, The path system is transformed into a network model, and its spatial network distribution is characterized using betweenness centrality. Secondly, a deep learning approach is used to measure the people's flow at the selected 102 observation points. Then a multiple linear regression(MLR) analysis is conducted using the flow data as dependent variable. And there are 7 independent variables in three types, including betweenness centrality C, H1 and H2 that related to spatial hyperlinks, and B1, F1, F2, and F3 that related to floors. Thirdly, analyzing the MLR model.There are two conclusions. First, using multiple independent variables is better than one variable to fit the people's flow distribution using the regression model. Second, escalators have the effect of enhancing people's flow, while elevators have the opposite effect.

Keywords. Spatial Hyperlink; 3D spatial networks; Commercial Complex.

1. Introduction

The concept of spatial hyperlinks is derived from the web's hyperlinking technology, which is an icon, graphic, or text that links to another file or object. Hyperlinks allow web pages to connect to other web pages without knowing their URL. Likewise, we can consider paths that do not use natural movement in buildings, such as elevators and escalators, as spatial hyperlinks. In spatial hyperlinks, pedestrians do not need to move by themselves but "jump" from one space to another with the help of technology. At present, these spatial hyperlinking paths are appearing more and more in our cities.

Today, commercial complexes have become an essential part of cities worldwide and are considered as the prototype of the vertical city in the future. They contain many elevators, escalators, and other paths that create spatial

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 509-518.

hyperlinks from the beginning of construction. This study attempts to address two questions. The first one is how to quantify the effect of spatial hyperlinks on the distribution of people in a commercial complex. And the other is what are the differences between different types of spatial hyperlinks. Answers to the two questions are the research gap this paper hopes to fill.

1.1. RESEARCH REVIEW

Network science is a subject studying network that regards a complex system's main element as its nodes and the relationships between them as edges that we can assign weights. Through the mathematical and statistical study of the network, a holistic understanding of the system can be gained. Space syntax proposed by Bill Hillier(1984) is a network science-based approach using undirected network to analyzing spatial layouts and human activity patterns in buildings and urban areas, based on the natural movement of the human being. This theory has the advantage of simplicity. But it has two drawbacks. The first is that it does not take into account the phenomenon of spatial hyperlinks. The other is that because the edges of the network are all undirected in this theory, there will be some errors when analyzing spatial systems that contain directed paths such as escalators.

Current research on the phenomenon of spatial hyperlinks is mainly in the field of urban studies. Law, Chiaradia, and Schwander(2012) studied London's street network and subway network and found that the two systems fit the reality better when constructed them together. Sheng, Yang, and Hou(2015) researched the subway and street system in Chongqing and concluded that streets around subway stations show a spatial hyperlink effect due to the subway network development.

To address the spatial network within the commercial complexes, Zhang, Zhuang, and Dai(2012) studied three commercial complexes in Shanghai using an axis model based on spatial syntax. Their study compared the significance of individual variables in the regression model and found that local integration(R3) is the most influential factor, followed by vertical transition, entrance, and level. The vertical transition factor represents spatial hyperlinks. However, their study was unable to distinguish the effects of different types of spatial hyperlinking paths on the people's distribution.

1.2. STUDY AREA

Taikoo Li Sanlitun, one of the most prosperous commercial complexes in Beijing, was selected as the case in this study. The building has five floors, one underground and four above ground, and its construction area is 172,000 square meters. As a representative example of the blocking commercial complexes in Beijing. It contains 17 elevators and 29 escalators, making it a suitable place for studying the phenomenon of spatial hyperlinks in this study.

2. Methodology

Three research methods are used in this study. First, transforming the commercial complex's path system to a network model. The second is to output the pedestrian's flow by the "Gate Count" method using a deep learning algorithm. The third is to calculate a multiple linear regression(MLR) model reflecting spatial hyperlinks under three distance measures, including topological, metric, and angular distance.

2.1. NETWORK MODELING

In a commercial complex, the path system connects all other systems, such as the sale system, service system, etc. Because all the pedestrians' movement in a building depends on the path system and all other systems only provide space for people to stay. Therefore, the path system is chosen as the modeling object in this study. This section is programmed on C sharp in Rhino/Grasshopper. Three questions need to be answered as follows.

First, we have to decide which element in the path system as nodes and which element as edges when constructing a network. There are two modeling ways in Figure 1: The first is the primal representation, which is the simplest. In this representation, we use junctions as nodes and the path between two junctions as edges, which can use both topological distance and metric distance between two paths as edge weight. The second is the dual representation. This representation uses junctions as edges and the path between them as nodes, which can use the topological distance, metric distance, and angular distance between two paths as edge weight. Because this study needs to calculate the network's centrality using angle distance as edge weights, the dual representation method is chosen as the modeling method.

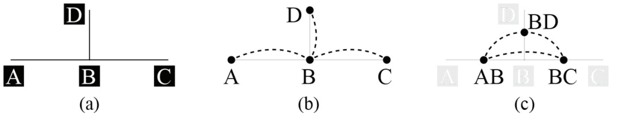


Figure 1. (a) Original spatial network(b) the primal representation (c) the dual representation.

Second, there are two types of spatial hyperlinking paths showed in table 1, i.e., escalators and elevators, and we need identify their characteristics to determine their modeling approach. Escalator is directed paths that pedestrians cannot move in the opposite direction on it. Elevators consist of multiple coupled paths, and if one of them fails, none of the other paths can be used simultaneously.

Third, network science uses centrality to assess the importance of nodes in a network, and we need to decide which centrality to use to characterize the network. This study uses betweenness centrality(BC) to evaluate networks proposed by Freeman (1977). Betweenness centrality is a measure of centrality based on the shortest path, and the value of BC for each node is the number of these shortest paths that pass through the node. It is mathematically defined as follows:

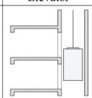
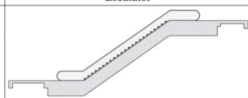
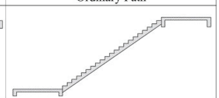
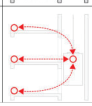
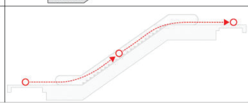
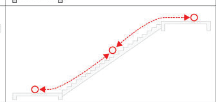
$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (1)$$

where σ_{st} is the total number of shortest paths from node s to node t, and $\sigma_{st}(v)$ is the number of those paths that pass through v. The BC calculated by the above formula is generally large, which results in a small coefficient of BC when calculating MLR model. Therefore, BC is normalized, i.e., all values are mapped to the interval [0,1], which is calculated as follows:

$$\text{Normalized } BC(v) = \frac{BC(v) - \min(BC)}{\max(BC) - \min(BC)} \qquad (2)$$

Figure 2 illustrates three ways of calculating the distance, and we use it as edge weight when building a network. This paper calculates the BC for each node based on these three measures.

Table 1. Network model representation for different types of paths.

Path Type	Coupling Path	Uncoupling Path	
		Directed Path	Undirected Path
Example	Elevator	Escalator	Ordinary Path
Spatial Type			
Network Model			

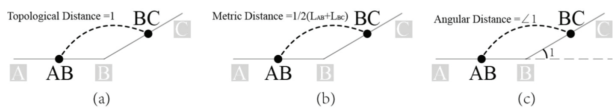


Figure 2. The edge weight using topological(a), metric(b), and angular(c) distance.

2.2. PEDESTRIAN FLOW COUNTING

Traditional pedestrian flow counting methods rely heavily on the researcher's visual inspection, which is the most commonly used method. However, it is impossible to count the precise number of people at an observation point by visual inspection when a large number of people passing through. The deep learning-based Yolo-v3 (You Only Look Once) and DeepSORT (Simple Online And Realtime Tracking With A Deep Association Metric) algorithms are used to calculate the people flow at each observation point to solve the question. In this part, we describe how to use the video taken from an observation point to count of people present in it. This section is programmed on Python by Tensorflow and Keras as the deep learning package and OpenCV as the computer vision package, which can be divided into the following three steps(Figure 3).

First, Yolo-v3 is used for pedestrian detection, which calculates every pedestrian's position and gets the predict boxes in each video frame. Four data u, v, r, and h can be obtained by the predict boxes, where (u, v) are center coordinates of it, r is its area, and h is the aspect ratio. Yolo-v3 is a real-time object detection system proposed by Redmon and Farhadi(2018), and it was selected in this study for the following two reasons. On the one hand, Yolo-v3 can detect objects of various sizes effectively because it uses darknet-53 as its backbone to extract features of the image and can output feature maps at three different scales. On the other hand, Yolo-v3 can derive the predict boxes' coordinates directly from the image without other steps, which is faster than other algorithms such as Faster-RCNN.

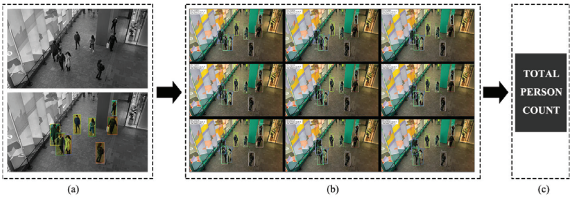


Figure 3. Approach of Pedestrian Flows Counting.

Second, DeepSORT is used for pedestrian tracking to quantify the number of people passing through in the entire video. DeepSORT, proposed by Wojke, Bewley, and Paulus(2017), is an updated version of the SORT algorithm presented in 2016. We use an octave vector $\left(u, v, r, h, \overline{u}, \overline{v}, \overline{r}, \overline{h}\right)$ to represent the trajectory's state of pedestrians at a given moment where $\overline{u}, \overline{v}, \overline{r}$, and $\overline{h}$ are respective velocities of u, v, r, and h between two adjacent frames. SORT only uses the Hungarian algorithm, a combinatorial optimization algorithm that solves the assignment problem and anticipated later primal-dual methods to track pedestrians. Its disadvantage is that the number of identity switches is high when there are obstructions. DeepSORT alleviates this problem by adding cascading classifiers with the Mahalanobis distance and Deep Appearance Descriptor, a small-scale CNN(Convolutional Neural Networks) with 2,800,864 parameters.

The last step is to calculate the pedestrian flow. We obtain the number of pedestrians N_i in a video using Yolo-v3 and DeepSORT, and we also get the duration time T_i of it using OpenCV. The formula is as follows:

$$c = \sum_{i=0}^{n} \frac{N_i}{T_i} \tag{3}$$

where i is the number of videos shot at this observation point, and c is the pedestrian flow count, which unit is *person/min*.

2.3. MULTIPLE LINEAR REGRESSION(MLR) MODEL

Due to the phenomenon of spatial hyperlinking, the distribution of BC does not precisely match the pedestrian distribution in the network. This study addresses this question by establishing the MLR model concerning the research of Zhang, Zhuang, and Dai (2012), and we use it to explain the spatial hyperlinking phenomenon. This section is programmed on Python by Statsmodels package and is divided into the following three steps.

First, a unary linear regression(ULR) model was developed to measure the correlation between pedestrian flow and BC by calculating the coefficient of determination, R-square(R^2). R^2 represents the proportion of variance for a dependent variable explained by an independent variable or variables in a regression model. The larger the R^2, the more reliable the equation.

Second, to quantify the spatial hyperlinking phenomenon, we developed a multiple linear regression(MLR) model. There are seven independent variables selected in this study, which can be divided into three categories. The first one is normalized betweenness centrality(C). The second is related to spatial hyperlinks, which contain two independent variables. Variable H_1 and H_2 respectively represent whether a path is an elevator and escalator, and if a path is an elevator, H_1 is 1, and if a path is an escalator, H_2 is 1. Variable B_1, F_1, F_2, F_3 represent the floor of a path. The model is as follows:

$$N = b_0 + b_1 C + B_2 H_1 + b_3 H_2 + b_4 B_1 + b_5 F_1 + b_6 F_2 + b_7 F_3 + \epsilon \quad (4)$$

where N is the dependent variable representing the people's flow. b_0 to b_7 are the regression coefficients of the independent variables, and ϵ is the residuals.

The third is to test the resulting equation, which can be divided into two steps. We test the reliability of the whole equation by calculating the R^2 and using the F test. And in the F test, we use p values to measure the reliability. The equation holds when the p values are less than 0.05. Another step is to check whether each independent variable is significant through T-tests. The variable holds when the p values are less than 0.05 as well.

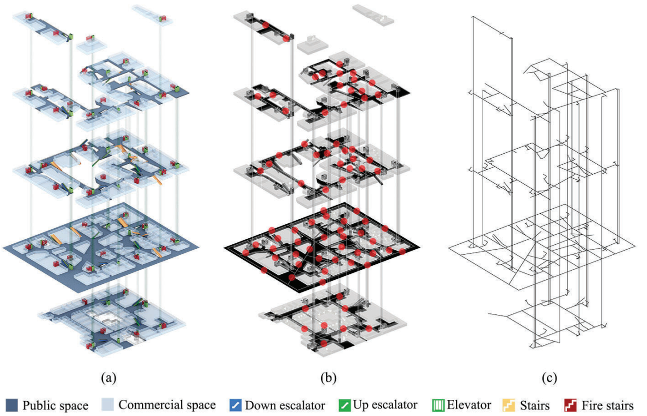


Figure 4. (a) The function of TaiKoo Li Sanlitun (b) The spaces accessed by customers and observation points (c) The segment model.

3. Analysis and result

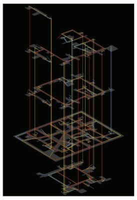
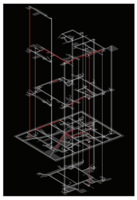
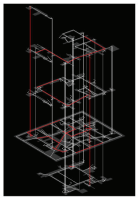
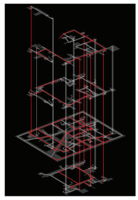
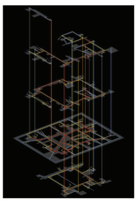
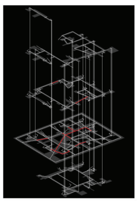
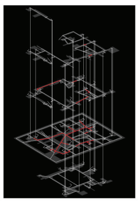
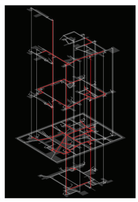
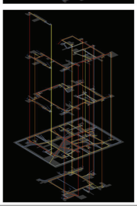
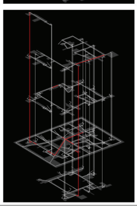
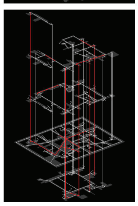
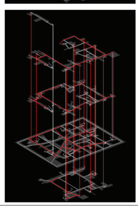
Figure 4 illustrates the distribution of Taikoo Li Sanlitun. This study's research area is the customer area of Taikoo Li Sanlitun due to the employee areas and firefighting spaces are inaccessible to customers. The all fourth floor of the building is inside the stores, so it is not included in the modeling area. After building the network, we first calculate the BC distribution for three distances: topological, metric, and angular distance. Then we calculate the pedestrian flow using the deep learning algorithm and then compute the MLR model. In the last section, we explain the phenomenon of spatial hyperlinks using the MLR model.

3.1. SPATIAL NETWORK CHARACTERISTICS

The site is rectangular, and the building above ground is divided into 19 separate volumes. Horizontally, the paths are distributed in a grid above the ground and a ring on the underground floor. Vertically, elevators, escalators, and stairs are uniformly distributed in it.

Table 2 shows the three BC distributions and we use top 5%, 10% and 25% as quantiles. The common point of the three is the vertical distribution of centrality, where the closer a floor is to the ground floor, the more paths of high BC the level contains. The distribution of metric BC varies most between floors, with its high centrality paths heavily distributed on the ground floor. And the distribution of topological BC differed least between floors.

Table 2. The distribution of betweenness centrality.

Centrality	Distribution of Centrality	Top 5% Segment	Top 10% Segment	Top 25% Segment
Topological BC				
Metric BC				
Angular BC				

3.2. MLR ANALYSIS

This study uses the MLR analysis to find out the relationship between pedestrian flows and other parameters, including parameters representing spatial hyperlinks.

We conducted three field studies on October 24, November 8, and November 15, 2020, all of which were sunny. We set 102 observation points to shot videos, and 228 videos were taken(Figure 4). Each video is about 5 minutes long. We calculate the pedestrian flow from these videos in each observation point.

Figure 5 shows the unary linear regression (ULR) model calculated by N(the pedestrian flow count) and BC. When using three types of BC, the R^2 is 0.169(topological BC), 0.349(metric BC), and 0.111(angular BC). The three R^2

are too small to a weak correlation statistically. As a result, there is a weak relationship between the N and the three BC. Using BC alone is not useful in predicting the pedestrians' distribution in Taikoo Li Sanlitun.

We used the MLR model to solve the above problem. The results show that the R^2 calculated using the three BC is 0.797(topological BC), 0.869(metric BC), and 0.745(angular BC), all of which are substantially higher than the R^2 using ULR analysis. And the three MLR models are respectively capable of explaining 79.7%, 86.9%, and 74.5% of the pedestrian distribution. The F ratio (64.53, 108.7, and 48.11, respectively) in both models is highly significant (p<0.001). Apparently, by adding other parameters into the linear regression process, the BC becomes a significant regressor.

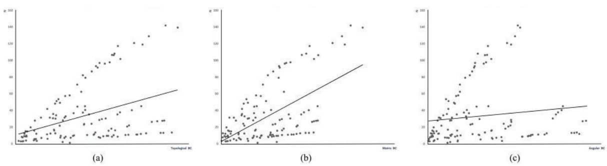


Figure 5. the unary linear regression (ULR) model.

Table 3. The result of multiple linear regression model.

	MLR(Angular BC)				MLR(Metric BC)				MLR(Topological BC)			
	coef	std err	t	P>|t|	coef	std err	t	P>|t|	coef	std err	t	P>|t|
Constant	-6.8886	6.260	-1.100	0.273	-12.5329	4.504	-2.782	0.006	-13.2235	5.706	-2.318	0.022
C	83.0336	8.986	9.240	0.000	92.9765	5.621	16.540	0.000	70.8225	6.065	11.677	0.000
H_1	-14.2049	7.175	-1.980	0.050	-12.3862	5.105	-2.426	0.017	-15.5276	6.403	-2.425	0.017
H_2	22.5801	7.855	2.875	0.005	21.8448	5.601	3.900	0.000	19.7715	6.957	2.842	0.005
B_1	24.5090	9.444	2.595	0.011	21.0589	6.757	3.117	0.002	22.2331	8.410	2.644	0.009
F_1	58.2460	6.613	8.808	0.000	48.4158	4.792	10.104	0.000	54.5597	5.916	9.222	0.000
F_2	18.1750	7.740	2.348	0.021	2.6603	5.608	0.474	0.636	7.9659	6.936	1.149	0.253
F_3	-4.7520	7.108	-0.669	0.505	-7.3102	5.107	-1.431	0.155	-6.6594	6.356	-1.048	0.297

Table 3 presents the results of the statistical significance analysis for each of the independent variables for the three MLR models using the T-test. In all three models, the coefficients F_2(p=0.253) and F_3(p=0.297) are unimportant when using topological BC, the coefficients F_2(p=0.636) and F_3(p=0.155) are unimportant when using metric BC, and the coefficients Cnatant(p=0.273) and F_3(p=0.505) are unimportant when using angular BC. And in all models, parameters H1 and H2 that characterize the spatial hyperlinking phenomenon are statistically significant.

We compare the t value of each independent variable in the three models, and it characterizes the variables' contributions. In descending order, the contributions of the topological BC model and angular BC model to the seven coefficients are C, F_1, H_2, B_1, H_1, F_2, and F_3, and the metric BC model's order is $C, F_1, H_2, B_1, H_1, F_3$, and F_2. This result indicates that BC has the most significant influence on the people's distribution in Taikoo Li Sanlitun. In the four coefficients about the floor, the ground floor(F_1) has the most enormous effect on people's flow. Among the two coefficients related to spatial hyperlinks, escalators(H_2) have a greater influence than elevators(H_1). The escalator's slope is positive, while the elevator's slope is negative in the opposite direction in all three equations.

3.3. EXPLANATION OF SPATIAL HYPERLINK

This section compares two types of spatial hyperlinking paths, elevators and escalators from the three MLR models.

Figure 6 shows that three average BC of elevators is higher than three BC of escalators, but the count of the pedestrian flow of the escalators(*33.054 person/min*) is much greater than it of the elevators(*10.392 person/min*). As shown in 3.2, the regression coefficients for H_1 are positive, and H_2 are negative, indicating that the people's number on a path is positively correlated with the path being an escalator and negatively correlated with being an elevator. This means that the flow of people in an elevator is less than the ordinary path with equal BC(H_1<0), whereas the flow of people in an escalator is greater than the ordinary path with equal BC(H_2>0).

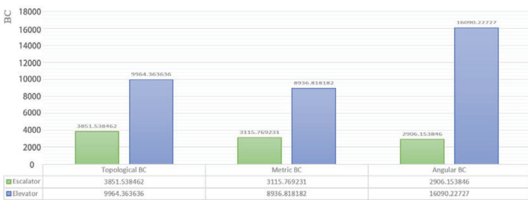


Figure 6. average BC of elevators and escalators .

The causes of this phenomenon are as follows. There are two reasons for the low maximum number of people that the elevator path can carry. One is the elevator itself can only take a limited number of people. For example, the elevator in Taikoo Li Sanlitun has a maximum load of 1000kg and a maximum capacity of 13 people each time, as stated in the Chinese national standard. The other is the elevators have to stop operating to pick up or set down passengers. Contrary to elevators, escalators can carry far more pedestrians, and they generally do not stop working. That is why escalators have a positive spatial hyperlinking effect, but elevators have a negative one.

4. Discussion

This study quantifies the phenomenon of spatial hyperlinks using a network science approach. However, three factors might affect the analysis.

First, this paper studies only one case, so the findings' generalizability needs to be verified. We hope to use the same approach in future research to study more commercial complexes to draw more generalized conclusions.

Second, this study focuses on the commercial complex's spatial network and does not include building perimeter paths. However, the spatial network of the building's surroundings can also have an impact on the inside spatial network, which can also influence the conclusions of this study.

Third, this research uses Yolo-v3 for pedestrian flow counting, which is not completely accurate for identification. For example, the façade of Taikoo Li Sanlitun uses many reflective materials, such as glass, mirrors and metal panels, which leads to errors in pedestrian identification due to duplicate records when recognition. It is not only necessary to avoid selecting observation points in areas with reflective materials but also need to adopt a more appropriate human recognition algorithm in the future.

5. Conclusion

This paper quantifies the phenomenon of spatial hyperlinks by using an MLR model and identifies the effects of two types of spatial hyperlinking paths, elevators and escalators. It also attempts to provide a new perspective for researchers in architecture and urbanism to understand the complex three-dimensional spatial structures in contemporary cities. And it has the following two conclusions.

First, the BC calculated by the network science algorithm cannot characterize the distribution of people in the commercial complex, and more coefficients need to be added to represent the real distribution of the people. When multiple factors were considered together, BC's effect on the population distribution is the most significant.

Second, the phenomenon of spatial hyperlinks affects the distribution of people in commercial complexes, and the two path types with spatial hyperlinks have different effects. Escalators enhance the flow of people, while elevators do the opposite. The reasons for this are related to the operating mechanisms of the two types of paths themselves. Comparing the t values of the independent variables H_1 and H_2 in three MLR models, it is found that escalators have more influence on the people's distribution than elevators.

References

Farhadi, A. and Redmon, J.: 2018, Yolov3: An incremental improvement, *Computer Vision and Pattern Recognition*.

Freeman, L.C.: 1977, A set of measures of centrality based on betweenness, *Sociometry*, **1977(01)**, 35-41.

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

Law, S., Chiaradia, A. and Schwander, C.: 2012, Towards a multimodal space syntax analysis: A case study of the London street and underground network, *Proceedings of the 8th International Space Syntax Symposium*, Santiago de Chile, Chile, Vol. 36.

Sheng, Q., Yang, T. and Hou, J.: 2015, Continuous Movement and Hyper-link Spatial Mechanisms——A Large-scale Space Syntax Analysis on Chongqing, *Journal of Human Settlements in West China*, **30(4)**, 18-22.

Wojke, N., Bewley, A. and Paulus, D.: 2017, Simple online and realtime tracking with a deep association metric, *2017 IEEE international conference on image processing (ICIP)*, 3645-3649.

Zhang, L., Zhuang, Y. and Dai, X.: 2012, A configurational study of pedestrian flows in multi-level commercial space. Case study Shanghai, *Proceedings of the 8th International Space Syntax Symposium*, Santiago de Chile, Chile, Vol. 398.

ARCHIBASE:A CITY-SCALE SPATIAL DATABASE FOR ARCHITECTURAL RESEARCH

YICHEN MO[1], BIAO LI[2], JIAQIAN WU[3] and PENG TANG[4]
[1,2,3,4]*Southeast University*
[1,2,4]*{moyichen|jz_studio|tangpeng}@seu.edu.cn*
[3]*wuchiachien@163.com*

Abstract. The explosion of geolocation data and data-based algorithms has the potential to analyze sophisticated urban areas and foster a more robust urban model. To better collect and organize the city data, this paper introduces a city-scale spatial database called ArchiBase, built upon Java and web APIs of open source databases. With hierarchical, layered, and regularly-updated spatial data defined by relation table, ArchiBase allows indexing and geometric searching of the entire city and supports applications and extensions for different cities. This research is from a graduate urban design course aiming to renew Prato, an industrial city in Italy. ArchiBase first creates the base version of Prato from multiple data sources, then illustrates the usability and expandability through three simple applications. The use of ArchiBase can better interpret future cities and demonstrate the unparalleled opportunities of collaboration and remote work for urban researchers and designers.

Keywords. Spatial Database; Data Model; Urban Design; Design Support Tools.

1. Introduction

The digitalization of urban life embeds the spread of ubiquitous computing. State-of-the-art machine learning technologies are improving quickly both on efficiency and capability based on text or image. Yet the representation of cities is not simply text or images, but geolocation spatial data. This poses the challenge for machine learning and urban analysis.

In order to organize, retrieve, and index city data, this paper introduces a novel city-scale spatial database called ArchiBase, which builds upon Java and web APIs to utilize open data sources. ArchiBase allows indexing and geometric searching of the entire city. The spatial data defined by the relation table are both hierarchical and layered. After the first setup, ArchiBase regularly updates itself with the latest data on the Internet, eliminating the need to retrieve the entire piece of data each time. The structure of the data table is flexible for applications and extensions for different cities. ArchiBase provides a forum in which researchers, architects, and technologists test the potentials of data-based

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 519-528.

algorithms in addressing contemporary urban challenges. The project and related experiments are public on the open-source platform.

The rest of the paper organizes as follows: Section 2 shows that ArchiBase is a city-scale and user-friendly spatial database, providing a collaboration platform for urban planning decision making. In Section 4, a few analyses on Prato show that ArchiBase example a framework for data-based urban design and site analysis for all cities. The construction of ArchiBase is beyond traditional data collection method; Section 3 describes how ArchiBase is built automatically with Java.

2. ArchiBase and Related Works

2.1. RELATED WORKS

Existing research has already tried to propose theoretical databases for specific urban design project or format data representation for the entire city. Recently, more and more data-based algorithms and visualizations reflect the value of this research.

Database: With precise design and modeling techniques, the database supports a holistic approach to urban design practice. Gil et al. (2011) implement a spatial data model that serves as a backbone of the City Information Model, including the urban environment and design process domain. Coorey and Jupp (2013) give a parametric-based schema to extract geometric and topological spatial data from the 3D building model with MySQL. Xu and Li (2019) create the city case base for searching and retrieving similar sites. These works perform data abstraction of the architecture of the city, albeit the scale is usually limited to a specific project and lacks the procedural of data acquisition and integration.

Data format: For interoperability and compatibility, the database uses standard specifications for the query language. OpenGIS Simple Features defines mostly 2-d geometries (such as point, line, polygon, multi-point, multi-line) used in the field of geographic information systems (de La Beaujardiere, 2006). There also exists a data model and exchange format to store city data, like CityGML(Kolbe et al. 2005), standardized by Open Geospatial Consortium(OGC), using Simple Features to present its geometry attributes. In recent works, CityJSON presented (Ledoux et al., 2019) a JSON encoding and recording the topological information in a compact format.

Data-based algorithms: In recent years, with the spread of deep learning, researchers are shifting to data-based algorithms to exploit abundant data generated by cities' daily activities. By measuring street network from data with statics, the orientation and configuration define city spatial logic and order (Boeing, 2019). While urban morphology meets deep learning, millions of cities could compare and evaluate in the same urban model (Moosavi, 2017). With thousands of geotagged satellites and perspective images, machine learning portrays a city's personal view without any previous knowledge about the cities (Alvarez-Marin and Ochoa, 2020). To depict the power of visualization, MorphoCode and Senseable City Lab uses detailed datasets such as NYC Open Data, revealing the latent information from data. However, not all cities have such organized data. ArchiBase, therefore, builds a database on general city comparatively without sufficient data in the current stage.

Above all, ArchiBase aims to be the basis of data-based algorithms, visualization, and analysis. Derived from geospatial data, it takes architectural needs under consideration, reorganizes, and integrates into a hierarchy and layered relation database.

2.2. FEATURES OF ARCHIBASE

The collection and preparation phase are typical and effortful due to the variety of data formats and design tasks. ArchiBase partly automate these tedious tasks, aggregating to a *city-scale spatial* database, which is *versional* and *collaborative*.

City Scale: ArchiBase builds upon the entire city, manipulating built environments containing roads, buildings, urban spaces, functions. Such a choice is for three purposes: (1) city-scale data model provides an emphasis on typology in urban planning and architecture (2) build a database on the city is a challenging task, while it is unnecessary to do this when research on a small city block (3) in the practice of urban design, projects in the same city usually share some common properties. (see Sec.3.3)

Spatial Query: ArchiBase built upon the backbone of open source software PostgreSQL and PostGIS. The latter adds support for geographic objects to PostgreSQL, including spatial predicates and operators provided by the GEOS library. It supports Geospatial measurements like area, distance, length; set operations like union, difference, buffers; 3x3 DE-9IM for determining geometries' interaction. Besides, ArchiBase also provides a few functions and examples to retrieve and index the city for convenience.

Version Control: Most data-based algorithms are offline. Cities are deterministic and static: algorithms concentrate on the cities per see. However, the spatial data online changes each day. ArchiBase could set up regular updating tasks with upstream web mapping services and keep the historical data version if needed.

Coworking: ArchiBase is an interactive and participative platform for researchers to develop data-based algorithms conveniently. Its infrastructure deploys on a database server for sharing and synchronization, providing high-speed connection and integration. Collaborative working allows researchers to extend the content of the database, which increases the ability and knowledge of ArchiBase.

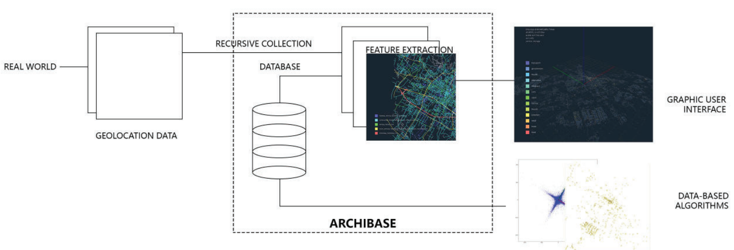


Figure 1. Overview workflow of ArchiBase.

3. Building ArchiBase

As an ambitious project, ArchiBase is aiming to automatically generate the whole city database from the data on the Internet. After parsing data with the specific data format, the author preprocess, extract practical information, then enter into the database with its structure and relation (Figure 1).

3.1. DATA ACQUISITION AND MAINTAINING

Nowadays cities are producing abundant data spontaneously from geotagged social media and web mapping (Alvarez-Marin and Moosavi, 2017). Open Street Map, as a collaborative web map, has a relatively high-quality data set covering the whole planet (Haklay, 2010). ArchiBase mainly chooses OSM as the data source; data from other sources need to translate into the same geographic coordinate system following a similar acquisition methodology. With the input range of the city, the data acquisition procedure divides the bounding box of the map according to the HTTP status code. Our algorithms recursively send requests for collecting data adaptive to the data density.

Once the ArchiBase is built, the maintaining procedure also implements by operating the web API. First, ArchiBase gets the ChangeSet ID for a certain period; Then the detailed changing of data is requested. There are three strategies to integrated information into the database: adding, modifying, and deleting. Adding clean the data and place them into the database; modifying select the specific data to change; deleting choose the data and tag them with deprecated.

3.2. INTERACTION AND REPROJECTION

Construction of ArchiBase is working synergistically with visualization of data to confirm the correctness. To understand and manipulate data, ArchiBase provides the user interface and necessary visualizations in Java, including a reprojection from geographic coordinate system to model coordination and a color toolbox to color geometric data with its specific labels.

3.3. FEATURE EXTRACTION FOR MIGRATION

Before migrating from the online data sources to ArchiBase, it is critical to extract information from geospatial data. The Web API provided by the Internet usually uses an elaborated tag system. According to tags' characters, they are simplified to a few particular categories. This part uses the theoretical knowledge of architecture and city morphology to ensure the expertise of feature extraction.

Functions: ArchiBase uses POIs to describe the functional characteristics of a zone. The labels are grouped into 13 particular functions by its similarity. The original attributes - like name and rating of the place - is recorded for later usage.

Roads: The hierarchical structure of city is related to the transportation network. By grouping the data labels, the LineString of road is divided into five levels: R1, R2, S1, S2, and S3 (Beirão et al., 2009).

Blocks: After removing of the maximum level R1 and minimum level S3 of the roads, the LineString collection are divided into the road-defined polygons, which is used roughly as city blocks.

Buildings: Building is the main body of the city, useful to create the graphic-ground relation imaging of a city and weaving the texture of a field. OSM taginfo shows building=yes as the most used tag.

Imagery: The landmarks or artifacts are essential to shaping common memories of local people (Rossi et al., 1982). Plazas, education, and cultural, industrial buildings are identified from massive data. Natural features, like the water and greenfield, is also filtered by this part.

3.4. DATABASE SCHEMAS

Technically, ArchiBase uses JDBC to access a PostgreSQL database with extension plugins including PostGIS and HStore. PostGIS enable the spatial query with its stored geometry information in well-known text form. HStore uses a data type able to record the original key-value type for further usage. The database schemas which structure described the knowledge of ArchiBase, is divided in to database tables in a spatial relational database. Current data tables: functions, roads, blocks, buildings, and urban spaces correspond to the five building elements of 3.3. For scalability and adaptability, the users can alter table, add columns according their requirements.

4. Applications: A case study of Prato

In this section, the author uses a case study of Prato to show the application of ArchiBase. Prato is the third-largest city in central Italy and the second largest in Tuscany. As an industrial city, Prato focused its urban renew on improving abandoned factory areas and finding solutions to cultural conflicts. ArchiBase created the environment for the entire design project. The database has been deployed on a server that can be accessed through the network. Therefore, students can execute Structured Query Language to obtain the required data and use it for subsequent analysis using their programming. By analyzing and abstracting universal urban elements, research conducted on Prato implements robust algorithms applicable and scalable for most cities.

4.1. CITY DATA OF PRATO

The first data setup of Prato includes 31273 buildings, 8756 roads and 1228 blocks; 10 other types of urban space are also identified from tag info(Figure 2). The general information about the city, including the city name, latitude and longitude coordinate ranges, and geographic coordinate system, is recorded in the database tables. In order to extend the characteristics of the general city information, the author implement algorithems for Prato to calculate the city orientation and shape index.

City orientation: Pinpointing the city orientation reveals the basic structure in the city building data. In ArchiBase, building data is represented as the closed LineString. They are divided into segments and defined them as vectors (plot as blue points in Figure 3). By finding optimal components, principal component analysis (PCA) reduces the dimension from (102267, 2) into (2, 2), offering the orientation of the city.

Shape Index: To index similar shape of the city, ArchiBase implements Boyce-Clark shape index algorithms (Figure 4), which is able to show the similarity of shape (Boyce and Clark, 1964).

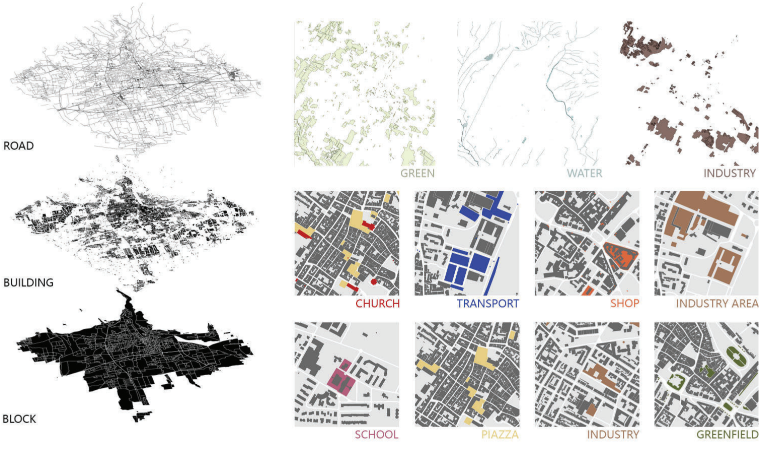


Figure 2. City data of Prato.

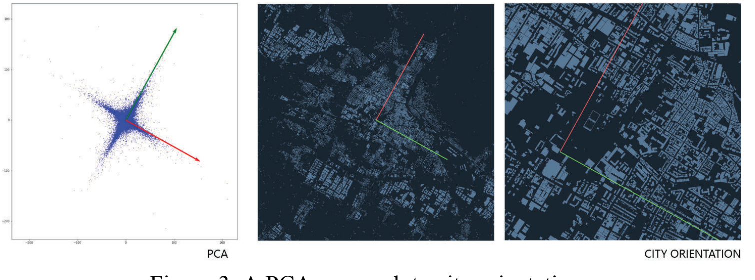


Figure 3. A PCA approach to city orientation.

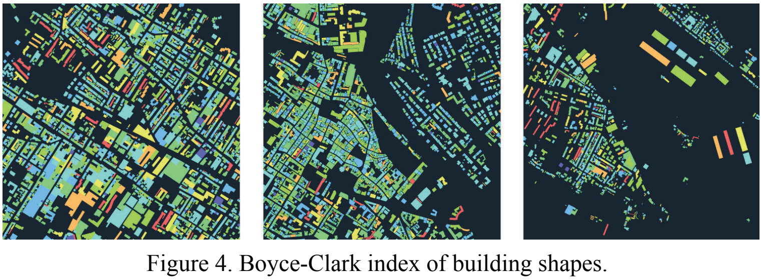


Figure 4. Boyce-Clark index of building shapes.

4.2. FUNCTIONAL ZONES OF PRATO

In light of the Internet and mobile devices, POI data of map services dynamically implies the activities of the city and the functions of an urban area. Google Places API provides 23925 POI data, which demonstrate the functional zones of Prato. The 100 detailed categories of POI are divided into 13 broad types as Sec. 3.3 indicates. ArchiBase provides a simple grid viewer for showing POI data. By selecting the type and scope of statistics, the viewer displays the distribution of POI points interactively (Figure 5). The algorithm counts numbers of POI points in each grid and then fills each cell by its quantity. As shown in left part of Figure 5, 150x150m grid has the best display effect.

Figure 5. Viewer screenshots. Showing the type and scope of statistics results of POI data.

In terms of revealing the connectivity and magnitude of regions, the DBSCAN algorithm groups the points that are closely packed together into 36 clusters. The result of the spatial cluster algorithm is different from counting POI numbers in road-defined blocks (see Figure 6).

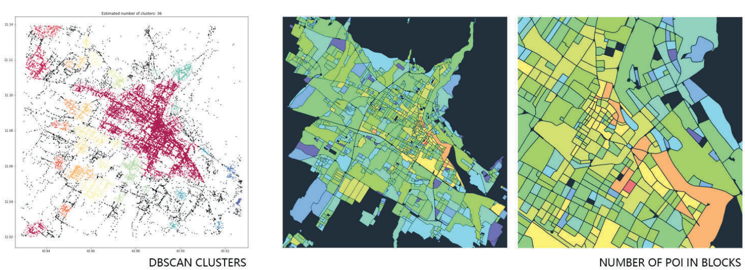


Figure 6. DBSCAN results in 36 clusters, including more information than counting numbers of POI in blocks.

4.3. SPACE AND TIME IN CHINESE IMMIGRANT POPULATION

Language identification depicts Prato's distinctive urban structure and adds data columns to the database. As the second-largest Chinese immigrant population, Prato is one of the few cities in Italy with a growing economy. From the official website, the percentage of the Chinese population in the total population increased from 0.9% to 11.8% between 1995 and 2018. Another evidence is the spatial occupation from POI data. Google Cloud Translate identifies the language of the POI name and finally found 866 Chinese-related points from 23925 data. These identified Chinese names mainly use pinyin for its English name, which is a unique phenomenon in Chinese culture. Figure 7 shows that two areas with the highest density are none other than Macrolotto Zero and the factory-strewn Macrolotto I.

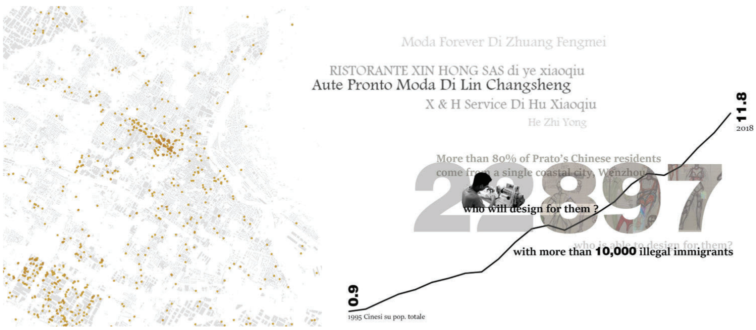


Figure 7. the distribution of Chinese POI and the proportion of Chinese population between 1995 and 2018.

4.4. CITY SENSATION OF STREET BLOCKS

Using street view images of Prato, deep learning demonstrates methods for measuring the built environment of the city with a subjective sensation. By transfer learning on ResNet50 (He et al. 2015) with Place Pulse 2.0 dataset (Salesses et al. 2013), the model evaluates a street view image into 6 perspectives including safety, lively, depressing, boring, beautiful, and wealthy. The author uniformly sampled points on city streets and collected street view images of the points. The evaluation results show the consistency of the discrete samples (Figure 8). After computing with the model, the score of the points contributes to the nearby city blocks. The sensation maps (Figure 9) depicts a significant correlation with the distance to the city center (result from Sec. 4.2).

Figure 8. ArchiBase indexes the best 5 places and vice versa, showing their street view and 6 scores.

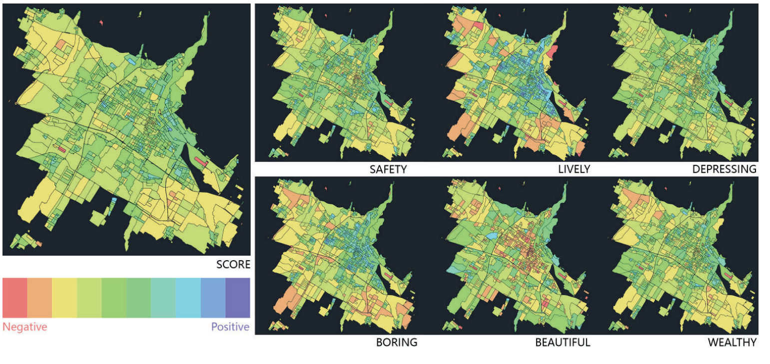


Figure 9. The sensation score of city blocks.

5. Conclusion and Future Works

This paper mainly focuses on the framework for collaboration and representation of city data extracted from the Internet. The value of ArchiBase lies in:

1. The abstraction of city data and its representation in a spatial database.
2. The automated construction and updating tool reducing the burden of data acquisition.
3. An attempt to realize a universally applicable urban analysis algorithm.

Current limitations of ArchiBase include the insufficient variety of algorithms and feature representations. Therefore, in the future: (1) more algorithms could test and evaluate through exploiting ArchiBase (2) feature extraction of data requires theories and experiments to meet the challenge of urban design tasks.

The use of open-source geographic tools in this research demonstrates that programming can partially remove professional barriers. Today, programming is also no longer a specialized skill for professionals. Through the understanding of data representation, it is possible to analyze cities with lightweight programs. The data definitions and structures of ArchiBase can better interpret future cities and offer unparalleled opportunities for researchers and designers in computational research and design.

References

Alvarez-Marin, D. and Moosavi, V.: 2017, Inverting normative city theories and computational urban models: Towards a coexistence with urban data streams, *CoRR*, **abs/1707.03678**, http://arxiv.org/abs/1707.03678..

Alvarez-Marin, D. and Saldana Ochoa, K.: 2020, Indexical Cities: Articulating Personal Models of Urban Preference with Geotagged Data, *CoRR*, **abs/2001.10615**, https://arxiv.org/abs/2001.10615.

Beirão, J., Montenegro, N., Gil, J., Duarte, J.P. and Stouffs, R.: 2009, The city as a street system: A street description for a city ontology, *Proceedings of the 13th Congress of the Iberoamerican Society of Digital Graphics*.

Boeing, G.: 2019, Urban spatial order: Street network orientation, configuration, and entropy, *Applied Network Science*, **4**(1), 67.

Boyce, R.R. and Clark, W.A.V.: 1964, The Concept of Shape in Geography, *Geographical Review*, **54**(4), 561-572.

Gil, J., Almeida, J. and Duarte, J.: 2011, The backbone of a City Information Model (CIM): Implementing a spatial data model for urban design, *Proceedings of 29th eCAADe Conference*, Ljubljana, Slovenia.

Haklay, M.: 2010, How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets, *Environment and Planning B: Planning and Design*, **37**(4), 682-703.

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*.

Moosavi, V.: 2015, Computational Urban Modeling: From Mainframes to Data Streams, *Workshops at the Twenty-Ninth AAAI Conference on Artificial Intelligence*.

Moosavi, V.: 2017, Urban morphology meets deep learning: Exploring urban forms in one million cities, town and villages across the planet, *CoRR*, **abs/1709.02939**, http://arxiv.org/abs/1709.02939.

OpenStreetMap, C.: 2017, “Planet dump retrieved from https://planet.osm.org” . Available from <https://www.openstreetmap.org/>.

Rossi, A. and Eisenman, P.: 1982, *The architecture of the city*, MIT press Cambridge, MA.

Salesses, P., Schechtner, K. and Hidalgo, C.: 2013, The collaborative image of the city: mapping the inequality of urban perception, *PloS one*, **8**, 7.

Xu, J. and Li, B.: 2019, Application of Case-Based Methods and Information Technology in Urban Design-The Renewal Design of the urban region around Roma Railway Station, *Intelligent & Informed - Proceedings of the 24th CAADRIA Conference*, Wellington, New Zealand, 625-634.

SENSITIVITY ANALYSIS OF PEDESTRIAN SIMULATION ON TRAIN STATION PLATFORMS

DANRUI LI[1], RONG HUANG[2] and YIHAO WU[3]
[1,2,3]*Tongji University*
[1,2,3]*{1930063|1930053|1930064}@tongji.edu.cn*

Abstract. As the concerns for pedestrian safety in station design are growing, multi-agent simulation becomes more widely used nowadays. While the difference between inputs in regard to their impacts on simulation outputs needs further research, previous studies fail to provide a global analysis of it in complex environments with limited computation resources. Therefore, regression-based SRC and revised Morris Method are employed in a sensitivity analysis of train station platform simulations. Results show that preference for escalators and alighting rate are influential parameters to all three concerned outputs while the standard deviation of walking speed is negligible. Given that most simulation users have limited time and resources, this paper provides a list of parameters that deserve the time and effort to calibrate together with a factor fixing method that can be applied in similar scenarios. In this way, simulation users can lower the uncertainty of train station simulations more efficiently.

Keywords. Sensitivity analysis; Train station; Pedestrian; Simulation; Morris Method.

1. Introduction

As the concerns for pedestrian safety in station design are growing, multi-agent simulation becomes more widely used nowadays. A great number of studies focuses on pedestrian heterogeneity, which deals with how pedestrians vary in regard to their walking speeds(Ma, 2011), group sizes(Moussaïd et al., 2010), luggage(Ye, Chen and Jian, 2012) and so on. However, when train station designers try to integrate all of them into simulation practice, they will end up with overparamaterized models which are impractical for designers because they have no time to calibrate all the parameters mentioned in those studies. Train station designers need to figure out the most influential inputs which need further calibrations without wasting time on negligible ones.

That's when sensitivity analysis stands out as a tool for evaluating the importance of different inputs in pedestrian simulations. But two shortcomings are identified in related studies. First, most of them focus on simple scenarios like tunnels(Teknomo and Gerilla, 2005), bottlenecks(Gödel, Fischer and Köster, 2020), and evacuations(Lord et al., 2004). But sensitivity analysis in complex environments like train stations has not been thoroughly discussed. Second, the

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 529-538.

sensitivity measures used in many previous studies are either local measures which fail to explore the entire space of inputs, or time-consuming ones which are not suitable to simulations for complex environments.

Fortunately, recent studies have provided numerous observation data and behavioral models in train stations, which paved the way to the sensitivity analysis in such complex environmenets. As for the second gap, two sensitivity measures which have rarely been used in previous pedestrian simulation studies may help. First, although regression-based methods like SRC can only deal with linear or monotonic parts of the models(Borgonovo and Plischke, 2016), they consume far fewer computation resources. Besides, screening methods like Morris can also conduct low-cost analysis by a coarse exploration of input space(Saltelli et al., 2004, p. 93; Campolongo, Cariboni and Saltelli, 2007).

Therefore, based on observation data and models from various studies, this paper tries to make new contributions by a sensitivity analysis for pedestrian heterogeneity in a complex environment rather than simple scenarios. Besides, with the help of the two measures above, a global sensitivity analysis is carried out with far fewer computation resources compared to previous research.

The paper is organized as follows: In Section 2, the selected train station platform and simulation software is briefly introduced. Then eight inputs and their probability spaces are summarized through literature reviews and observations, followed by the selection of three outputs. The briefings of the two sensitivity measures are also provided. Section 3 presents the results, verifications, and validations of the method. The last section covers conclusions and outlook on future work.

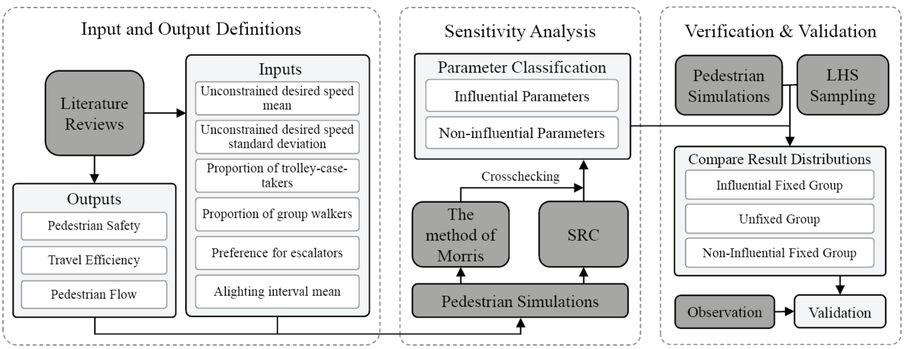


Figure 1. The analytical framework of this paper.

2. Model and Methods

2.1. TRAIN STATION PLATFORM MODEL

A train station platform in China is selected in this study. And this study focuses on simulations of alighting events, when passengers get off train carriages, leave the platform, and enter the arriving hall. The simulation model is illustrated in figure 2, consisting of platforms, gates from which passengers alight, together with stairs and escalators which are connected to the arriving hall. As this paper mainly focuses on alighting events of one single terminal shift, boarding passengers are not taken into considerations and the model ends with the entrances to the arriving hall, not including the entire process of leaving the station.

Previous studies have explored various agent-based pedestrian models. Social-force-based models, firstly introduced by Helbing(Helbing et al., 2005), are the most widely used ones. In the realm of simulation applications in microscopic environments like train stations, open-source or licensed software like AnyLogic(Chen, 2014), Legion(Wang, 2011) and MassMotion(Lang, 2018) are often chosen as pedestrian simulators. This paper uses MassMotion 10.6 with related SDK as the simulation platform, which has been used and validated by other researchers(Rivers et al., 2014; Arup, 2015; Mashhadawi, 2016).

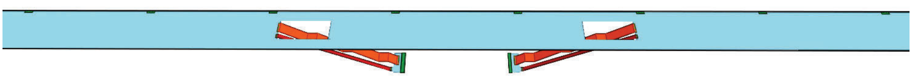


Figure 2. Train station platform model shown in MassMotion .

2.2. INPUT PARAMETERS

According to a previous study(Davidich and Köster, 2013), parameters can be categorized into stationary inputs, quasi-stationary inputs and dynamic inputs according to their changing speed. And inputs that are picked for sensitivity analysis should be suitable for the aim of the study. As this paper aims for simulations at the design stage of train stations, dynamic parameters like the number of passengers are fixed during sensitivity analysis because they are mainly used in simulations for routine operations. Besides, as this paper focuses on pedestrian-related parameters, stationary inputs like built environment geometries are also fixed in this paper.

Therefore, inputs in this paper are mainly quasi-stationary inputs, which may change gradually but can be treated as stationary ones for the prediction period, ranging from pedestrian characteristics to facility preferences. All probability spaces of input parameters are summarized by literature reviews. Since this paper focuses on evaluating the impacts of the inputs in the context of the whole China, a majority of reviewed data is in the context of China and the probability spaces are set by picking maximums and minimums among all reviewed surveys.

All inputs with their possibility spaces are summarized below. Besides, in order to detect which inputs are negligible, a control parameter which is actually not used in the simulations is added to the model.

Table 1. Uncertain inputs and their probability spaces used for the sensitivity analysis.

	Parameter and the source of related observations	Abbr.	Unit	Range
1	Unconstrained desired speed mean	avg_spd	m/s	$\mathcal{U}(1.25\ ,1.4)$
2	Unconstrained desired speed standard deviation Zhang(2009), Ma(2011), Chen(2014), Wu(2016)	std_spd	m/s	$\mathcal{U}(0.15\ ,0.3)$
3	Proportion of passengers who carry large luggage like trolley cases Pearce et al.(2008), Ye(2009), Ye, Chen and Jian(2012), Chen(2014), Tang(2017), Jin(2018)	trl_shr		$\mathcal{U}(0.4\ ,0.7)$
4	Proportion of passengers who walk in groups Chen(2014), Tang(2017), Moussaïd et al.(2010) , Zhang et al(2019)	grp_shr		$\mathcal{U}(0\ ,0.65)$
5	Preference for escalators* Cao(2009), Zhang, Zhang and Zhang(2015), Zacharias and Tang(2015)	str_cst		$\mathcal{U}(10\ ,40)$
6	Alighting interval mean Yuan(2007)	avg_int	s/ppl	$\mathcal{U}(1.3\ ,2.2)$
7	Control parameter	ctrl_par		$\mathcal{U}(0\ ,1)$

* This parameter is applied in MassMotion by configuring the additional distance cost of stairs. The probability space is set to be in parallel with observation data in related studies.

2.3. OUTPUT PARAMETERS

2.3.1. Output definitions

The assessment objectives of previous studies mainly focus on travel efficiency, pedestrian flow and pedestrian safety. These types are discussed below respectively with parameter definitions for this paper.

As for efficiency, criteria like average pedestrian speed(Hoogendoorn, Hauser and Rodrigues, 2004), total time cost(Chen, 2014; Bao, 2019) and speed ratio(Bao, 2019) is widely used. Since walking speed has been set as input in this paper, average time cost ratio, a measure which is similar to speed ratio is adopted to eliminate direct impacts from changing walking speed. The formula is presented as below

$$ATR = \frac{1}{N}\sum_{i=1}^{N}\frac{T_i}{\frac{D_i}{v_i}} \tag{1}$$

where N is the total amount of passengers in the simulation, T is the actual time cost for a specific pedestrian, D is the pedestrian's travel distance and v is the unconstrained desired speed of a specific individual. Therefore, ATR indicates the mean value of the ratios of actual time costs to expected ones.

Maximum flow rate(MFR) is a common measure for description of pedestrian flows so this paper picks it. In addition, flow rate data are calculated as averages of 41-second-long periods so as to get more stable results. The formula of MFR is presented as below

$$MFR = \max \left\{ \frac{\sum_{t-b \leq i \leq t+b} F_i}{2b+1} \right\} when\{b \leq t \leq L-b\} \tag{2}$$

where L is the time length of the simulation in seconds, F is the number of passengers who just left the simulation in a given time i, 2b+1 is the length of the period sample.

Maximum densities at bottlenecks are often selected for safety measure(Hoogendoorn, Hauser and Rodrigues, 2004; Gödel, Fischer and Köster, 2020) so this paper picks the same measure. The formula is presented as below

$$MDB = \max \left\{ \frac{\sum_{t-b \leq i \leq t+b} P_i}{2b+1} \times \frac{1}{A} \right\} when\{b \leq t \leq L-b\} \tag{3}$$

where L is the time length of the simulation in seconds, A is the area of the bottlenecks in square meters, P is the population of bottlenecks in a given time i, 2b+1 is the length of the period sample.

2.3.2. Behavioral uncertainty management

As pedestrian simulations are executed by generating randomized agents. Model can produce different outputs in multiple runs even if the same inputs are provided. This phenomenon is described as behavioral uncertainty of the model by Ronchi, Reneke and Peacock(2014). Therefore, model needs to be executed several times to get the mean value of the results for every set of inputs. According to the study of Ronchi, the number of runs for the same scenario can be determined by calculating this:

$$TET_{convj} = \left| \frac{TET_{avj} - TET_{avj-1}}{TET_{avj}} \right| \tag{4}$$

where TET_{avj} is the average of the output from j runs, TET_{avj-1} is the average of the output from $j-1$ runs. When TET_{convj} is less than 0.5%, j can be used as the optimal number of runs. So each set of inputs is repeatly executed until TET_{convj} reaches below 0.5%.

2.4. SENSITIVITY MEASURES

As discussed in the Introduction above, this paper prefers methods that don't take too much computation time. So regression-based methods like SRC become desirable choices because their time cost is not related to the number of inputs(Borgonovo and Plischke, 2016). However, SRC only works for linear parts of the model(Saltelli et al., 2004, p. 10). So a model-independent measure should be applied as a complement. Since this paper aims to detect the most and the least important parameters in train station platforms rather than discomposing the variance of the model, screening methods like Morris can be put into use. The computation cost of this method is a linear function of the number of inputs(Saltelli et al., 2004, p. 107), which consumes fewer resources than variance-based methods(Dellino and Meloni, 2015, p. 116).

Therefore, this paper uses SRCs firstly, which is the square root of the fraction of the output variance due to each input(Saltelli et al., 2004, p. 9). After that, a revised method of Morris is applied as a cross-checking tool. By generating sample trajectories(Campolongo, Cariboni and Saltelli, 2007), two measures are calculated. The first one is named σ, which is used as a measure for detecting factors involved in interactions with other factors. The other one, which is named μ * , is used to detect inputs with an important overall influence on the outputs. The Morris Method is executed by SALib(Herman and Usher, 2017) on the Python platform.

3. Results

3.1. SRC AND THE METHOD OF MORRIS

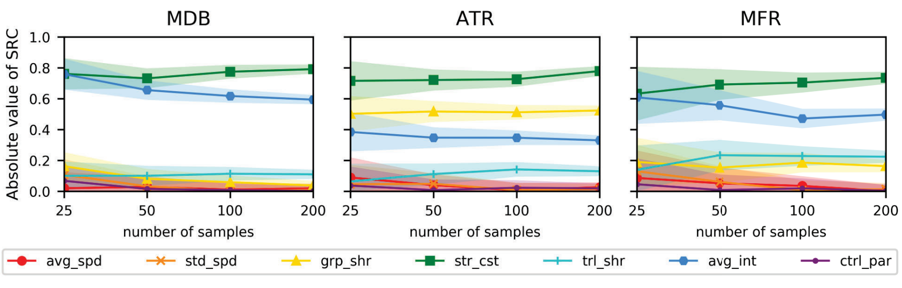


Figure 3. Absolute values of standardized regression coefficients(SRC) of inputs, changing as the number of samples increases. Each light-colored area refers to the 95% confidence interval of each SRC.

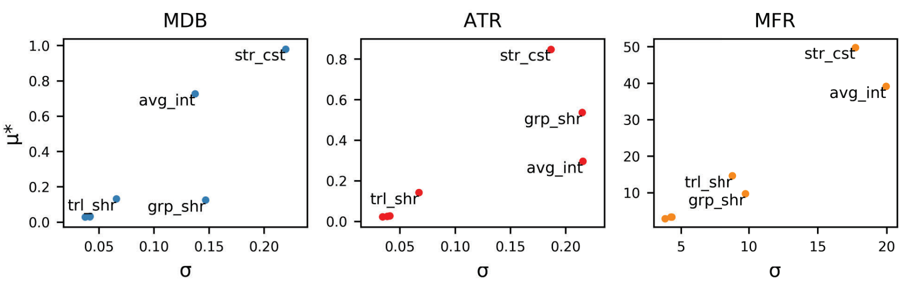


Figure 4. Scatterplots of the result of the method of Morris. The most influential inputs are annotated.

Linear regression models are built for three outputs respectively and SRCs are shown in Figure 3. All regression models reject the null hypothesis of an F test with coefficients of determination which are over 0.9, even though the models in this paper are assembled by non-linear parts. As for the method of Morris, 50 trajectories are evaluated and the results are shown in Figure 4.

As the figure illustrates, both methods produce similar results. Preference for escalators (str_cst) and alighting interval mean (avg_int) are prominent parameters for all three outputs. It indicates that if more people prefer to use escalators and people alight from carriages more quickly, there will be significantly more severe congestion at bottlenecks, lower flow rates, and people will spend longer time on travel than they expected. Besides, it also suggests that good management of alighting events can significantly reduce congestion at bottlenecks.

The mean value of walking speed distribution(avg_spd) also plays a part in MDB and MFR, but its impacts are smaller than the two inputs mentioned before. It is noticeable that the proportion of group walkers(grp_shr) is important to ATR, while avg_spd becomes negligible. The impact of the standard deviation of walking speed is not detected in both measures, indicating that it is a negligible parameter.

3.2. VERIFICATION: FACTOR FIXING

The findings of the two methods are testified by the observations of result distributions when different inputs are fixed to constant values. As figure 5 implies, when negligible inputs are fixed(see Fixed 1 group), the result distributions rarely change, indicating that they can be set to any value within the probability spaces in simulation practice. Meanwhile, when influential parameters are fixed(Fixed 2 group), the result distributions sharply shrink, suggesting careful calibrations of such inputs will lower the uncertainty of the simulation results greatly. The distribution of ATR is not narrowed to an ideal range in Fixed 2 group because influential inputs for ATR are different from the other two outputs, which is shown in the previous section.

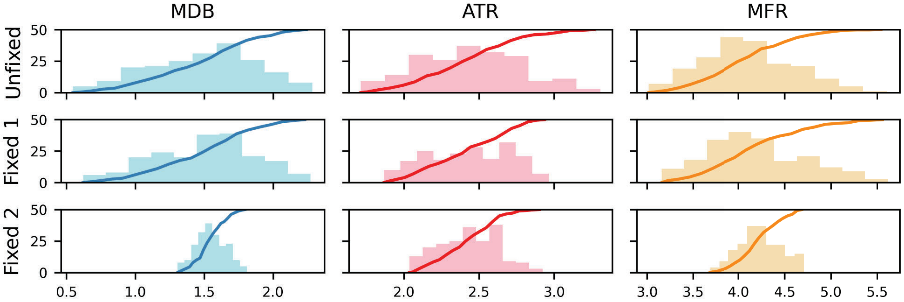


Figure 5. Histograms of simulation results under different input conditions. Cumulative distribution functions are also plotted. Unfixed: All inputs are sampled by LHS(Latin Hypercube Sampling) method. Fixed 1: Negligible factors(std_spd, grp_shr) are fixed to their midpoints of probability spaces while others are sampled by LHS. Fixed 2: Influential factors(avg_int, str_cst) are fixed.

3.3. VALIDATION

The model is validated by observation data in the train station platform. Firstly, the number of passengers and the most influential inputs(avg_int, str_cst) derived from the previous section are calibrated by observation data. Other inputs that are identified as non-influential, are set to the medium values of the probability spaces in section 2.2. The input settinng is shown in Figure 6 (right). Then, the simulation is executed 30 times. After that, the cumulative population and flow rate of the simulation are compared with empirical data.

	Parameter	Value
1	avg_spd	1.325
2	std_spd	0.225
3	trl_shr	0.55
4	grp_shr	0.325
5	str_cst *	15
6	avg_int *	1.41

* Calibrated parameters

Figure 6. (left) Empirical data is extracted from video recordings. (right) The parameters of the validation process.

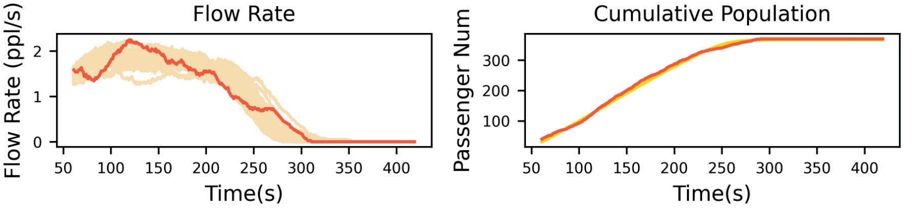


Figure 7. Flow rate at the vertical walking facilities(left) and the cumulative number of people who exited the simulation(right). Empirical data is illustrated by dark orange lines. And light yellow lines represent simulation results.

The results show that the model with only two inputs calibrated can predict the time when a majority of passengers leave the simulation very well. And the tendency of flow rate variation can also be simulated. The result of MFR(2.02) is close to the empirical data(2.24) but this should be further studied with more observations. Due to the limitations of the measuring method, the other two outputs are difficult to observe so they are not included in the validation process.

4. Conclusion and outlook

For train station designers, this paper helps them figure out the most influential parameters in alighting event simulations by conducting a sensitivity analysis. So they can just focus on calibrations of important inputs without losing the result accuracy in similar simulations. Specifically, the standard deviation of walking speed distribution, though widely studied and measured in other studies, is identified as a non-influential parameter in this paper. So it can be fixed for further similar studies and simulation practice. Preference for escalators and alighting rate are the most influential inputs to all three outputs so they need more careful calibrations. Other inputs impose smaller impacts on the results so simulation users can treat them differently according to their own needs.

Besides, this study also suggests a more time-efficiently sensitivity metric when designers need to conduct a new sensitivity analysis in other simulations which involve complex environments. Although the simulation model is often made up of non-linear parts, as long as the combination shows strong linearity, linear-regression-based SRC can be put into use to save computation resources.

However, the limitations still exist. Firstly, all inputs are assumed to be independent of each other in this study while the reality may not be the case. So the relative importance between influential inputs needs further research by considering dependencies between the inputs. Besides, while this study has been validated by empirical data, a larger-scale validation is needed to prove its compatibility. Also, the sensitivity analysis in this paper is restricted to alighting event simulations on train station platforms. It's worth applying the same methodology to other scenarios to compare the results between different environments. Finally, putting the findings into architectural design practice can be part of future work.

References

Arup, initials missing: 2015, "The Verification and Validation of MassMotion for Evacuation Modelling" . Available from <https://www.oasys-software.com/wp-content/uploads/2017/11/The-Verification-and-Validation-of-MassMotion-for-Evacuation-Modelling-Report.pdf>.

Bao, X.: 2019, *Passenger flow Simulation and Spatial Optimization Design of Metro transfer Station based on Agent-Taking Shiyuan Station of Beijing Metro as an example*, Master's Thesis, Beijing Jiaotong University.

Borgonovo, E. and Plischke, E.: 2016, Sensitivity analysis: A review of recent advances, *European Journal of Operational Research*, **248**(3), 869-887.

Campolongo, F., Cariboni, J. and Saltelli, A.: 2007, An effective screening design for sensitivity analysis of large models, *Environmental Modelling and Software*, **22**(10), 1509-1518.

Cao, S.: 2009, 城市轨道交通乘客交通特性分析及建模, Ph.D. Thesis, Beijing Jiaotong University.

Chen, J.: 2014, *THE STUDY ON THE TRANSFER BETWEEN RAIL AND URBAN RAIL TRANSPORTATION BY MEANS OF SIMULATION—A CASE STUDY IN CHENGDU*, Master's Thesis, Southwest Jiaotong University.

Davidich, M. and Köster, G.: 2013, Predicting Pedestrian Flow: A Methodology and a Proof of Concept Based on Real-Life Data, *PLoS ONE*, **8**(12), e83355.

Dellino, G. and Meloni, C.: 2015, *Uncertainty management in simulation-optimization of complex systems*, Springer, Boston MA.

Gödel, M., Fischer, R. and Köster, G.: 2020, Sensitivity Analysis for Microscopic Crowd Simulation, *Algorithms*, **13**(7), 162.

Helbing, D., Buzna, L., Johansson, A. and Werner, T.: 2005, Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions, *Transportation science*, **39**(1), 1-24.

Herman, J. and Usher, W.: 2017, SALib: An open-source Python library for Sensitivity Analysis, *The Journal of Open Source Software*, **2**(9), 97.

Hoogendoorn, S.P., Hauser, M. and Rodrigues, N.: 2004, Applying microscopic pedestrian flow simulation to railway station design evaluation in Lisbon, Portugal, *Transportation research record*, **1878**(1), 83-94.

Jin, M.: 2018, *Research on the design of railway passenger hub entry space based on capacity*, Master's Thesis, Southwest Jiaotong University.

Lang, L.: 2018, *RESEARCH ON DESIGN STRATEGY OF ENTRANCE SPACE OF COLLEGE COMPREHENSIVE TEACHING BUILDING BASED ON PEDESTRIAN FLOW SIMULATION*, Master's Thesis, Harbin Institute of Technology.

Lord, J.: 2004, Uncertainty in egress models and data: investigation of dominant parameters and extent of their impact on predicted outcomes-initial findings, *Proceedings of the 5th international conference on performance-based codes and fire safety design methods*.

Ma, Y.: 2011, *Passenger rail transportation hub stream line organization of the individual*, Master's Thesis, Chang'an University.

Mashhadawi, M.: 2016, *MassMotion Evacuation Model Validation*, Master's Thesis, Ghent University.

Moussaïd, M., Perozo, N., Garnier, S., Helbing, D. and Theraulaz, G.u.y.: 2010, The Walking Behaviour of Pedestrian Social Groups and Its Impact on Crowd Dynamics, *PLoS ONE*, **5**(4), e10047.

Pearce, L., Powell, P., Duff, R., Anibogu, J. and Kerr, A.: 2008, Passengers with reduced mobility: modelling their behaviour in underground stations, *EUROPEAN TRANSPORT CONFERENCE 2008*.

Rivers, E., Jaynes, C., Kimball, A. and Morrow, E.: 2014, Using Case Study Data to Validate 3D Agent-based Pedestrian Simulation Tool for Building Egress Modeling, *Transportation Research Procedia*, **2**, 123-131.

Ronchi, E., Reneke, P.A. and Peacock, R.D.: 2014, A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling, *Fire Technology*, **50**(6), 1545-1571.

Saltelli, A., Tarantola, S., Campolongo, F. and Ratto, M.: 2004, *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models*, John Wiley \& Sons Ltd, Chichester.

Tang, X.: 2017, *Studying on the Transfer Mode Choice Behavior of Arrival Passengers in High-speed Railway Passenger Transport Hub—Taking Xi*, Master's Thesis, Chang'an University.

Teknomo, K. and Gerilla, G.P.: 2005, Sensitivity analysis and validation of a multi-agents pedestrian model, *Journal of the Eastern Asia Society for Transportation Studies*, **6**, 198-213.

Wang, H.: 2011, *Research on Organizational Design of Pedestrian Flow in Comprehensive Transportation Hub*, Master's Thesis, Chang.

Wu, H.: 2016, *Research on Simulation of Pedestrian Flow in Traffic Facilities of Urban Rail Transit Station Considering Heterogeneity*, Ph.D. Thesis, Beijing Jiaotong University.

Ye, J.: 2009, 行人交通行为与交通流特性研究, Ph.D. Thesis, Tongji University.

Ye, J., Chen, X. and Jian, N.: 2012, Impact analysis of human factors on pedestrian traffic characteristics, *Fire Safety Journal*, **52**, 46-54.

Yuan, M.: 2007, *Study on Layout of Passenger Station in Junction Terminal and Transport Capacity of Passage*, Master's Thesis, Beijing Jiaotong University.

Zacharias, J. and Tang, B.: 2015, Choosing between stairs and escalators in China: The impact of location, height and pedestrian volume, *Preventive Medicine Reports*, **2**, 529-532.

Zhang, G.: 2009, *Pedestrian traffic behavior and microscopic simulation research on station square of synthetical passenger transport hub*, Master's Thesis, Beijing Jiaotong University.

Zhang, R., Yang, J., Yang, C.w. and Dai, S.x.: 2019, Pedestrian Simulation Modeling of Subway CorridorConsidering Group Behavior, *Journal of Transportation Systems Engineering and Information Technology*, **19**(5), 163-168.

GLOBAL URBAN CITYSCAPE - UNSUPERVISED CLUSTERING EXPLORATION OF HUMAN ACTIVITY AND MOBILITY INFRASTRUCTURE

TANIA PAPASOTIRIOU[1] and STEPHAN CHALUP[2]
[1,2]*The University of Newcastle, Australia*
[1]*Soultana.papasotiriou@uon.edu.au*
[2]*stephan.chalup@newcastle.edu.au*

Abstract. It is widely accepted that cities cultivate innovation and are the engines of productivity. The identification of strengths and weaknesses will enchant social mobility providing equal opportunities for all. The study at hand investigates the relationship between social mobility and transportation planning in 1,860 central urban areas across the globe. Datamining processes combining open-sourced, automated, and crowdsourced information from four major pillars of social mobility (demographics, human activity, transport infrastructure, and environmental quality) are used to describe each location. Next, unsupervised clustering algorithms are used to analyse the extracted information, in order to identify similar characteristics and patterns among urban areas. The process, which comprises an objective framework for the analysis of urban environments, resulted in four major types of central areas, that represent similar patterns of human activity and transport infrastructure.

Keywords. Information retrieval; similarity measures; computer methodologies; unsupervised clustering; urban performance.

1. Introduction

In early 2020 the World Economic Forum performed a holistic assessment of 82 countries, classifying them according to their performance on critical aspects of social mobility (WEF, 2020). One of the main findings of this study is the need to develop global momentum to tackle the inequality that arises from new social mobility challenges. However, these challenges are not spatially homogenous as cities are complex and dynamic bodies of mixed personal activities scattered across various locations. Understanding the spatial variability of urban structures is paramount for operators and stakeholders to define effective management policies and services, such as sustainable and innovative transport planning. As cities around the world are now recognising the value of tracking their performance and progress, various instruments, indicators and targets are being used to benchmark, identify and promote sustainable transport policies.

In parallel, the rapid growth of data availability and the exponential development of digital platforms allow the detection of mobility patterns in urban

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 539-548.

areas with more detail than ever before. As these patterns are highly related to spatial interaction and land use (Rodrigue, 2020), capturing the heterogeneity of urban ecosystems by means of digital data is one of the most important lines of research within the field of Urban Computing. Numerous studies are seeking for solutions to capture the dynamic characteristics of urban settlements, and different technologies and techniques are used to gather and analyse urban data produced by static, mobile and crowdsensing sensors (Zheng, 2019). While spatiotemporal variations in human mobility, urban functional regions and city-wide human activity have been studied extensively (i.e. Becker et al., 2013; Caceres & Benitez, 2018; Zhang et al. 2020), important gaps remain. Researchers have pointed out that most case studies are often limited to local city contexts and are based on the use of isolated datasets (Regmi, 2020). Moreover, traditional and static methods do not apply to real settings, where various functional areas perform quite differently depending on time i.e. on working weekdays and weekends/holidays (Terroso Saenz, et al., 2020). New studies of urban analytics (Calafiore, et al., 2021) highlight the power of open data in a variety of contexts worldwide. However, the attempt to unpack contemporary mobility, diversity and similarities of human dynamics is once more restricted to small samples of cities and isolated data sources.

Building on these arguments, the study at hand is combining heterogeneous sources to interrogate the characteristics of urban areas with dynamic use of land, and high human activity. A clustering analysis is employed to identify similarities and analogies of urban settings, highlighting the relationship between human activity and transport infrastructure across the globe. Given the enormous amount and diversity of digital data produced from different aspects of urban life, this study proposes an objective framework that allows researchers to extract knowledge from open-source raw data, that can be updated dynamically. This framework can support decision-makers in evaluating and benchmarking the current state of any urban location, as well as tracking the impact of interventions in the urban environment.

The paper is structured as follows: The first part, focused on data selection, presents a series of indicators used to describe the human activity and transport infrastructure, that are available for any given location around the world. Moreover, it outlines the datamining process and discusses sources of information used in the study. The second part is dedicated to the clustering process. It demonstrates the use of t-SNE algorithm (Van der Maaten & Hinton, 2008) to identify and represent similarities among the selected entities, and the application of the Mean Shift algorithm (Cheng, 1995) to detect clusters that depict similar urban behaviours. Next, an overview of the resulting cluster outcomes is presented, followed by a discussion outlining the main conclusions.

2. Data collection

2.1. SELECTION OF URBAN INDICATORS

Several efforts have been made towards the establishment of social mobility and transport infrastructure indicators for urban areas (Arcadis, 2017; Chestnut

& Mason, 2019; Dixon et al., 2019). However, the indicator sets used in the mentioned studies vary widely, and consensus towards a widely accepted system that can be applied across cities is yet to be reached. Moreover, local regulations make the application of some assessment tools in certain regions of the globe questionable, or even invalid (Macedo et al., 2017).

In this study, we combine three types of data extracted from Open APIs or publicly available databases, specifically: directed (open-sourced and free licensed), automated (scraped or constructed), and volunteered (crowdsourced). Extraction of the data took place from 8/6/2020 until 15/6/2020. Table 1 is showing a summary of the selected indicators and their sources. The indicators correspond to major pillars of social mobility such as demographics, transport infrastructure, human activity, and environmental quality. The methods used to extract the data are outlined in the following.

Table 1. Summary of domains and indicators of the urban profile dataset.

Domain	Indicator	Attributes	Source	Type
Areas of interest	location	City , Country	(UN, 2019)	Directed
	centroid coordinates	Latitude, Longitude	(UN, 2019)	Directed
	centroid type	type of centroid	(OSM, 2020)	Directed
	isochrone radius	radius of urban unit	(OSM, 2020)	Automated
Demographics	population	Number of residents	(UN, 2019)	Directed
Human activity	POI / number of Venues	Arts & Entertainment, College & University, Event, Food, Nightlife, Spot Outdoors & Recreation, Professional & Other Places, Residence, Shop & Service, Travel & Transport	(Foursquare, 202	Volunteered
	Walkability	Walk score	(Walkscore, 202	Automated
Transport infrastructure	Pois / Mobility	parking ,taxi hubs, public & transportation	(OSM, 2020)	Automated
	Network infrastructure	street length total, street length average, street segments, intersections, street density, intersection density	(OSM, 2020)	Automated
Environmental quality	Air quality	Air Quality Index (AQI)	(AERIS, 2020)	Automated

2.2. DESCRIPTION OF DATA MINING

Areas of interest: We consider 1,860 cities with a population that exceeds 300,000 residents from around the globe. The 2018 Revision of World Urbanisation Prospects (UN, 2019) contains an extensive database with details regarding the population and the geographical characteristics (latitude and longitude) of the centroid of each city. The description and type of each centroid (city centre or urban agglomeration centre) is provided from taginfo (OSM, 2020). Here we focus on the central locations of each city, defined as the area within 30 minutes walking distance (travel speed 4.5km/h) from the centroid. Each area corresponds to an "urban unit". For the calculation of the isochrone radius r_{iso} of each urban unit we have used Open Street Maps (OSM) (Haklay & Weber, 2008) combined with the OSMnx Python package (Boeing, 2017a, 2017b)

Transport infrastructure: The same sources that were employed to calculate the isochrone radius (OSM and OSMnx) were used to retrieve mobility Points of Interest (POIs) such as parking facilities, taxi stops and public transport stops within the urban units. Moreover, through the statistics modules of OSMnx we have identified the geometrical characteristics of the road network of each unit such as total street length, average street length, number of street segments (S), and number of intersections (I). The last two attributes were used for the calculation of street density (D_s) and clean intersection density (D_i) as follows: $D_s = \frac{S}{A}$ and $D_i = \frac{I}{A}$ where A refers to the isochrone area and is calculated as $A = \pi \cdot r_{iso}^2$

Human activity: The application Foursquare (Foursquare, 2020) provides a global database of user content on venue data. This information is organized in a hierarchical order of multiple levels and the selection of the hierarchical level is relevant to the scale of this study. Through the application's API, we retrieved 10 high-level venue categories that describe popular human activities: Arts & Entertainment; College & University; Event; Food; Nightlife; Outdoors sports & Recreation; Professional & Other Places; Residence; Shop & Service; Travel & Transport. Moreover, to obtain a better understanding of the character of human activity, we used again open API's to identify the walk score (Walkscore, 2020) of the centroid of every location.

Environmental quality: To describe the environmental characteristics of each urban unit we extracted the Air Quality Index (AQI) for each centroid corresponding to 4 periods of a working day (every 6 hours) through the AERISweather API (AERIS, 2020). The final AQI score was the mean value of the extracted information.

2.3. DATA PROCESSING

Following data collection, the dataset was processed, and the gained information that used to calculate the street and intersection density and total air quality (i.e. street length, street segment count, intersection count, radius and AQI metrics) was excluded from the final selection. The dimension of the final dataset is (1860, 19) corresponding to 19 indicators that describe the use and behaviour of the 1,860 urban units.

Before proceeding to the next part of the analysis, we need to normalise our dataset and bring the different ranges of raw features to a common scale. This has been achieved by scaling each indicator to values between 0 and 1 via the sklearn MnMaxScaler function. The normalised valued X_{scl} for each indicator X is given as: $X_{scl} = \frac{X - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}$, where X_{max} and X_{min} is the maximum and minimum values of the indicator across the dataset, respectively.

It is worth noting that the abovementioned urban attribute dataset was compiled from publicly available sources. No imputation methods were used during or after data collection and no commercial sources were used for this analysis, except the AERIS Dataset, a trial version of which was sourced for the needs of this study.

3. Clustering process

Compilation of the dataset described above allowed interrogating the characteristics of urban units to detect similarities and patterns in human activity and transport infrastructure.

To uncover sets of urban units with similar characteristics we employed an unsupervised clustering prosses of the abovementioned high dimensional space of 19 indicators. The process takes place in four steps (Algorithm 1): After pre-processing and data scaling, the high dimensional data are projected into a 2D map using the t-SNE algorithm, and then we apply Mean-shift clustering to identify clusters of similar patterns. Finally, we plot the clusters to overview and interpret the produced clusters. This procedure is described in the following algorithm.

```
*Algorithm 1: t—SNE and Mean shift clustering*
For each domain
Scale  data ——> X_scl
For perplexity in range (10, 50,10)
    Compute t—SNE (X_scl)
    Select the min KL divergence ——> t—SNE
    Plot t—SNE
For n_samples in range (10, 50,5)
    Compute bandwidth (n—samples) ——> bandwidth
    Means shift clustering (bandwidth,t—SNE)
    Estimate the number of clusters ——> cluster labels
    Plot clusters
Make Plots ——> boxplots and basemaps
```

3.1. DIMENSIONALITY REDUCTION

An algorithm capable of transforming high-dimension databases in two- or three-dimensional vectors that can be easily visualised in a scatter plot is the ‘t-Distributed Stochastic Neighbour Embedding’ or t-SNE for short (Van der Maaten & Hinton, 2008). Generally, t-SNE is employed to project high-dimensional data to a low-dimensional two-dimensional XY space, while preserving much of the local structure. This is achieved by minimising the Kullback-Leibler divergence between the original distribution and probability distribution of points in the low-dimensional map.

The low-dimensional projections are represented in such a way, that nearby points correspond to similar objects and distant points correspond to dissimilar objects. This facilitates visualising isolated cluster structures. The t-SNE algorithm due to its cost function can produce different results under different initializations. In the study at hand, we used the default algorithm parameters (refer to sklearn.manifold.TSNE) except of perplexity, which was set to 50 to gain a better understanding of global geometry. In addition, the number of iterations was set to 10000 (Wattenberg et al., 2016). The outcome of the clustering process is graphically depicted in Figure 1.

3.2. MEAN-SHIFT CLUSTERING

Although several clustering techniques can be applied to the resulting 2D feature space, we have selected the Mean-shift algorithm (Comaniciu & Meer, 2002) on the grounds of its lower computational requirements, its ability to find groups with various shapes, and the low number of hyper-parameters that require fine-tuning. Mean-shift is capable of identifying core clusters that are generating strong stance and outliers with a small influence that will not belong to a cluster. The aim is to identify peaks of densities in the feature space using Gaussian kernels. Each point is iteratively shifted towards the mean of all the points within the kernel until all points converge to a local maximum of density nearby them, hence group into the same cluster. The radius of the kernel (bandwidth) determines the number of peaks detected from the algorithm and it can be estimated automatically using cross-validation in a probabilistic setting.

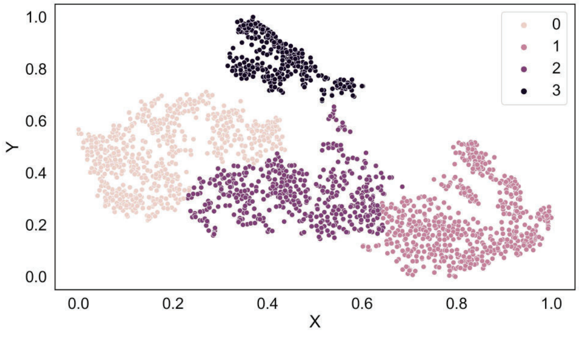


Figure 1. Visualization of the t-SNE two-dimensional feature space highlighting the clustering outcome of the Mean-shift algorithm.

For the application at hand, we have used the sklearn implementation, testing the default parameters for bandwidth estimation. To evaluate the stability of the Mean-shift outcome we used the Calinski-Harabasz Index (CH) (Caliński & Harabasz, 1974; Wang & Xu, 2019). Since there are no ground truth labels, the evaluation is performed using the model itself and higher CF scores respond to models with better-defined clusters (Table 2). Moreover, in Table 3 we compare the outcome with other clustering algorithms. A detailed description of the way these algorithms operate is outside the scope of this paper. The algorithm resulted in the identification of 4 clusters, no outliers were detected (Figure 1) and the produced labels were assigned to each urban unit.

Table 2. (Left) Evaluation of clustering stability of Mean shift outcomes with different bandwidth. Table 3: (Right) Comparison of Calinski-Harabasz Index between different clustering algorithms.

N_samples	Number of clusters	CH score
10	9	3280.80
15	7	3265.46
20	5	3262.57
25	4	3229.74
30	4	3314.54
35	4	3255.21
40	4	3308.85

Clustering algorithm	Number of clusters	CH score
Mean shift	4	3314.54
Birch	4	2989.87
K Means	4	3101.19
AGNES	4	947.19
DBSCAN	4	96.0222

4. Clustering overview

The clustering process discussed above resulted in 4 major types of urban units (Clusters) scatter across the globe, shown in Figure 2. Our initial assumption that urban units in each constellation will have similar stance reveals the characteristics of each group. Figure 2 also depicts the general behaviours regarding each feature. The characteristics of each Cluster are briefly outlined in the following.

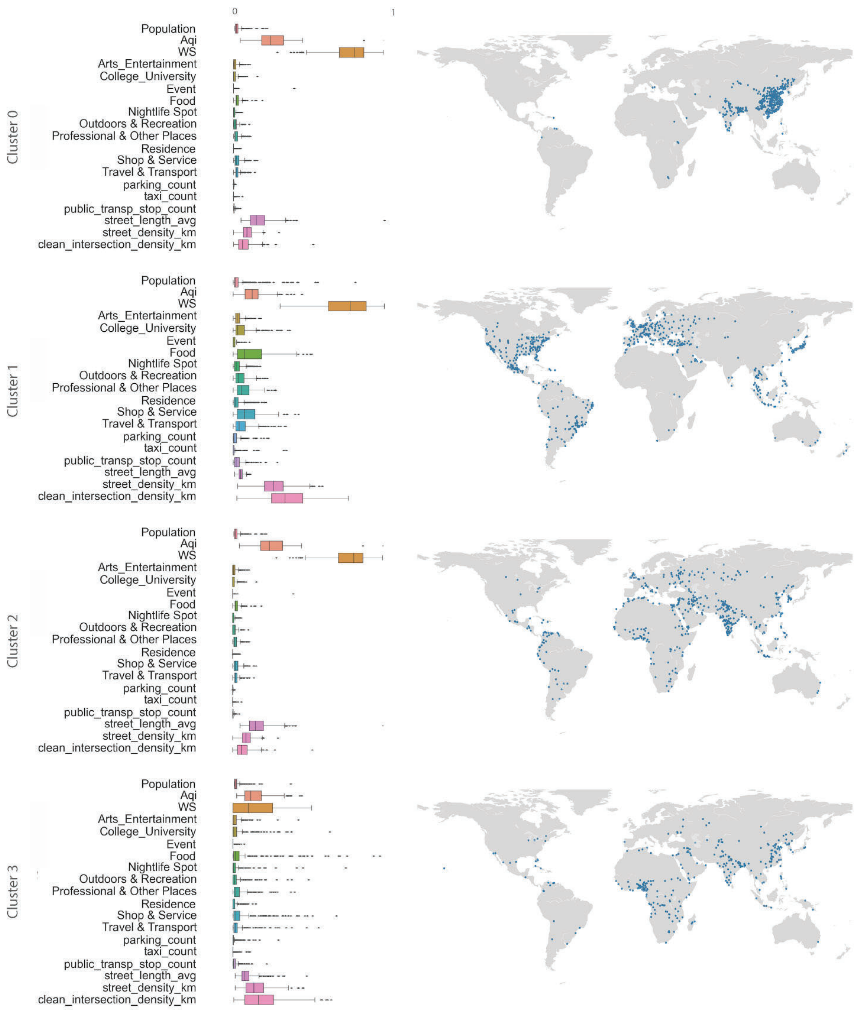


Figure 2. Distribution of clusters across the globe and boxplot of features.

Cluster 0 (number of urban units = 437): Represents cities with a minor number of venues within the urban units and minimum POIs of transport infrastructure. These units are walkable, with long streets, however, they exhibit low air quality.

Samples are mostly found in Eastern Asia, with China and India dominate the cluster.

Cluster 1 (number of urban units = 613): Vibrant urban units with an increased number of venues and substantial transport infrastructure belong to this cluster. The central areas of the cities are very walkable with good environmental conditions. The street network is dense with small segments and increased intersection density. Cities that belong in this cluster are scattered across the globe with strong presence in Europe, USA, Canada, Brazil, Japan and Australia.

Cluster 2 (number of urban units = 498): This cluster describes walkable units with moderate air quality and dense road networks that do not have high numbers of venues or advance transport infrastructure. Cities exhibiting such characteristics are found mostly in India, Russia, Iran and north-east parts of South America.

Cluster 3 (number of urban units = 312): The last cluster represents urban units with extremely dense and short street networks. The cities that belong to this cluster are barely walkable with poor air quality, and the existing transport infrastructure is limited. Most of these units are in China, India, Nigeria and Congo.

5. Discussion and conclusion

The concept of social mobility is widely considered as an indicator measuring countries' ability to provide equal opportunities for all. (OECD, 2011). This study, through an objective and data-driven process, explores heterogeneous, openly available, city-level information to identify similarities in urban behaviours that operate, according to Sorokin, as indicators for social openness(Sorokin, 1959).

The presented process revealed that 73 countries (Figure 2) have central urban units in more than two clusters. This fact demonstrates high levels of living standards inequalities between neighbouring cities. From those 9 countries - China, Colombia, India, Philippines, Saudi Arabia, South Africa, South Korea, Venezuela, Vietnam - with cities in all four clusters display extremely different living standards and urban behaviours in the selected indicators. In the same notion, the central urban units of 24 countries belong in 3 clusters revealing significant differences in human activity, transport infrastructure and environmental conditions with potential socio-economic deprivation. Some of these countries are Australia, Brazil, Canada, Italy, Qatar, Russia, Taiwan, and USA.

Clusters within countries	Number of countries
4	9
3	24
2	40
1	77

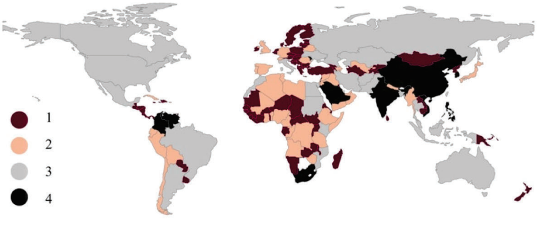


Figure 3. Choropleth map of different types of urban units within countries. .

This study has two limitations that call for further investigation. First the lack of open and accessible datasets that provide in a consistent manner city level information regarding economic factors, such as cost of living and purchasing power. As cities are searching for ways to improve livability and track their performance, this type of information is expected to become publicly available in a standarised form, for more and more cities. Second the demographic and geographic biases of crowdsourcing information retrieved from Foursquare. The application is usually referring to young and technology savvy users, and provides inadequate information for certain locations.

The described methodology demonstrates how we can extract - to a reasonable extent -reliable and up-to date city-level data for every urban location around the world, in a systematic and objective manner. The framework can support decision-makers in evaluating and benchmarking the current state of cities, tracking progress and performance of urban planning interventions and identifying best practices within cities of similar context . Moreover, the framework can be used to quickly identify differences and deprivation within urban settings of the same country, steering policy makers towards interventions that will support equal opportunities for all.

Acknowledgements

The first author would like to acknowledge the support from the University of Newcastle during her PhD studies. The authors would like to thank Sam Spurr, Nicholas Foulcher and Asad Abbas, for the fruitful discussions during the course of this research.

References

Aeris, [.: 2020, “AerisWeather API” . Available from <https://www.aerisweather.com/support/docs/api/> (accessed June 2020).

Arcadis, [.: 2017, “Arcadis Sustainable Cities Mobility Index” . Available from <https://www.arcadis.com/media/8/B/8/%7B8B887B3A-F4C4-40AB-AFFD-08382CC593E5%7DSustainable%20Cities%20Mobility%20Index.pdf> (accessed June 2020).

Becker, R., Cáceres, R., Hanson, K., Isaacman, S., Loh, J.M., Martonosi, M., Rowland, J., Urbanek, S., Varshavsky, A. and Volinsky, C.: 2013, Human mobility characterization from cellular network data, *Communications of the ACM*, **56**(ISSN 0001-0782), 74-82.

Boeing, G.: 2017a, OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks, *Computers, Environment and Urban Systems*, **65**, 126-139.

Boeing, G.: 2017b, “Isochrone Maps with OSMnx + Python” . Available from <https://geoffboeing.com/2017/08/isochrone-maps-osmnx-python/> (accessed June 2020).

Caceres, N. and Benitez, F.G.: 2018, Supervised land use inference from mobility patterns, *Journal of Advanced Transportation*, **2018**(ISSN 0197-6729), 8710402.

Calafiore, A., Palmer, G., Comber, S., Arribas Bel, D. and Singleton, A.: 2021, A geographic data science framework for the functional and contextual analysis of human dynamics within global cities, *Computers, Environment and Urban Systems*, **8**(ISSN 0198-9715), 101539.

Caliński, T. and Harabasz, J.: 1974, A dendrite method for cluster analysis, *Communications in Statistics-theory and Methods*, **2**(ISSN 0090-3272), 1-27.

Cheng, Y.: 1995, Mean shift, mode seeking, and clustering, *IEEE transactions on pattern analysis and machine intelligence*, **17**(ISSN 0162-8828), 790-799.

Chestnut, J. and Mason, J.: 2019, “Indicators for Sustainable Mobility.” . Available from <https://www.itdp.org/publication/indicators-sustainable-mobility/> (accessed June 2020).
Comaniciu, D. and Meer, P.: 2002, Mean shift: A robust approach toward feature space analysis, *IEEE Transactions on pattern analysis and machine intelligence*, **24**(ISSN 0162-8828), 603-619.
Dixon, s., Irshad, H., Pankratz, D.M. and Bornstein, J.: 2019, “The 2019 Deloitte City Mobility Index” . Available from <https://www2.deloitte.com/content/dam/Deloitte/br/Documents/consumer-business/City-Mobility-Index-2019.pdf> (accessed June 2020).
Foursquare, [.: 2020, “Foursquare Developer API” . Available from <https://developer.foursquare.com/.> (accessed June 2020).
Haklay, M. and Weber, P.: 2008, Openstreetmap: User-generated street maps, *IEEE Pervasive Computing*, **7**(ISSN 1536-1268), 12-18.
Van der Maaten, L. and Hinton, G.: 2008, Visualizing data using t-SNE, *Journal of machine learning research*, **9**, 2579-2605.
Macedo, J., Rodrigues, F. and Tavares, F.: 2017, Urban sustainability mobility assessment: indicators proposal, *Energy Procedia*, **134**(ISSN 1876-6102), 731-740.
OECD, (.F.E.C.-O.D.: 2011, *Divided we stand: Why inequality keeps rising*, OECD Publishing, Paris.
OSM, (.S.M.: 2020, “Taginfo” . Available from <https://taginfo.openstreetmap.org/keys/place#values> (accessed June 2020).
Regmi, M.B.: 2020, Measuring sustainability of urban mobility: A pilot study of Asian cities, *Case Studies on Transport Policy*, **8**(ISSN 2213-624X), 1224-1232.
Rodrigue, J.P.: 2020, *The geography of transport systems (5th ed.)*, Routledge.
Terroso Saenz, F., Muñoz, A. and Arcas, F.: 2020, Land□use dynamic discovery based on heterogeneous mobility sources, *International Journal of Intelligent Systems*, **36**(ISSN 0884-8173), 478-525..
Sorokin, P.: 1959, Social and cultural mobility, *New York*, **4**, 99-145.
UN, (.N.: 2018, “World urbanisation prospects” . Available from <https://population.un.org/wup/Download/Files/WUP2018-F22-Cities_Over_300K_Annual.xls> (accessed June 2020).
Walkscore, [.: 2020, “Walkscore API” . Available from <https://www.walkscore.com/professional/api.php> (accessed June 2020).
Wang, J., Huang, Z., Xu, H. and Kang, Z.: 2018, Clustering analysis of human behavior based on mobile phone sensor data, *Proceedings of the 2018 10th International Conference on Machine Learning and Computing*, 64-68.
Wattenberg, M., Viégas, F. and Johnson, I.: 2016, How to use t-SNE effectively, *Distill*, **1**(ISSN 2476-0757), e2.
WEF, (.E.F.: 2020, “The Global Social Mobility Report 2020 Equality, Opportunity and a New Economic Imperative” . Available from <http://www3.weforum.org/docs/Global_Social_Mobility_Report.pdf> (accessed June 2020).
Zhang, X., Sun, Y., Zheng, A. and Wang, Y.: 2020, A New Approach to Refining Land Use Types: Predicting Point-of-Interest Categories Using Weibo Check-in Data, *ISPRS International Journal of Geo-Information*, **9**(ISSN 2220-9964), 124.
Zheng, Y.: 2019, *Urban Computing*, MIT Press..

COMPREHENSIVE ANALYSIS OF THE VITALITY OF URBAN CENTRAL ACTIVITIES ZONE BASED ON MULTI-SOURCE DATA

Case studies of Lujiazui and other sub-districts in Shanghai CAZ

CHENYU HUANG[1], PIXIN GONG[2], RUI DING[3], SHUYU QU[4] and XIN YANG[5]
[1,2,3,4,5]*School of Architecture and Art, North China University of Technology*
[1,3,4]*{huangchenyu303|dingrui418|qushuyuu}@163.com*
[2]*253501297@qq.com* [5]*bjyangxin@126.com*

Abstract. With the use of the concept Central Activities Zone in the Shanghai City Master Plan (2017-2035) to replace the traditional concept of Central Business District, core areas such as Shanghai Lujiazui will be given more connotations in the future construction and development. In the context of today's continuous urbanization and high-speed capital flow, how to identify the development status and vitality characteristics is a prerequisite for creating a high-quality Central Activities Zone. Taking Shanghai Lujiazui sub-district etc. as an example, the vitality value of weekday and weekend as well as 19 indexes including density of functional facilities and building morphology is quantified by obtaining multi-source big data. Meanwhile, the correlation between various indexes and the vitality characteristics of the Central Activities Zone are tried to summarize in this paper. Finally, a neural network regression model is built to bridge the design scheme and vitality values to realize the prediction of the vitality of the Central Activities Zone. The data analysis method proposed in this paper is versatile and efficient, and can be well integrated into the urban big data platform and the City Information Modeling, and provides reliable reference suggestions for the real-time evaluation of future urban construction.

Keywords. Multi-source big data; Central Activities Zone; Vitality; Lujiazui.

1. Introduction

How to enhance the vitality of cities through design is one of the key issues that have long plagued urban scholars. One of the solutions is that introducing the concept of Central Activities Zone (CAZ)in the *Shanghai City Master Plan (2017-2035)* (hereinafter referred to as *Master Plan*)to replace the previous concept of Central Business District (CBD).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 549-558.

The concept of the CAZ first appeared in *the Greater London Plan* in 2004, whose original intention was to solve the problem of lack of vitality in the central area caused by the focus on functional zoning in urban planning. The main functions of the CAZ in the *Master Plan* are defined as "core bearer of global urban functions including highly integrated finance, commerce, business, culture, leisure, tourism and other functional areas." In addition, the *Master Plan* also emphasizes the establishment of a dynamic monitoring and a timely maintenance mechanism for the implementation of the plan to realize the dynamic update. In the context of today's continuous urbanization and high-speed capital flow, how to identify the development status and vitality characteristics of the CAZ is the prerequisite for realizing the dynamic update of the plan. While urban big data and artificial intelligence technology will play an important role in it.

In fact, in the past few years, urban big data has underlain a great number of city researches including CAZ development. LIU Liu et al. (2018)use Point of Interest (POI) data to identify potential CAZ areas in the city, and proposes a method of defining CAZ boundary based on functional blending degree. Based on urban big data and multiple modeling methods, LONG et al. (2014) propose a method to build a refined urban model to support policy formulation. NIU and SONG (2014) use mobile phone data to identify the spatial structure of Shanghai as well as the city's different functional areas and mixed functions. In the research field of urban vitality, in addition to the research on architectural form derived from Jane Jacobs's theory of diversity and vitality, data research has gradually become a more convincing way. Bosselmann (2012) believes that urban vitality can be characterized by crowd flow to a certain extent. On this basis, a method for urban vitality research using real-time crowd flow distribution data from Baidu heat map has been developed in China. Wu and YE (2016) use Baidu heat map to identify the periodic characteristics of Shanghai's population gravity center.

Based on the above background, 8 typical areas are taken in Shanghai such as Lujiazui CAZ as examples, the hourly Baidu heat map data is applied as an explicit representation of the CAZ vitality. Meanwhile, commercial quality data, functional POI, Second-hand house data, geographic data etc. are respectively obtained, on which establishes a total of 19 indexes, the potential correlation between each index and vitality is explored. Finally, a shallow neural network is built to establish a regression model for the 8 most relevant indexes, in order to reveal the relationship between the indexes and the vitality of CAZ, so as to guide future urban design and planning.

2. Methods

Shanghai is a representative megacity in China, and its spatial structure and development mode have been extensively studied worldwide. According to the *Master Plan*, 7 sub-districts in the CAZ are selected including Lujiazui, The Bund, East Nanjing Road, West Nanjing Road, Middle Huaihai Road, Jing'an Temple and Zikawei. Besides, as a traditional CBD, Wujiaochang is a representative area to be selected. Sub-district selection is shown in Figure 1.

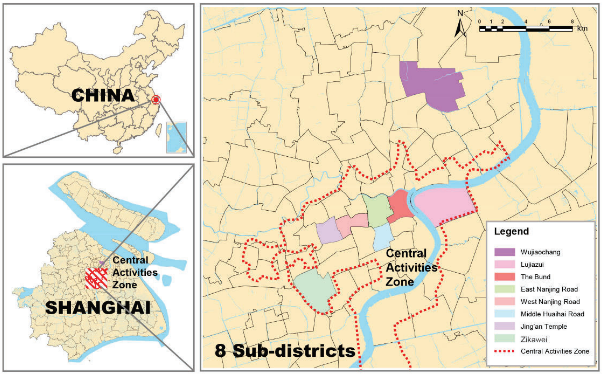


Figure 1. Geographical location of the 8 sub-districts studied.

Multi-source data has been obtained in this study and reliable index calculation and data analysis is conducted on the above 8 sub-districts. Figure 2 shows the data used and the indexes set in this paper, including four types of data: heat map data, functional data, geographic data and street view data respectively sourced from 5 different data platforms. Based on these data, 2 vitality values and 19 multi-dimensional indexes were established, including Commercial Quality Indexes, Housing Conditions Indexes, Functional Facilities Indexes, Morphological Indexes, Perceptible Indexes. Finally, an all-round understanding of the site is achieved, and potential indexes that affecting vitality are explored. The data processing and calculation methods of a series of indexes will be described in detail in this section.

2.1. CALCULATION OF CAZ VITALITY VALUE

Baidu heat map data of Shanghai on weekday (Dec.10, 2020) and weekend (Dec.12, 2020) is downloaded, and the data sampling accuracy is 1h from 7:30 in the morning to 23:30 in the evening, 17 data per day. The cleaned data was imported into ArcGIS software, and the map with coordinates (WGS84 Universal Transverse Mercator Zone51) was used for geographic calibration and processed into vector image. The relative value of the density can only be applied because of the open data source not providing accurate legends. In this study, the vector heat map is classified according to the grid value, and a heat value ranging from 0-1 is defined as the representation of CAZ vitality. It is shown in the Figure 3 that the heat value of Shanghai has been graded by 10 levels of color, and the accuracy of the data can be seen from the figure on the right.

Given that the indexes created in this study are mostly static such as functional facilities and building forms, 17 hourly heat maps of weekend and weekday are superimposed on a 100*100m fishing net and averaged.

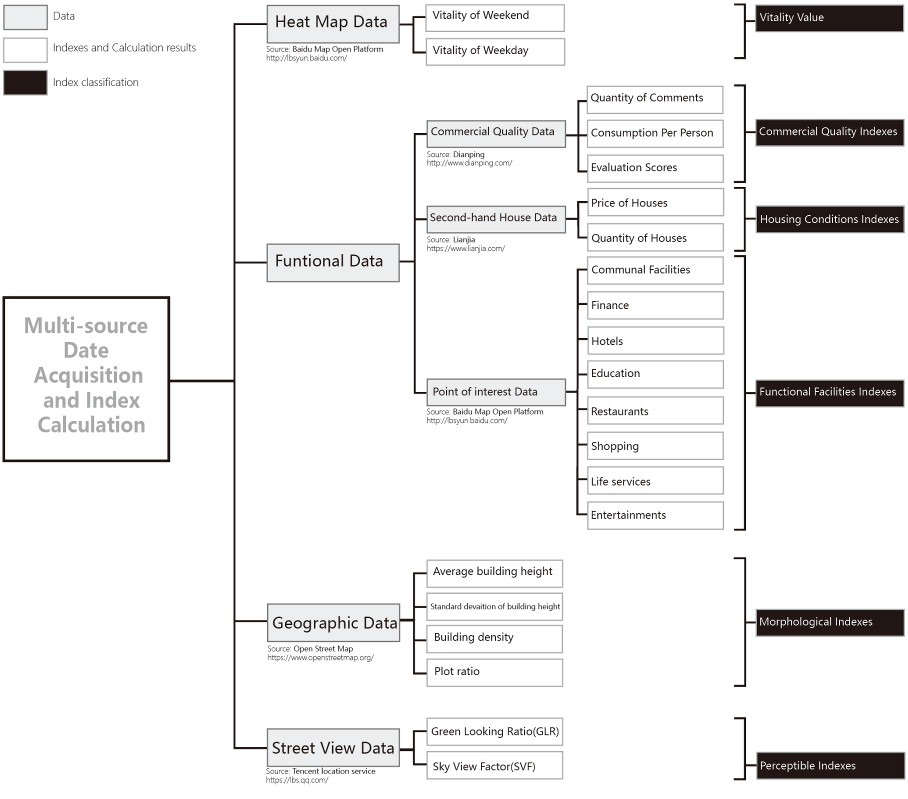


Figure 2. Multi-source data acquisition and index calculation framework.

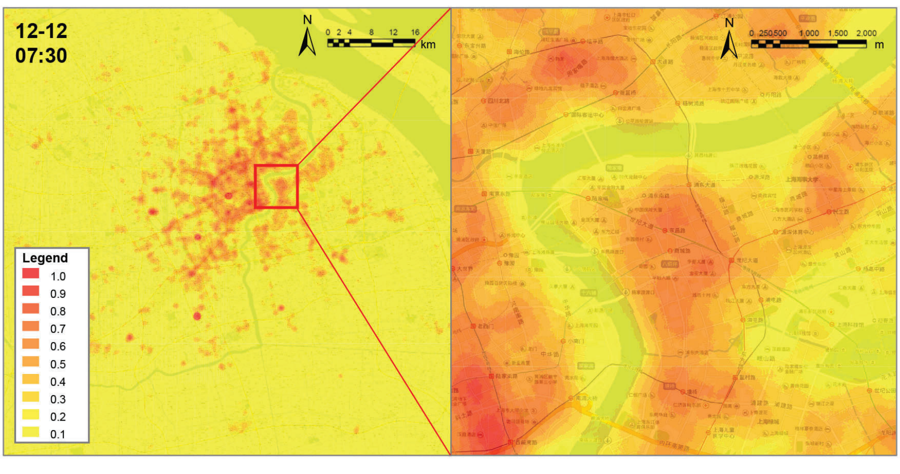


Figure 3. The vector heat map displayed hierarchically by heat value.

2.2. CALCULATION OF FUNCTIONAL INDEXES

The *Master Plan* puts forward comprehensive requirements for the functions of the CAZ. In order to achieve the comprehensive goal from financial business to cultural education to tourism and leisure, commercial quality data (quantity of comments, consumption per person and evaluation scores), second hand house data (price of houses and quantity of houses) and POI data of functions and facilities (communal facilities, finance, hotels, education, restaurants, shopping, life services, entertainments) are obtained by Python respectively from the Dianping, Lianjia and Baidu Map Open Platform.

Similarly, a 100*100m fishing net is used to cut 8 sub-district, counting the number of functional facilities (such as the number of restaurants or the number of entertainment) or the average value of indexes (such as the average value of house prices) on each 100*100m land . The calculated results will be given in Section 3.

2.3. CALCULATION OF MORPHOLOGICAL INDEXES

According to Jane Jacobs's theory, urban form factors such as small-scale compact urban texture, short and winding streets can trigger activities and interactions, which are essential to the formation of a city's diversity and vitality. In fact, by performing spatial and geographic operations on geographic data, more indexes that can describe the urban morphology can be obtained, which allows us to continuously quantify the theoretical results of Jacobs. Based on the geographic data (buildings, roads, etc.) obtained from the Open Street Map combined with ArcGIS software, this study created four morphological parameters to describe cities that have potential effects on urban vitality form. Several basic parameters are determined by the definitions in Figure 5, and the calculation formulas of the morphological indexes are given in Table 1.

Table 1. Equations of morphological indexes.

Building morphology index	symbol	Unit	Equation
Average building height	H_{ave}	m	$H_{ave} = \frac{1}{n}\sum_{i=1}^{n} H_i$
Standard deviation of building height	σ_H	m	$\sigma_H = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_i - H_{ave})^2}$
Building density	λ_P	%	$\lambda_P = (\sum_{i=1}^{n} A_{Pi})/A_T$
Plot ratio	PR		$RP = \sum_{i=1}^{n} A_{Pi} \times F_i / A_T$

In the table above, H_i is the height of the building, n is the number of the building, A_P is the footprint area of the building, A_T is the lot area of the urban lot, F_i is the number of the floor of a building. In this study, the average values of the four morphological indexes for each 100*100m of land for 8 sub-districts are calculated. The results will be given in the Section 3.

2.4. CALCULATION OF PERCEPTIBLE INDEXES

It is assumed that Green Looking Ratio(GLR) and Sky View Factor(SVF) have potential effects on attracting people and enhancing urban vitality, which are defined as perceptible indexes. The reason is that the green of the vegetation in the field of vision plays an important role in regulating people's psychology, which has been proved by many studies. On the other hand, The reason why SVF can be used as an important morphological index is that it has a strong description of urban spatial enclosure. In other words, a space with a higher GLR may cause people to gather; a space with a lower SVF indicates a high degree of spatial enclosure, which conforms to Jacobs's theory that small-scale space may be contribute to the promotion of urban vitality.

A deep learning technique called image semantic segmentation is used in the calculation of these two indexes. A semantic segmentation network SegNet based on VGG-16 net, a convolutional neural network (CNN), is established to classify each pixel in the image to generate a segmented image by category. The street view image is acquired by calculating the center point coordinate parameters of the 100*100m fishing nets of 8 sub-districts from Tencent webservice API of Tencent Location Service.

360-degree street view images are used for stitching and polar coordinate transformation to generate fisheye images. The above network is also used to segment and calculate the proportion of the sky. The calculation results of the two indexes of GLR and SVF will be given in Section 3.

3. Calculation results and analysis

3.1. CALCULATION RESULTS

Figures 4-9 show the calculation results in Section 2 taking Lujiazui as an example, by mining multi-sources of big data, an accurate quantitative understanding of the site can be achieved.

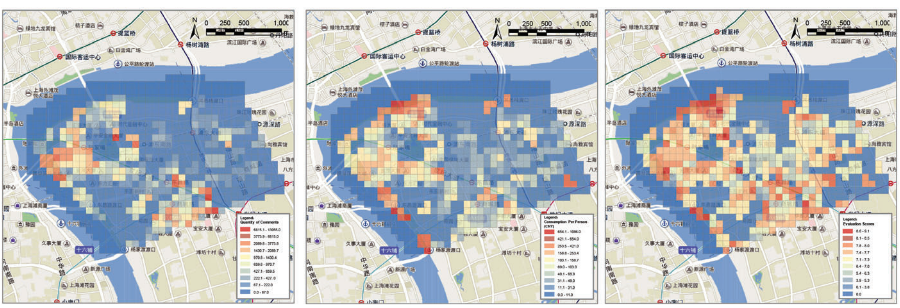


Figure 4. Calculation results of commercial quality indexes of Lujiazui (from left to right are quantity of comments, consumption per person and evaluation scores).

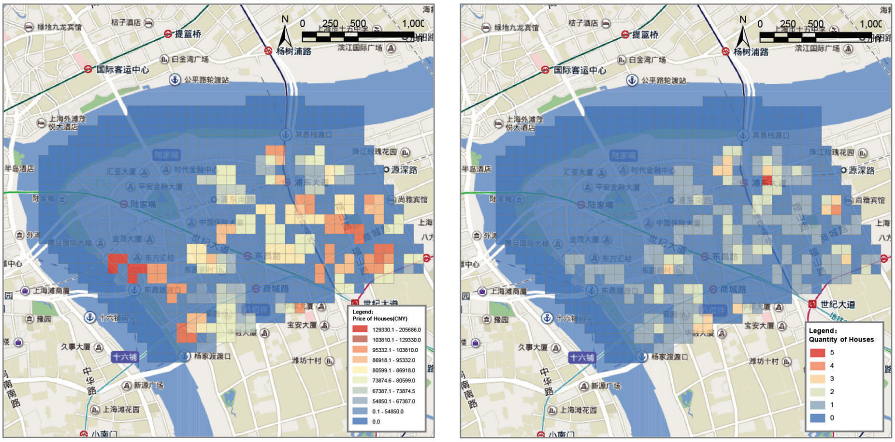


Figure 5. Calculation results of housing conditions indexes of Lujiazui (from left to right are price of houses and quantity of houses).

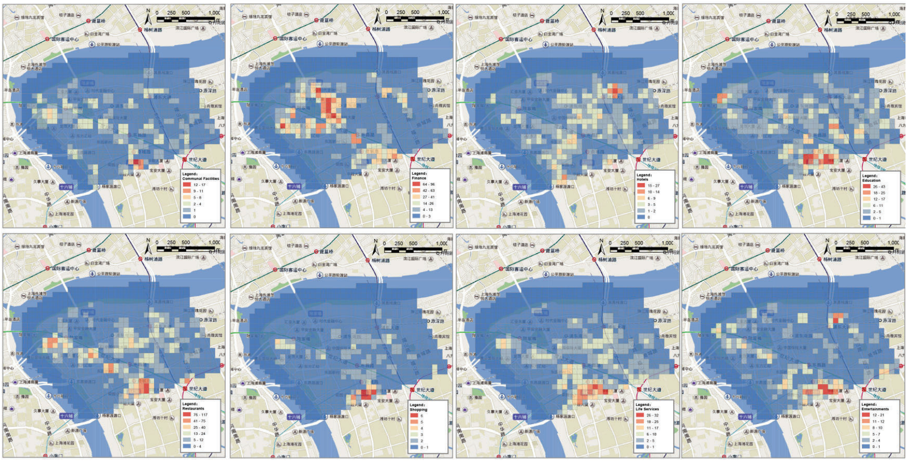


Figure 6. Calculation results of functional facilities indexes of Lujiazui (from top left to bottom right are communal facilities, finance, hotels, education, restaurants, shopping, life services and entertainments).

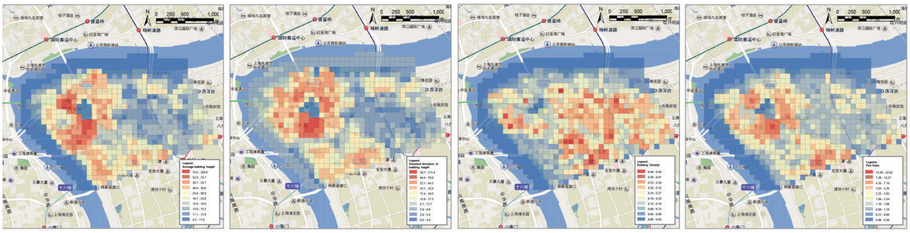


Figure 7. Calculation results of morphological indexes of Lujiazui (from left to right are average building height, standard deviation of building height, building density and plot ratio).

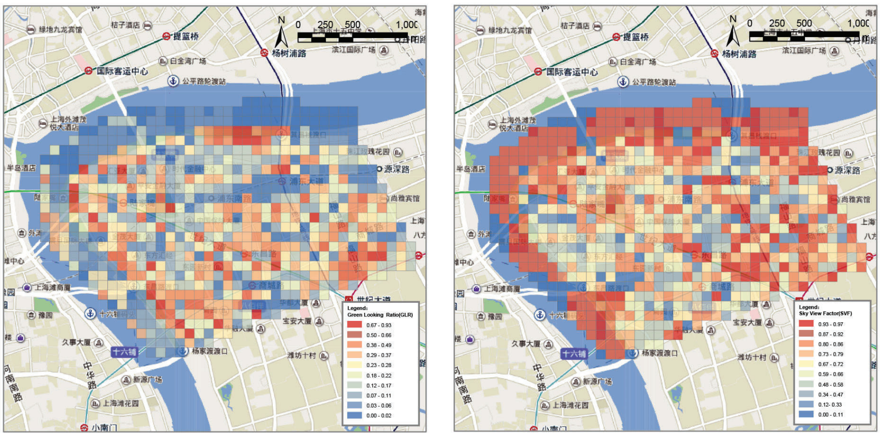


Figure 8. Calculation results of perceptible indexes of Lujiazui (from left to right are GLR and SVF).

East Nanjing Road and other 7 sub-districts are calculated based on the previous method. By counting the average and standard deviation of the indexes of the 8 sites, we can compare CAZ in a quantitative manner. And taking the highly dynamic sub-districts as an positive example, improve the overall vitality of CAZ by means of supplementing functional facilities, optimizing building morphology or improving commercial quality.

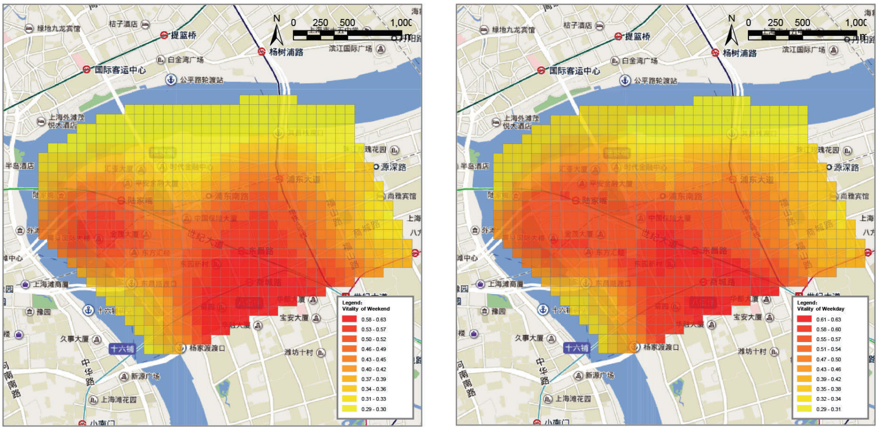


Figure 9. Calculation results of vitality value (from left to right are vitality of weekend and vitality of weekday).

3.2. CORRELATION ANALYSIS

In order to reveal the correlation between various indexes and vitality, correlation analysis was adopted. After preliminary calculation, there is not a linear correlation between the index and the vitality value, so the Spearman method should be used to analyze the correlation of each variable. Spearman correlation coefficient reflects the correlation between index and vitality value. A positive value indicates a positive correlation, and a negative value indicates a negative correlation. The greater the absolute value, the stronger the correlation. Through correlation analysis we can draw some interesting conclusions. The 19 indexes are different from the correlation between the vitality of the weekday and weekend For example, the positive correlation of the quantity of comments on the vitality of the weekday is stronger than that of the vitality of weekend, while life services, shopping and entertainments has a stronger correlation with vitality of weekend. It is also shown that the GLR has a weak influence on the vitality of CAZ and can be ignored. There is a negative correlation between SVF and vitality, which may be because the smaller the SVF, the better the sense of enclosure, which is conducive to the gathering of people and is consistent with empirical judgment.

In order to be able to effectively use the correlation between various indexes and CAZ vitality in future urban design and planning, we selected the eight indexes with the greatest correlation with vitality, and used shallow neural networks to build a regression model to predict the city how the design scheme and planning scheme influence the vitality of CAZ and provide effective support for dynamic planning. They are: plot ratio (ρ=0.528/0.532), building density (ρ=0.439/0.405), entertainments (ρ=0.439/0.426), life services (ρ=0.489/0.470), restaurants (ρ=0.457/0.456), hotels (ρ=0.394/0.404), finance (ρ=0.389/0.427) and quantity of comments(ρ=0.488/0.500).

Using MATLAB Statistics and Machine Learning Toolbox, a shallow neural network is built with 10 hidden layers, 70% of the sample data divided into the training set, 15% for verification, and 15% for independent generalization testing. Levenberg-Marquardt algorithm is used for training. In the entire sample data, the regression effect of the model is acceptable, which is $R^2 = 0.925$. The CAZ vitality prediction model created by using 8 indexes has great application potential. We hope to create an open model for CAZ vitality, which can continuously load new sample data and indexes for dynamic training. Through the way of vitality prediction, the real-time update and dynamic judgment of urban design and planning are forced.

4. Conclusions

With the use of the concept of Central Activities Zone in the *Shanghai City Master Plan (2017-2035)*, core areas such as Shanghai Lujiazui will be given more connotations in the future construction and development. In this study, Baidu heat data is used to characterize the city's vitality, function data, geographic data, and street view data are relatively obtained from several sources, and 19 indexes are established for 8 representative CAZ (or potential) sub-districts at a spatial resolution of 100*100m. Correlation analysis of the calculation results of the indexes yields 8 indexes that are most relevant to CAZ vitality. These indexes are used to build a vitality prediction model. However, the research in this paper is still inadequate, such as the lack of data acquisition and analysis of traffic facilities and traffic usage that may affect the vitality of CAZ. We will do more research and improvement in the future. Using multi-source big data can create a multi-dimensional accurate city portrait of the CAZ area, which is of great significance for comprehensive site identification. This paper not only provides an application method for multi-source big data, but also studies the potential related factors that affect the vitality of CAZ and draws interesting conclusions. The regression model created in this paper will become a tool to improve the disconnect between planning and design solutions and actual results in the foreseeable future and will provide a powerful tool for refined urban governance and dynamic planning.

Acknowledgments: This research was financially supported by Beijing Natural Science Foundation (8202017) and 2018 Beijing municipal university Academic Human Resources Development- youth talent support program (PXM2018_014212_000043)

References

LIU, L. and LIU, Z.Q.: 2018, *The Recognition of CAZ in Shanghai Based on Evaluated POI*, Springer.

LONG, Y., MAO, M.G. and MAO, Q.: 2014, FINE-SCALE URBAN MODELING AND ITS OPPORTUNITIES IN THE "BIG DATA" ERA: METHODS, DATAAND EMPIRICAL STUDIES, *HUMAN GEOGRAPHY*, **29**, 7-13.

NIU, X.Y., DING, L. and SONG, X.D.: 2014, Understanding Urban Spatial Structure of Shanghai Central City Based on Mobile Phone Data, *Urban Planning Forum*, **6**, 61-67.

WU, Z.Q. and YE, Z.N.: 2016, RESEARCH ON URBAN SPATIAL STRUCTURE BASED ON BAIDU HEAT MAP: A CASE STUDY ON THE CENTRAL CITY OF SHANGHAI, *City Planning Review*, **4**, 33-40.

STUDY ON THE DIFFERENCES OF DAY AND NIGHT BEHAVIOR IN URBAN WATERFRONT PUBLIC SPACE BASED ON MULTI-AGENT BEHAVIOR SIMULATION

CHUNXIA YANG[1], CHENGZHE LYU[2], ZIYING YAO[3] and MENGXUAN LIU[4]
[1]*College of Architecture and Urban Planning, Tongji University. Shanghai Key Laboratory of Urban Renewal and Spatial Optimization Technology*
[1]*yang_arch@163.com*
[2,3,4]*College of Architecture and Urban Planning, Tongji University*
[2,3,4]*{sansirorr|yzyyaoziying|liumengxuan93}@163.com*

Abstract. In the 'twenty-four hour city' era, how to optimize public spaces based on night behavior demands to promote full-time use has become a significant issue of urban design. Taking Shanghai North Bund as an example, the study collects data through site survey and questionnaire including environment elements, users' attribute and behaviors. Next, the study sets up the simulation environment and translate the interaction of space and behavior into model language. Then, by setting up agent particles, running and fitting, the study obtains an ideal model. Finally, through sub-simulation and analysis, the study quantitatively explores the interaction mechanism between the physical environment and behavior from three levels of different spaces, different groups of people and different light conditions. The study finds that the differences of day and night behavior are produced under the combined effect of changes in attractiveness of environmental elements and changes in users' demands and preferences. Compared with adults, the behaviors of elderly people and children show more obvious differences between day and night, and are more susceptible to space lighting, ground conditions and operating hours of facilities. Furthermore, the same kind of environment element will further affect users' behavior in the night under different light conditions.

Keywords. Self-Organization Behavior; Behavior Differences; Day and Night; Multi-Agent Behavior Simulation; Waterfront Public Space.

1. Introduction

With the prosperity of night economy, our city has gradually transformed into a 'twenty-four hour city' (Tim, 1997). As the main space for citizens' activities, public space is undergoing significant changes in the proportion of day and night activities carried. Facing an increasing number of nighttime users, the traditional urban public space design guided by daytime behavior can no longer meet the demands. It is imperative to promote the full-time use of urban public space.

In order to promote the full-time use of urban public space, it is necessary to study the differences of users‘ day and night behavior. The study first summarizes the current status of research on urban public space and night behavior, as well as research on multi-agent behavior simulation. Then, the study selects Shanghai North Bund to conduct field surveys, and uses multi-agent behavior simulation technology to establish an ideal model, so as to study the differences of users' day and night behavior and the causes. Based on the analysis, the study diagnoses the space combining the actual situation to provides a foundation for creating a public space that meets the demands of day and night behavior (Figure 1).

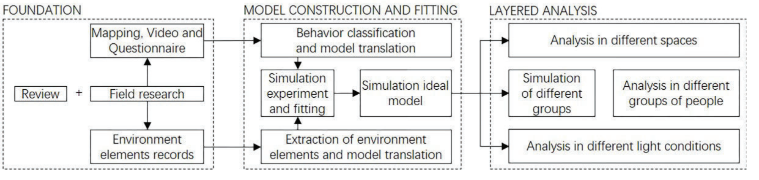


Figure 1. Research framework.

2. Literature review

2.1. RESEARCH ON URBAN PUBLIC SPACE AND NIGHT BEHAVIOR

Scenario-based researches have become a trend. Compared to discussing issues in ideal spaces or large-scale urban spaces, it is more conducive to analyze in depth based on a specific space. In recent years, community streets, streets and squares in commercial districts, and public spaces in urban villages have become important scenarios. Scholars have discussed the safety, walkability and spatial vitality of these urban public spaces at night through methods such as correlation analysis and regression analysis (Lee, 2013; Zhang, 2017). In contrast, research on the waterfront public space and the recreational behavior inside at night is relatively scarce.

The discrepancies of the impact of physical environment elements in day and night are gradually revealed. The diurnal changes in the impact of environmental elements are an important reason for the difference of day and night behavior. Thanks to the development of information technology, scholars have used big data to analyze the diurnal changes in the impact of environmental elements on spatial vitality or individual behavior from the urban morphology level (Wu, 2018; Zhang, 2020). These studies have found some macroscopic environmental elements that have significant diurnal changes in the impact, such as land use, intensity, street network, landscape greening, etc., but have not yet involved microscopic environmental elements.

Researches gradually go deep into the discussion of the particularity of night behavior and its mechanism. Lun analyzed the differences of users' demands and behavior characteristics in day and night from three aspects: demographic structure, perception and behavior. It was found that the psychological feelings, perceptions and behavior characteristics of users in the night are significantly different from those in the day (Lun, 2017). But the research lacked the discussion on the spatial dimension.

2.2. DEVELOPMENT AND APPLICATION OF MULTI-AGENT BEHAVIOR SIMULATION TECHNOLOGY

Multi-agent behavior simulation treats pedestrians as individuals with rational behaviors, which can help researchers analyze the relationship between individual behaviors and the relationship between individual behaviors and environment from a micro dynamic perspective. For example, cellular automata model, social force model, etc. can better realize the simulation of individual path choice, conflict avoidance and other behaviors. On this basis, some simulation software platforms also provide the possibility of secondary development, which helps scholars to optimize the model to meet their research needs (Chen, 2015; Jia, 2017).

In terms of application, the application of multi-agent behavior simulation technology has gradually expanded from the simulation of evacuation behavior in small-scale traffic and building nodes to the simulation of leisure and recreation behavior in large-scale outdoor space research. In recent years, scholars have simulated and predicted behaviors such as leisure walking, recreational viewing, and commercial consumption through statistics and summary of pedestrian travel patterns in different outdoor spaces (Wang, 2017; Kevin, 2019; Sun 2019). In the simulation process, some scholars try to optimize and improve the model to obtain a more suitable ideal model, and use MATLAB to verify the optimized model.

3. Methodology

3.1. SUBJECTS

3.1.1. Site status and environment elements

The study takes Shanghai North Bund as the example which is the key node of the 45-kilometer public space connection project on both sides of the Huangpu River. Compared with some urban public spaces such as squares, parks, and streets, waterfront public space is more complicated because of its special elements such as different height base planes and shorelines. How to extract and sort out complex environment elements will directly affect the effectiveness and accuracy of subsequent simulations. Combining site survey, questionnaire and the overview of researches on waterfront public space elements (Geraldine, 2013; Nihal, Tayfun, Reyhan, 2011), this study sorts out the environment elements of the site into three levels: base planes, facilities and buildings, totaling 18 categories (Figure 2).

3.1.2. Crowd composition and behavior types

The site surveys are conducted on workdays and weekends with clear weather and suitable temperatures in October 2020. At this time, the COVID-19 pandemic in China has been brought under control and citizens' travel has returned to normal. The survey time during the day is 14:00-16:00, at night is 20:00-22:00. In order to obtain user attributes and behavior data, the study adopts multiple methods such as mapping, video recordings, and questionnaires to make up for the incompleteness and limitations of a single method. Mapping marks the user's attributes and behavior in the site plan. The video recordings record gender, group, travel route, distribution status, etc. The questionnaires obtain age, purpose, route, attraction preference, etc. Composition of crowd and behavior are shown in the figure (Figure 3).

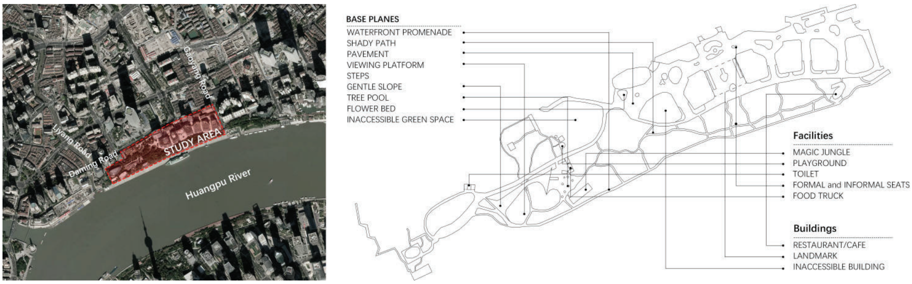


Figure 2. Site location and environment elements.

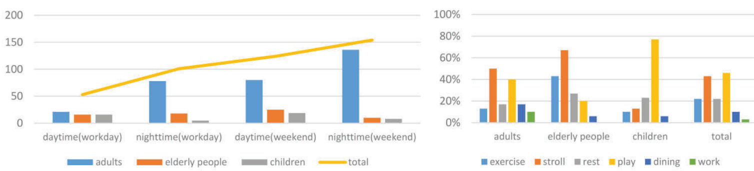


Figure 3. Composition of crowd and behavior.

3.2. SIMULATION METHOD

3.2.1. Translate environment elements into model language

The modeling platform selected in this study is Anylogic 8.6.0 Personal Learning Edition& Professional. In order to obtain a virtual environment model that reflects the real situation, the study divides the extracted environment elements into attractors and basic environment and uses the built-in environment module of the software to translate them (Table 1).

3.2.2. Translate behavior into model language

The study uses the combination of different behavior modules and environmental modules to translate behavior. Through the establishment of space-behavior unit models, the study also observes the dynamic behavior of particles to verify the feasibility of translation. The study translates static leisure behaviors into the PedWait and dynamic leisure behaviors into the PedGoTo, which are also corresponded to the environment elements. For example, rest is translated into PedWait_AreaX and corresponded to formal or informal seats (Figure 4), exercise is translated into PedGoTo_PathwayX and corresponded to various walkways, the outdoor dining behavior is translated into PedWait_AreaX, while the indoor dining behavior is translated into PedSource & PedGoTo+PedSink.

Table 1. Model Translation of Environment Elements.

Classification	Elements	Space Markup
Attractors	restaurant/café, food truck, playground, Magic Jungle, pavement, landmark, viewing platform, toilet	Area
	waterfront promenade, shady path	Target Line
	formal and informal seat	Area + Attractor
Basic Environment	step, gentle slope	Area + Direction
	flower bed, tree pool, inaccessible building, inaccessible green space	Wall

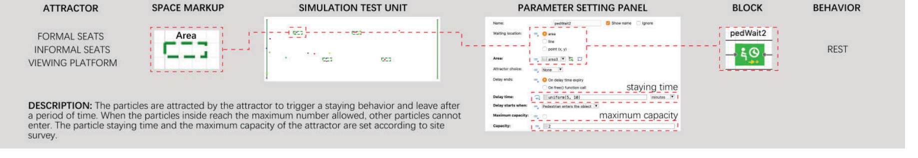


Figure 4. Model translation of rest behavior.

3.2.3. Setting preferences of behavior to environment elements

The preferences of the agent's behavior to environment elements determine to a certain extent the particle's distribution in space and the behavior types that particles conduct. This is also a key step in the study of self-organization behavior from a microscopic perspective. Through the design and distribution of questionnaires, the study enumerates the environmental elements of public space and asks respondents to rate their attractiveness. Through percentage calculations, the preferences of different age groups to different environment elements are obtained, and finally assigned into the model to ensure the initial simulation.

3.3. SIMULATION AND FITTING

On the basis of translation and preferences setting, a preliminary simulation is carried out. During the simulation process, the result of preliminary simulation showed an obvious difference with the actual situation. In order to improve the matching degree, this study uses methods such as adjusting the attractors' parameters, adding fixed routes, etc. For example, considering the actual situation that waterfront promenades are unable to provide shade during the day and users are more willing to choose shady paths to carry out activities, the study adjusts upwards the attractiveness parameter of shady paths and downwards the attractiveness parameter of waterfront promenades in daytime. Considering that some nearby residents have confirmed exercise routes, the study adds fixed routes to guide particles movement in some spaces. Through multiple rounds of parameter adjustment and simulation, there is a high similarity between the simulation results and actual situation.

4. Simulation-based analysis of the differences and their causes of day and night behavior

4.1. ANALYSIS IN DIFFERENT SPACES

At the different spaces level, the study will analyze three spaces with significant differences of day and night behavior (Figure 5).

Figure 5. Simulation diagrams of day and night behavior in three spaces.

SPACE 1 is the central square which connects the entrance in the north and the waterfront promenade. The types of behavior are mostly play, rest, stroll, exercise and dining. Through the simulation, the study finds that the activity intensity in this space is greatly reduced after entering nighttime. In the process of time conversion, the changes in the function of some environment elements and the changes in the space light conditions are the main reasons that affect the above problem. Taking food trucks, playground and Magic Jungle as examples, these elements have a strong attraction to dining and play behavior of adults and children during the day. After entering nighttime, affected by business hours, these environment elements gradually lose their original functions, becoming inaccessible for users, and eventually leading to the disappearance of some types of behavior around them. In addition, due to the lack of lighting facilities, SPACE 1 is relatively dim at night, which is not conducive for users to carry out activities.

SPACE 2 includes two main spaces which are the shady path and the waterfront promenade. These two spaces are important activity spaces running through the east and west sides of the site. The types of behavior are mostly stroll, view, rest, exercise and dining. Through simulation, the study finds that the two spaces exhibited diametrically opposite behavior intensity during day and night. In the process of time conversion, the changes in the attractiveness of some environment elements and the changes in the light conditions are the main reasons that affect the above issue. The plants on both sides of the shady path are not only good visual attractions in daytime, but also can play a role in shade, which make the shady path more attractive. After entering nighttime, the attractiveness of the lush greenery is greatly reduced in the artificial lighting condition, which not only becomes an obstacle for users to watch the scenery on the other side of the Huangpu River, but also restricts the space more closed and narrower. At this time, in contrast, the waterfront promenade attracts more users because of its good view, bright environment and pleasant scale. It should be noted that the increase in activity intensity will also bring about the problem of congestion. Through simulation, it is found that whether it is the shady path in daytime or the waterfront promenade in nighttime, there are varying degrees of congestion in places with dense attractions. The problems that are prone to occur in this kind of linear space can be alleviated by adding open space nodes around the attraction point.

SPACE 3 is enclosed by the office buildings and connects with the entrance in the north. The types of behavior are mostly stroll and exercise. Through simulation, the study finds that although the activity intensity of this space has been greatly increased after entering nighttime, only a few adults and elderly people carry out exercise here, most people just walk through. Being able to attract people but not being able to retain them is the most obvious problem in this space at night. Compared with other spaces, the base plane here is dominated by hard pavement and lacks changes in both the horizontal and vertical directions, which make the space homogeneous and boring. In addition, the office buildings not only restrict users‘ possibility of communicating with the interior space by setting the closed facades, but also uses transparent materials and indoor lighting to turn the ground floor space into a bright and boring box. These make the ground floor space unable to become a functional place that can be stepped into, nor do them have the value of viewing from outside. To a certain extent, the closed ground floor spaces also lead to the lack of functional facilities, which further affect users' behavior.

4.2. ANALYSIS IN DIFFERENET GROUPS OF PEOPLE

Based on the ideal model, the study conducts sub-simulations on three age groups (Figure 6), and accurately analyzes the impact of environment elements on the behavior of people at different ages by exporting the simulation results (Table 2). In the sub-simulation, the study defines the number of particles at each entrance based on the pedestrian flow data obtained from the site survey, and defines the particle parameters of each age group based on the literature research (Hu, 2016) and the site survey.

Sub-simulation of the adults. During daytime, the behaviors of adults are mainly play and stroll, accompanied by a certain amount of dining. At this time, adults are mainly distributed in the central square and shady paths. During nighttime, the behaviors of adults are mainly stroll, exercise, view and dining. At this time, the distribution is more scattered, but there is a certain agglomeration on the waterfront promenade and its vicinity. Compared with other age groups, the behavior distribution of adults appears to be more discrete and random, especially at night, which shows that the attractiveness threshold of environment elements required by adults to conduct behaviors is lower. Adults are more adaptable to space. In terms of behavior distribution, it is similar between day and night, and only differs in activity intensity. In terms of behavior demands, adults show stronger demands for play in the day, and stronger demands for dining and viewing cultural landscapes in the night, which are also reflected in the changes in the attractiveness of environment elements in day and night.

Table 2. Comparison of the impact of environment elements.

		restaurant/cafe	food truck	toilet	Magic Jungle	playground	waterfront promenade	shady path	pavement	viewing platform	seat	landmark
Adults	daytime	0.04	0.10	0.04	0.05	0.09	0.09	0.32	0.04	0.10	0.07	0.05
	nighttime	0.19	0.01	0.04	0.01	0.01	0.38	0.07	0.02	0.05	0.06	0.17
Elderly people	daytime	0.04	0.08	0.06	0.04	0.03	0.10	0.38	0.04	0.09	0.09	0.06
	nighttime	0.14	0.01	0.05	0.01	0.01	0.37	0.07	0.02	0.05	0.07	0.16
Children	daytime	0.03	0.10	0.03	0.05	0.15	0.07	0.31	0.03	0.09	0.09	0.04
	nighttime	0.17	0.01	0.04	0.01	0.02	0.42	0.03	0.02	0.05	0.05	0.18

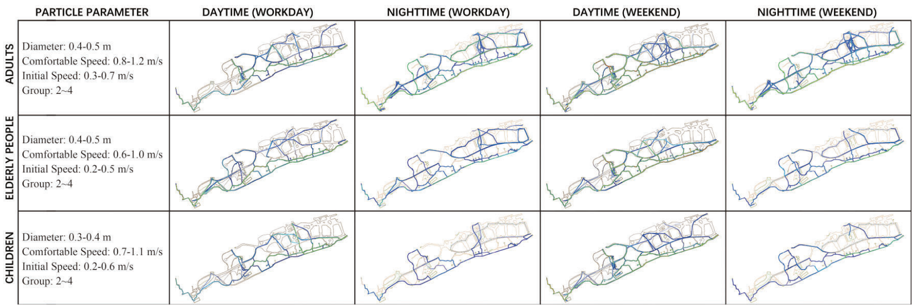


Figure 6. Particle parameters and sub-simulation results of different groups.

Sub-simulation of elderly people. During daytime, elderly people's activities are mainly distributed in shady paths and its vicinity, and the behavior types are mainly exercise, stroll and rest. At this time, shady paths and seats are more attractive to elderly people than adults and children. During nighttime, elderly people's activities are mainly distributed in the waterfront promenade and its vicinity, and the behavior types are mainly stroll, rest and exercise. Through the comparison with other age groups, it is found that the types of elderly people's behavior is relatively fewer. Stroll and exercise are the main types of elderly people's behaviors. In addition, the distribution of behaviors of elderly people at night is significantly reduced compared with that during the day, which is mainly reflected in areas with variable base heights and dim lights. This shows that elderly people have more stringent requirements for the night environment, especially the ground and lighting conditions. Elderly people are more inclined to perform activities in open, flat and bright spaces at night.

Sub-simulation of children. During daytime, children's activities are mainly distributed in the north entrance, the central square and shady paths, and the behavior type is mainly play. Environment elements as playground, food truck, etc. show a higher attraction to children in this time. After entering nighttime, the number of children has been greatly reduced, and their distribution has a higher correlation with adults. The main type of behavior is still play. During the day, children can actively choose venues to play; but in the night, affected by the closure of amusement facilities, children passively follow their caregivers and conduct activities around them. For example, when parents are dining in a restaurant or resting on a seat, children play within the visible range. In general, the current public space is not so child-friendly in the night. In the future, it can be improved by extending the operating time of amusement facilities and adding more amusement facilities in places where adults can easily rest.

4.3. ANALYSIS IN DIFFERENT LIGHT CONDITIONS

Among light environment indicators, illuminance and color temperature are important factors that affect users' behavior (Davoudian, 2020). In order to analyze the impact of different light conditions, the study selected 13 formal seats installed in the same space type (shady paths) but under different light conditions to compare their attractiveness (Table 3).

Table 3. Comparison of the attraction of seats in different light conditions.

	seat attraction in different light conditions			
	high illumination high color temperature	high illumination low color temperature	low illumination high color temperature	low illumination low color temperature
adults	0.15	0.11	0.05	0.12
elderly people	0.18	0.16	0.04	0.09
children	0.16	0.11	0.06	0.12

Focusing on the illuminance, high illuminance environment is always more attractive to the people of different ages, especially to elderly people. Combined with the actual situation of the crowd's ability to move and perceive, elderly people need a higher illuminance to help them identify environment elements, assist decision-making, and obtain a sense of psychological security. In contrast, adults and children need less illuminance thresholds to identify environment elements and obtain a sense of psychological security than elderly people. Focusing on the color temperature, in a high illumination environment, environment elements with a high color temperature is easier to attract users than that with a low color temperature environment. However, in a low illumination environment, the results are just reversed. Combined with analysis of people of different ages, adults and children are more sensitive to color temperature changes under different illuminances, and are more likely to make corresponding behavioral responses, while elderly people are slightly slower to color temperature changes. For elderly people, it is most important to ensure basic environment illumination.

5. Summary

Research on the difference of day and night behavior in public space and its causes is an important proposition for the study of urban spatial-temporal behavior, and it is also the theoretical basis for promoting the full-time use of urban public space. With the help of multi-agent behavior simulation technology, the study can present the self-organization behavior rule behind the complex environment in a more in-depth humanistic and dynamic perspective, and reveal the logic behind the differences. The study makes up for the lack of microscopic perspective in the refined research of urban issues, provides a bottom-up design basis for the renewal and transformation of urban public spaces, and provides the possibility for the prediction of behavior after the renewal and transformation. It should be pointed out that the process of using multi-agent behavior simulation models to study urban space problems is a process of using digital technology to analyze the interaction between behavior and the environment. Its essence is a layered analysis and discussion of the environment, individual behavior and the logic of their interaction. In future research, with the deepening of the understanding of the interaction between behavior and space, this research trend of combining analysis and practice will be promoted to develop in a more precise and in-depth direction. For example, consider the influence of group effects and social culture on behavior at the environment level, and continue to expand the influence of psychological perception on behavior at the individual level.

Acknowledgement

This research was sponsored by the Open Subject (2020010203) of Shanghai Key Laboratory of Urban Renewal and Spatial Optimization Technology, also supported by the 'Research on the Vitality Reshaping of Urban Waterfront Renewal Area-Based on Multi-agent Behavior Simulation' project.

References

Chen, Y.Y., Chen, N., Wang, Y. and Feng, G.C.: 2015, A Cellular Automata Model Considering Attractive Incidents, *Journal of Transportation Systems Engineering and Information Technology*, **15(03)**, 56-63, 88.

Davoudian, N. and Mansouri, A.A.: 2020, Does Street Lighting Affect Pedestrian Behavior at Night?, *PROCEEDINGS OF CIE 2016 LIGHTING QUALITY AND ENERGY EFFICIENCY*, 588-595.

Geraldine, K.: 2013, Port of Los Angeles, *Inbound Logistics*, **32(1)**, 462-462.

Hu, M.W. and Huang, W.K.: 2016, *Methods and Techniques of Behavior Simulation*, Tsinghua University press.

Jia, X.L.: 2017, *Simulation study on the evading and surpassing behavior of pedestrians in walking facilities with obstacles*, Master's Thesis, Beijing Jiaotong University.

Kevin, M., Matthias, B., Felix, K. and Silvia, T.: 2019, Nearby outdoor recreation modelling: an agent-based approach, *Urban Forestry & Urban Greening*, **2019(40)**, 286-298.

Lee, S.J.: 2013, A Study on the Effect of Improving Road Space Environment on Walking Satisfaction at Night, *Journal of recreation and landscape*, **7(02)**, 53-59.

Lun, K.X.: 2017, *Study on the Correlation between Population Activity and Time in Commercial Leisure Space*, Master's Thesis, Shenzhen University.

Nihal, S., Tayfun, S. and Reyhan, Y.: 2011, A Comparative Investigation of Spatial Organization and Industrial Location Interaction in Context of the Automotive Industry, *Gazi University Journal of Science*, **24(3)**, 573-584.

Sun, H.L.: 2019, *Research on Microscopic Traffic of Pedestrians and Simulation in Living Street*, Master's Thesis, Changan University.

Tim, H.: 1997, The twenty-four hour city concept—A review of initiatives in British cities, *Journal of Urban Design*, **2(2)**, 193-204.

Wang, Z.Z.: 2017, *Walking space design strategies based on pedestrian simulation: a case study of Chongqing Nanqiao district*, Master's Thesis, Harbin Institute of Technology.

Wu, C., Ye, X. and Ren, F.: 2018, Check-in behavior and spatio-temporal vibrancy: An exploratory analysis in Shenzhen, China, *Cities*, **77(July)**, 104-116.

Zhang, L.H.: 2017, *Research on Optimal Design of Night Public Space in Shenzhen Urban Village: a case study of XiaSha Village*, Master's Thesis, Shenzhen University.

Zhang, A., Li, W. and Wu, J.: 2020, How can the urban landscape affect urban vitality at the street block level? A case study of 15 metropolises in China, *ENVIRONMENT AND PLANNING B-URBAN ANALYTICS AND CITY SCIENCE*.

PREDICTING THE HEAT MAP OF STREET VENDORS FROM PEDESTRIAN FLOW THROUGH MACHINE LEARNING

XINYUE SHOU[1], PINYANG CHEN[2] and HAO ZHENG[3]
[1]*Bartlett School of Architecture, University College London, London, UK*
[1]*xinyue.shou.20@ucl.ac.uk*
[2]*Graduate School of Design, Harvard University, Boston, USA*
[2]*pinyangchen@gsd.harvard.edu*
[3]*School of Design, Shanghai Jiao Tong University, Shanghai, China*
[3]*zhhao@design.upenn.edu*

Abstract. Street vending is a recent policy advocated by city governments to support small and intermediate businesses in the post-pandemic period in China. Street vendors select their locations primarily based on their intuitions about the surrounding environment; they temporarily occupy popular locations that benefit their business. Taking the city of Chengdu as an example, this study aims to formulate the rules governing vendors‘ location selection using machine learning and big data analysis techniques, thus identifying streets likely to become vital street markets. We propose a semantic segmentation method to construct heat maps that visualize and quantify the distribution of street vendors and pedestrians on public urban streets. The image-based generative adversarial network (GAN) is then trained to predict the vendors’ heat maps from the pedestrians‘ heat map, finding the relationship between the locations of the vendors and the pedestrians. Our successful prediction of the vendors’ locations highlights machine learning techniques‘ ability to quantify experience-based decision strategies. Moreover, suggesting potential marketing locations to vendors could help increase cities’ vitality.

Keywords. Machine Learning; Big Data Analysis; Semantic Segmentation; Generative Adversarial Networks.

1. Introduction

1.1. RESEARCH BACKGROUND

Street vending has become a common phenomenon in China as the country’s urbanization process has progressed. For the last few decades, vendors’ occupation of the streets has been considered illegal or informal. However, despite administrative opposition, street vending is still a prevalent phenomenon. Some scholars have pointed out the inevitability of their existence in the cities. S. Sassen suggested that vendors are a part of the informal urban economy, which is beneficial for small and intermediate businesses to adapt to the ever-increasing

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 569-578.

living cost in global cities (Sassen 1991). Street vending is a way of temporarily using urban public space, and vendors can become urban catalysts (Oswalt, Overmeyer et al. 2011) that serve as secondary diversity (Jacobs 2016) and even create urban "soft edges" (Gehl 2013).

The pro-street economic policies in the post-pandemic era, supported by Chengdu's government, is a strategy to recover the economic loss of the small-and-intermediate, self-employed economy. Streets are the primary and most essential components of the public realm, and the inclusiveness of vendors and street activities show the robustness of the urban public life and is a crucial measure of civilization (Kuntsler 1996). Popularity is a direct manifestation of the street vitality. The street vendors' location choices strongly correlate with the distribution of pedestrian flows.

1.2. LITERATURE REVIEW

Previous research has analyzed street vendors as a component of the informal economy in global cities (Sassen 1991). Street vendor location selection strategies have similarities with small retail businesses. Although the big data approach has been widely used in the business location selection process in recent years, few scholars have used information technologies to analyze street vendors' location selection decisions considering their unique selling strategies.

Heat mapping is a visualization method for geographical analysis that is widely used in quantitative and qualitative analyses in spatial planning and urban studies. The technique has contributed to the understanding of property prices (Elser 2011), crime rates (Sandig, Somoba et al. 2013), traffic planning (Hilton, Horan, et al. 2011), the spatial-temporal characteristics of bus travel (Yu and He 2017), and many other phenomena.

Machine learning builds on traditional big data analysis approaches by using input data and algorithms to estimate unknown future results. The technique learns from data to provide data-driven insights, decisions, and predictions. As inter-correlation does not impact machine learning approaches, machine learning can make better use of the full extent of available data (Reades, De Souza et al. 2019). Among machine learning models, the generative adversarial network (GAN) is a deep learning network that consists of a generator and a discriminator (Goodfellow, Pouget-Abadie et al. 2014). GAN aims to model natural image distribution by forcing the generated samples to be indistinguishable from natural images, which enables the network to learn and generate higher-order features (Schmidhuber 2015).

Since extensive data about human society is increasingly accessible, GAN is now applied to analyze many image-based data in the architecture and urban design realm. Shen et al. (2020) trained a dataset to predict the architectural filling on urban plan drawings based on color-labeled roads, green land, rivers, and other empty space elements. Huang and Zheng (2018) applied GAN to recognize and generate apartment plan drawings by assigning a unique color label to each room type.

1.3. PROBLEM STATEMENT

Previous site selection approaches by on-site observation and big data extraction and analysis rely heavily on researchers' empirical understandings and subjective judgments and can only yield analyses of sites. These approaches can predict neither the patterns governing vendors' location selection nor the distribution on sites with similar features as the analyzed sites. Moreover, on-site observation and recording are limited in their ability to summarize all the spatial and demographic features that affect street vendors' decisions.

Although big data approaches enable researchers to deduce street vendor location selection and distribution based on various factors, their predictive power is restricted by the human capability for data analysis. The processes of big data and simple linear regression analysis also involve a substantial amount of empirical presumption when seeking correlations between population distribution and street vendors.

Each of the aforementioned methods can only make a "best guess" about the existing data for which the analysis is valid. In the urban design and planning realm, a "best guess" is not enough. The full probability density distribution for a new prediction is of major interest. Machine learning provides a way to derive semantic understanding from the collected data.

1.4. PROJECT GOAL

This paper proposes a machine learning method to predict vendor distribution patterns with the input of pedestrian distribution heat maps along urban public streets in Chengdu, China. We paired pedestrian distribution heat maps with street vendor heat maps to train datasets for image-to-image translation by pix2pixHD (Isola, Zhu et al. 2017), a GAN-based neural network. Our ultimate goal is to create an app that recommends street vendor sites (Figure 1).

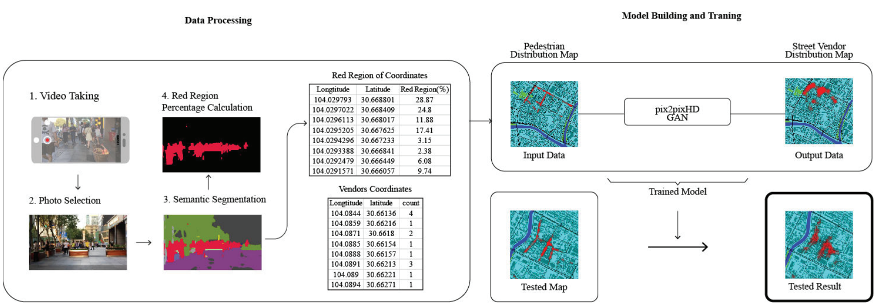


Figure 1. The overview of the workflow.

2. Methodology

2.1. STUDY AREA

In this study, we chose Chengdu, China as the study area. In the post-pandemic era in China, Chengdu was among the first cities to encourage street vending to recover the economic losses of small-and-intermediate, self-employed businesses. In order to collect the data for the distribution of the vendors and pedestrians, we conducted a street survey from 15 July, 2020 to 30 August, 2020, from 6:00 p.m. to 8:00 p.m. Beijing Time. Rainy days are excluded from our street survey. In the summer in Chengdu, most street vending occurred in the evening. During the period from 6 p.m. to 8 p.m., the number of vendors usually reaches its daily peak. This period's real-time pedestrian flow data has the best correlation with street vendor distribution patterns.

2.2. VENDOR SITE DATA COLLECTION

During the one and half period of time of on-site observation, we explored eight areas of the city. The potential trained and tested sites were selected according to the following criteria: 1) The sites that we chose for creating training datasets were relatively dense in population, and the sites attracted a certain number of vendors every evening. 2) The tested sites and the trained sites had to have similar features. 3) Most sites were located in residential areas with a mixture of (or next to) at least two types of functions 4) The regions were selected primarily based on the organization of main urban arterial roads. Each research region was bounded by at least three arterial roads. Finally, four regions were selected as representative sites for training data, and two regions were selected for testing data.

We used a six-foot geo-coordinate positioning and recording mobile phone application to record the location of every street vendor that we observed during the on-site research period. The latitude and longitude coordinates of every street vendor we observed were recorded on the sites based on the GCJ-02 coordinate system. Vendors clustered within 3 meters were considered to be at the same geo-coordinate.

2.3. PEDESTRIAN FLOW DATA COLLECTION

Population heat maps can show the agglomeration patterns and density distribution of populations. Some mapping software, such as Baidu Maps, AMaps, and Google Maps, provides real-time heat maps by obtaining geographic location information from mobile phone users‘ locations. However, the data collected by smartphone users' locations do not distinguish between people in private and public spaces, in cars, and out on the streets. Also, population data collected within some semi-private building compounds such as residential blocks, schools, and governmental buildings are considered invalid, as street vendors are not allowed to enter those spaces. Apart from that, the data collected by smartphone users‘ locations may cause data bias. The number of smartphones cannot accurately reflect the population, as not all people bring smartphones with them on the street all the time, and many people may turn off their phones' location function. This is especially true in some old residential blocks, which overlap significantly with the areas covered by this study.

Therefore, we constructed heat maps that reflect the distribution of pedestrian flow on the urban public streets as real-time data. We propose a semantic segmentation method to construct heat maps to visualize and quantify the distribution of street vendors and pedestrians on urban public streets. We applied the pyramid scene parsing network (PSPNet), a deep neural network model trained with the Cityscape dataset, to segment street images (Zhao, Shi et al. 2017). PSPNet incorporates suitable global and local features, assigning each pixel in an image a category label. A single PSPNet yields the mIoU accuracy 80.2% on Cityscapes. In our study, we aim to predict the percentage of pedestrian pixels in input images.

We used video recordings to collect pedestrian flow data along each observed street. The street was regarded as lines or polylines. We recorded the latitude and longitude coordinates of the start and end points of each segment. The videos were exported as a series of static images. As we attempted to maintain a constant walking speed, the images may be regarded as evenly distributed on each section of the streets. Five hundred photographs were generated approximately every 8 meters. A single photo that could best represent the population density at its geo-coordinate was chosen for the semantic segmentation process. The population density was calculated based on the proportion of color blocks of pixels recognized as people within the entire picture (Figure 2).

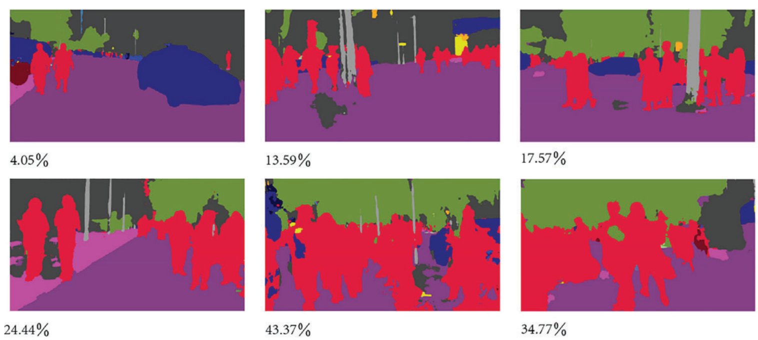


Figure 2. Percentage of people by results of semantic segmentation.

2.4. HEAT MAPPING

After the data was collected, the heat mapping process followed three parts: 1) The selected pictures were marked with a coordinate based on the GCJ-02 coordinate system. 2) We used the Amap API to create heat maps. AMap is a provider of digital map content, navigation, and location service solutions in China. AMap and the recording app are both based on the GCJ-02 coordinate system. 3) We used the AMap API to create user-defined map styles and add heat map layers from user data.

A labeling rule (Figure 3) was created to label five types of regional surfaces in the map: land, street, building, waterway, and green space. We established a clear differentiation in either G or B values between each pair of regional surface types so that the machine could recognize and distinguish them more accurately.

Regional Surface	RGB values R	G	B	Hex	Opac-ity	
Land	0	255	255	#00B4B4	100%	
Green Space	0	255	0	#00FF00	100%	
Highway/Road	0	0	0	#000000	100%	
Building	0	128	128	#005050	100%	
Water System	0	0	255	#0000FF	100%	

Figure 3. Heatmap color labeling principles.

The value in the R channel in all regional surfaces was 0, representing the heat maps. The legend bars show the corresponding relationship between the R value and the density of pedestrian flow and vendor distribution. The pedestrian and street vendor distribution heat maps of each block covered the same geographical region, and the paired images were unified to the same size. All the testing images were cut into smaller sections of 400×400 pixels. Then, 4,606 pictures were generated and marked in sequence. The input images showed the heatmap of pedestrians, and the output images showed the heatmap of the vendors (Figure 4).

Input Image - Pedestrian Flow Heat Map

Output Image - Vendor Distribution Heat Map

Figure 4. Heat map for training at Yulin District.

2.5. MODEL TRAINING

With the training dataset, we applied pix2pixHD (Isola, Zhu et al. 2017) to train the GAN model. There are two neural networks in GAN, the generator and the discriminator. The generator attempts to output fake images to cheat the discriminator, while the discriminator is trained to distinguish the fake images.

The pix2pixHD method is a conditional GAN framework for image-to-image translation. It consists of a generator G, which translates semantic label maps to realistic-looking images; and a discriminator D, which distinguishes real images from the translated ones. It contains a coarse-to-fine generator, a multi-scale discriminator, and a robust adversarial learning objective function. The training process was completed on a computer with a GeForce RTX 2060 Graphics Card.

The loss values of the generator and discriminator were recorded during the training process. Figure 5 compares the loss values of the two models. The training is a process in which the generator and discriminator "compete" with each other. When the discriminator loss value is higher, the generator loss value is lower. This changing trend proves the accurateness of the training results.

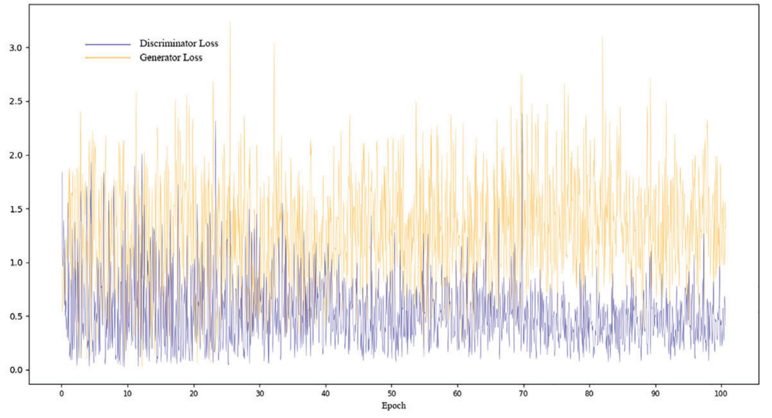


Figure 5. Loss values of Pix2pixHD training.

3. Results

3.1. TRAINING ACCURACY

The network went through all 4,916 pictures during every epoch. After one epoch of training, a representative input image was sent to the neural network. We could determine the completeness of the training by the output image.

Figure 6 shows the image pairs in each training epoch for the training model. We compared the synthesized images of epochs 18, 44, 90, and 100 with their ground truth images. At the beginning of training, the synthesized images produced inaccurate prediction results at a higher rate. In epoch 100, inaccuracies still occurred occasionally, but the output images showed the changing pattern from input images to the ground truth images. Thus, we decided to stop training at epoch 100 for the prediction of street vendor distribution heat maps.

3.2. VENDOR SITE PREDICTION

Figure 7 shows the predicted heatmap of vendor sites in other areas in Chengdu. We collected the pedestrian's heatmap as the input to the neural network and provided suggestions of the site choice based on the output vendors' heatmap.

The generated maps show that, in most cases, points with high pedestrian density and multi-section intersections can attract more street vendors. However, the trained results show a similar pattern as the input data in that the density of vendors and the density of pedestrian flow did not have an accurate positive correlation. Streets with a continuous flow of people tended to have a high density of street vendors. In the trained dataset, about four sites had a high pedestrian flow density but a low density of street vendors. Approximately three sites with low pedestrian flow density attracted street vendors. However, in the test result, no input images without pedestrian distribution (with a number in the R channel) produced a result with vendor distribution.

On the streets where street markets can be formed, the density of vendors at both ends of a street was not significantly high in our model's predictions. Vendors were more concentrated in the middle of the street in places with a higher density of pedestrians. In contrast, on the streets where pedestrian flow density was relatively low, street vendors were more likely to sell at the junction of the road. This is probably because these places have a higher visibility rate.

The results of this study did not reflect the direct impact of road width and building texture on the distribution of mobile vendors. However, we believe that there is a certain correlation between the density of pedestrian flow and road level. Secondary roads are considered more walkable than main urban arteries but also have a higher pedestrian flow density than tertiary and quaternary streets.

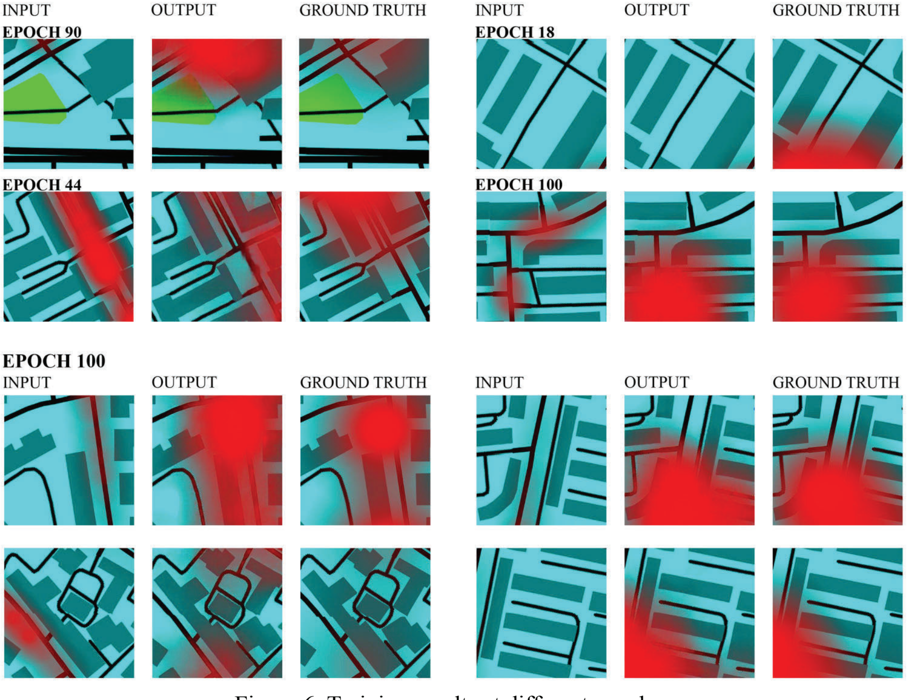


Figure 6. Training results at different epochs.

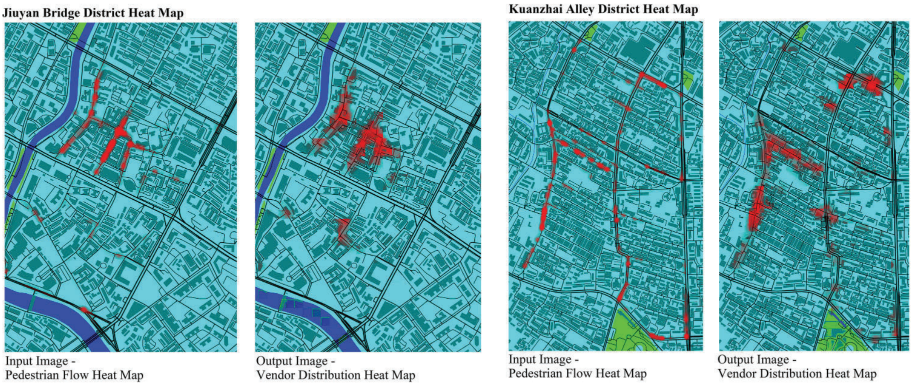


Figure 7. Testing results for predicting the vendors' site heatmap.

4. Conclusion and Discussion

Our machine learning model successfully predicts the heatmap of vendor sites based on the pedestrian heatmap. The successful prediction of vendor location highlights the ability of machine learning techniques to quantify experience-based decision strategies. In the future, we aim to create an App that can display larger scale vendor-site prediction heatmaps based on our proposed methodology. This APP is not only used as a positioning software, but it also entails social meanings: While it guides street vendors of site selection, it can also attract residents to that place. Suggesting additional marketing locations to vendors could help increase urban vitality. Futural urban design needs to take the former 'informal' economy into equal account as other economic sectors. The mapping could also provide designers and decision-makers data support to make a more inclusive city, and our research can largely prevent data biases caused by some data sources.

The question of whether vendors belong to urban spaces reduces to another question: how citizens make use of public space and how much they are willing to stay outdoors for street activities. This study can only illustrate where vendors are likely to stay mainly based on population flow, but the underlying reasons why people are willing to stay at specific locations cannot be explained without considering other socioeconomic conditions. The analysis of streetside behavior is also related to micro urban features, neighborhood dynamics, and the richness and types of nearby POI, etc. Therefore, more indicators should be added to the research to improve the accuracy of the forecasted results for future research.

This study used a labor-intensive method to collect the data due to the current inadequate street view image data from the pedestrian perspective. The cityscape dataset, which is based on street views taken in several European cities, may cause a mismatch with China's second-tier cities, including Chengdu. The better functioning of our App relies on real-time site-specific street view image data and the combination with other data sources from relevant location-based systems.

References

Elser, J.: 2011, *System and methods for comparing real properties for purchase and for generating heat maps to aid in identifying price anomalies of such real properties*, Google Patents.

Gehl, J.: 2013, *Cities for people*, Island press.

Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A. and Bengio, Y.: 2014, Generative adversarial nets, *Advances in neural information processing systems*, **2014**, 2672-2680.

Hilton, B. N., Horan, T. A., Burkhard, R. and Schooley, B.: 2011, SafeRoadMaps: Communication of location and density of traffic fatalities through spatial visualization and heat map analysis, *Information Visualization*, **10(1)**, 82-96.

Huang, W. and Zheng, H.: 2018, Architectural Drawings Recognition and Generation through Machine Learning, *ACADIA 2018*, Mexico City, Mexico, 156-165.

Isola, P., Zhu, J. Y., Zhou, T. and Efros, A. A.: 2017, Image-to-image translation with conditional adversarial networks, *Proceedings of the IEEE conference on computer vision and pattern recognition*, 1125-1134.

Jacobs, J.: 2016, *The death and life of great American cities*, Vintage.

Kuntsler, J. H.: 1996, *Home from nowhere: remaking our everyday world for the twenty-first century*, Nova York: Touchstone.

Oswalt, P., Overmeyer, K. and Misselwitz, P.: 2011, *Urban catalyst: Strategies for temporary use*, Birkhauser Basel.

Reades, J., De Souza, J. and Hubbard, P.: 2019, Understanding urban gentrification through machine learning, *Urban Studies*, **56(5)**, 922-942.

Sandig, J. D. E., Somoba, R. M., Concepcion, M. B. and Gerardo, B. D.: 2013, Mining online gis for crime rate and models based on frequent pattern analysis, *Proceedings of the World Congress on Engineering and Computer Science*.

Sassen, S.: 1991, *The global city*, New York.

Schmidhuber, J.: 2015, Deep learning in neural networks: An overview, *Neural networks*, **61**, 85-117.

Shen, J., Liu, C., Ren, Y. and Zheng, H.: 2020, Machine Learning Assisted Urban Filling, *CAADRIA 2020*, Bangkok, Thailand, 2:681-690.

Yu, C. and He, Z. C.: 2017, Analysing the spatial-temporal characteristics of bus travel demand using the heat map, *Journal of Transport Geography*, **58**, 247-255.

Zhao, H., Shi, J., Qi, X., Wang, X. and Jia, J.: 2017, Pyramid scene parsing network, *Proceedings of the IEEE conference on computer vision and pattern recognition*.

KPI-DRIVEN PARAMETRIC DESIGN OF URBAN SYSTEMS

THERESA FINK[1], MILENA VUCKOVIC[2] and ASYA PETKOVA[3]
[1,3]*AIT Austrian Institute of Technology, Vienna, Austria*
[1,3]*{theresa.fink|asya.petkova}@ait.ac.at*
[2]*VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, Vienna, Austria*
[2]*vuckovic@vrvis.at*

Abstract. We present a framework for data-driven algorithmic generation and post-evaluation of alternative urban developments. These urban developments are framed by a strategic placement of diverse urban typologies whose spatial configurations follow design recommendations outlined in existing building and zoning regulations. By using specific rule-based generative algorithms, different spatial arrangements of these urban typologies, forming building blocks, are derived and visualized, given the aforementioned spatial, legal, and functional regulations. Once the envisioned urban configurations are generated, these are evaluated based on a number of aspects pertaining to spatial, economic, and thermal (environmental) dimensions, which are understood as the key performance indicators (KPIs) selected for informed ranking and evaluation. To facilitate the analysis and data-driven ranking of derived numeric KPIs, we deployed a diverse set of analytical techniques (e.g., conditional selection, regression models) enriched with visual interactive mechanisms, otherwise known as the Visual Analytics (VA) approach. The proposed approach has been tested on a case study district in the city of Vienna, Austria, offering real-world design solutions and assessments.

Keywords. Urban design evaluation; parametric modelling; urban simulation; environmental performance; visual analytics.

1. Introduction

In recent years, the progressive application of computational design systems in urban design practices allowed for unprecedented and holistic explorations of a physical space. With conventional urban design and planning approaches being inherently inert and time-consuming, especially when it comes to consideration of numerous design alternatives and design optimizations, it is not surprising that these kinds of digital applications have brought about a new paradigm shift that led from analogue to a widespread digital thinking (Fink 2018). One of the most promising applications of such digital systems relate to parametric modelling, which, in principle, enables a multi-faceted assessment of form, design and, nowadays, even holistic environmental responses of considered planning

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 579-588.

strategies (Chowdhury and Schnabel, 2018; Vuckovic et al. 2017; Zhang and Liu, 2019). In general, the key advantages of parameter-driven approaches pertain to instantaneous visual feedback on the shape, dimensions, and spatial arrangement of model geometries once the desired parameters are modified. This allows for a timely consideration of multiple urban rules (e.g., spatial, structural regulations) and their interdependencies, which are then visualized and later can be evaluated based on an informed set of factors. This not only helps identify the potentially conflicting physical conditions and performance-related features, but it also supports urban designers when deciding upon the most optimal design solutions. Additionally, due to inherent flexibility and immediate visual response, these systems may foster real-time collaboration and participation of interested stakeholders in all stages of urban development (Steinø and Veirum, 2005). This is perceived as especially valuable considering that some more complex interventions in urban realm require substantial financial resources, along with time-intensive and well-coordinated planning and monitoring campaigns carried out by both urban planning and governing authorities. It can be thus said that parametric design procedures play a central part in sustainable collaborative urban transformation.

In this context, we aim to further exemplify the potential of such parametric approaches by applying a semi-automated workflow for data-driven algorithmic generation and analytical post-evaluation of alternative urban developments (Fink and König, 2019; Vuckovic et al., 2019). These urban developments are framed by a strategic placement of diverse urban typologies whose spatial configurations follow design recommendations outlined in existing building and zoning regulations, while offering some flexibility in open to closed ratio of resulting volumes. The proposed approach has been tested on selected building blocks in the ninth district in Vienna, Austria, offering real-world design solutions and assessments. Following, a performance assessment of resulting urban developments based on a defined set of KPIs is offered.

2. Methods

The novelty of our approach lies in the unique application of computational (parametric) modelling, environmental assessment approaches and interactive analytical techniques that are expected to unlock new perspectives in the collective field of urban science.

The envisioned parametric and environmental framework is set up within the 3D modelling software environment Rhinoceros 3D and its native plug-in Grasshopper (Rhino 3D, 2020). Whereby Rhinoceros 3D supports the generation and rendering of finitely-defined freeform 3D surfaces by utilizing NURBS (i.e., Non-Uniform Rational B-Splines), a mathematical representation of splines, Grasshopper (GH) complements and enhances Rhinoceros' capabilities by introducing a myriad of parametric functionalities. In our framework, the implementation workflow relies on a number of built-in and self-engineered modular components available in Grasshopper that allow for seamless data transfer between deployed generative components and simulation engines. Further complemented by advanced visual analytics techniques, the quality and performance of resulting parametrically derived spatial configurations is assessed given the selected KPIs. By carrying out the envisioned multidisciplinary steps of our framework, we likewise demonstrate the application potential of the framework itself.

2.1. RULE-BASED MODELLING OF URBAN SYSTEMS

As mentioned before, we considered six alternative urban developments (variant 1 to 6), each differing in the position and orientation of individual urban typologies. The spatial configurations of these individual urban typologies (i.e., fully-enclosed volumes with inner courtyards, semi-enclosed with partial openings, stand-alone volumes) follow design recommendations outlined in existing building and zoning regulations (LGBI, 2020; Stadt Wien, 2020). Thus, specific dimensional (e.g., vertical, horizontal restrictions) and spatial (e.g., geometry) constraints derived from the said regulations framed the resulting building assemblies (Figure 1). In the following step, specific rule-based generative algorithms are used to derive different spatial arrangements of these urban typologies, forming building blocks in ninth district in Vienna, given the afore-mentioned spatial, legal and functional regulations. These consider a set of explicit control inputs such as building class, maximal allowed building height, individual distances between the buildings, and relationship to the plot line.

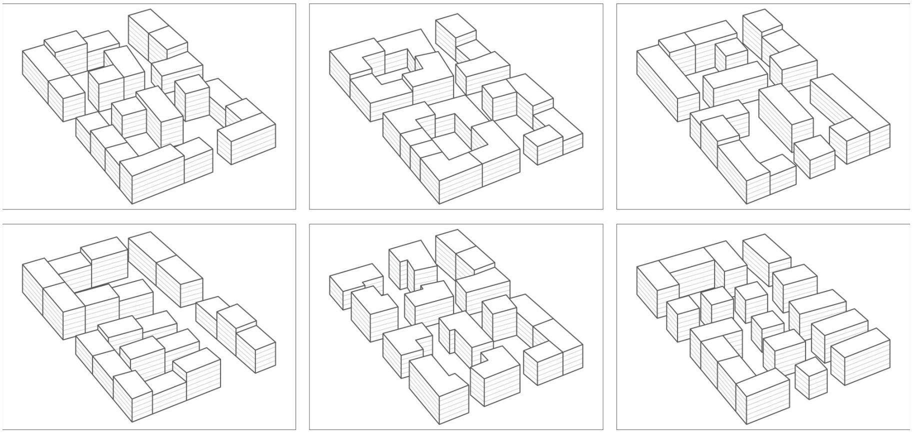


Figure 1. Figure 1. Six alternative urban developments composed of individual typologies.

2.2. SELECTED KPIS OF URBAN SYSTEMS

Once the envisioned urban configurations are generated, these are evaluated based on a number of aspects pertaining to spatial, economic, and thermal (environmental) dimensions, which are understood as the key performance indicators (KPIs) selected for informed ranking and evaluation. These namely entail the overall economic impact (construction and maintenance costs), built and open space ratio, green quality of urban space (trees), building energy requirements (heating and cooling demand), mean radiant temperature (MRT), universal thermal climate index (UTCI). Here, we focused on those urban aspects that are found to have an immediate effect on the quality of urban life (e.g., amount of green spaces, solar potential, heat stress, urban spatial structure, energy consumption).

Metrics pertaining to spatial dimensions are derived by conducting a spatial analysis of the resulting alternative 3D district geometry models, considering the respective transformations of physical environment, such as, the achieved buildable potential (built density, building height) and the resulting land cover configurations (ratio of unsealed to sealed cover - built-up area). These are namely derived using the readily available components in Grasshopper that allow for computation of areas [m^2] and volumes [m^3], whereby the respective values of each urban development iteration are then assessed in respect to the observed urban domain as a whole.

Metrics pertaining to economic impact relate to construction cost estimation arising from the newly formed urban structures, which was based on local construction cost index (BKI, 2020). As we aimed to reach a similar gross floor area (GFA) for each of the six alternatives, the economic impact is of a more qualitative character.

As an additional focal point of our investigations concerns thermal (environmental) response of considered solutions, we conducted a set of dynamic simulations of building energy and microclimatic conditions, providing thus a base for a comparative assessment and further design optimization. These are explained in more detail below.

2.3. ENVIRONMENTAL SIMULATIONS AND KPIS

Environmental and thermal assessments are carried out using the specific set of plug-ins from the family of Ladybug Tools (Ladybug Tools, 2020). Ladybug Tools (LBt) components allow for computation of complex interactions of built environment and climate resulting in detailed thermodynamic modelling on both urban and building scale (Vuckovic et al., 2019). To carry out such computations, a representative climate information via hourly-based weather file is provided, whereby we based our simulations on typical reference year composed for Vienna (EnergyPlus Weather, 2020). Subsequently, the building geometry is converted into thermal zone volumes (HB zones) with all thermal property information required to initiate an energy performance simulation (e.g., construction materials, surface boundary conditions, heating/cooling systems, occupancy schedules). Same transformation is done for ground surfaces, whereby all distinct soil types are identified and appropriate thermal properties assigned (e.g., asphalt roads, grass surfaces). With the model properly set up, annual energy simulation is carried out using the LBt-linked connection to EnergyPlus software (EnergyPlus, 2020). LBt-native Microclimate Map Analysis component is deployed towards the computation of desired thermal comfort indices (MRT, UTCI). These are then expressed through an area average and used as the KPIs for further evaluation.

2.4. VISUAL ANALYTICS FOR RANKING OF URBAN SYSTEMS

To facilitate the analytical analysis of derived numeric KPIs, to achieve data-driven ranking of generated design alternatives, we deployed a diverse set of analytical techniques (e.g., conditional selection, regression models) enriched with visual interactive mechanisms, otherwise known as the Visual Analytics (VA) approach. For this purpose, we used high-performance analytical VRVis Cockpits that allow for synthetizing the computed numerical and categorical data into cohesive and well-founded insights (Vuckovic and Schmidt, 2020). We pursued a 3-pillar approach, whereby all KPIs are fused into 3 distinct categories: spatial, economic, climate. We aimed for high GFA and low amount of sealed cover in spatial, low construction and maintenance costs in economic, and low MRT and UTCI values in climate category.

3. Results and Discussions

The considered urban design variants show a range of spatial variations, both in individual placement of volumes and resulting metrics. These are summarized in Table 1. It can be seen that those variants having the highest buildings (i.e., variants 5 and 6), at the same time take the least of the ground surface. This may be understood as potentially beneficial for allowing a desirable ratio of supplementary green infrastructure (trees and parks), thus increasing the overall quality of urban space. In terms of the construction costs, variants 1, 3, 4 and 6 were found to be the most expensive to construct, however these also allowed for the highest GFA to be reached. This insinuates potential confronting decisions during the evaluation stage, and these will be reflected upon at later discussion.

Table 1. An overview of selected computed KPIs.

VAR	GFA [m2]	Built-Up Area [m2]	No.of Trees	Building Height [m]	Construction Costs [EUR]	Total Load [kWh/m2]	Avg. UTCI [°C]
01	28776	5528.41	15	15.6	31942000	33.73	36.75
02	27731	6207.49	14	13.4	30782000	34.40	36.85
03	28701	5538.89	14	15.6	31859000	32.90	36.84
04	28733	5630.99	17	15.3	31895000	34.55	36.80
05	27788	5166.58	16	16.2	30845000	32.77	36.70
06	28772	4932.98	16	17.33	31938000	33.02	36.58

Looking at the spatial distribution of simulated thermal indices (we exemplify here the case of UTCI), a varying potential for solar shading by physical constructions may be observed across all six variants. It can be noted that the higher the distance between buildings, the higher potential for hot spots emerging. This is clearly visible in southern domain in variant 3 and southern and northern domains in variant 4, where UTCI tends to exceed 41°C. This may be, in part, mitigated by denser arrangement of trees, whereby the beneficial effect of such measures may be observed in the same southern domain in variants 1, 2 and 3. The potential reduction in UTCI equals 4.5°C. It can be further stated that having enclosed urban forms forming inner courtyards, as visible in variant 2, may result in favourable thermal conditions within. This may lower the cooling energy demand for living units facing courtyards, due to the overall reduction in direct solar gains. However, due to the lower sky view factor (SVF), this may also negatively affect the night-time cooling potential. This may be especially critical in smaller courtyards with a higher height-to-width ratio (i.e., narrower courtyards with higher buildings). Similarly, semi-enclosed tight tunnel-like formations, as seen in variant 4, may be beneficial during the day, due to reduced solar gain, but equally unfavourable during the night, due to the potential accumulation of heat caused by impeded air flow and SVF. On the contrary, semi-enclosed irregular formations, as seen in variants 1 and 3, allow for adequate spacing between buildings and unrestricted air flow, with likely favourable thermal effects. Finally, when considering fully-open stand-alone formations, as seen in variant 6, and especially when complimented with a balanced positioning of trees, we may achieve the optimal percentage of beneficial thermal conditions.

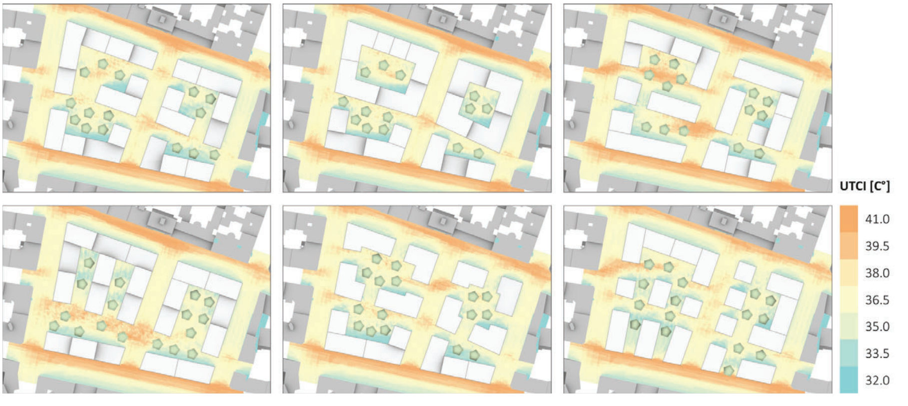


Figure 2. UTCI simulation results calculated for the six typologies.

Looking at the building level, the floor-by-floor distribution of total annual thermal loads (i.e., combined heating and cooling load) appears to vary to a slight degree. As expected, the fully exposed higher floors endure the highest absorption of incoming solar radiation, as seen in all variants. This might be partly mitigated by consideration of unequal building heights, which may promote solar shading caused by surrounding higher volumes. In agreement with our previous discussion, the spatial arrangement of individual urban typologies may likewise affect the resulting thermal loads. This means that the higher the distance between the buildings (variants 3 and 4), the higher the exposure of building facades to solar radiation, resulting in greater thermal loads. The same may be said for the stand-alone building volumes, as they have less volume to be heated up and higher solar exposure on all facades, resulting in faster warming rate. Again, this may be mitigated by strategically placing the surrounding trees, where potential improvements to this end may be identified in variant 6. Looking at the heating and cooling loads independently, our results suggest almost no difference to annual cooling loads, but some in annual heating loads. Variants 5 and 6 seem to perform the best, whereby variant 4 reveals the highest heating loads.

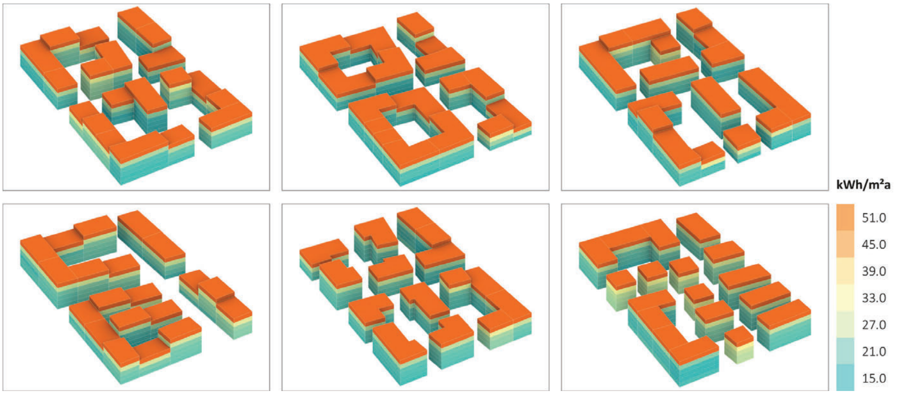


Figure 3. Total thermal load (representing heating and cooling demand) per floor in kWh/m²a for residential use.

We proceeded with the analytical evaluation of the derived KPIs. Figure 4 exemplifies the interlinked system and instantaneous visual feedback (e.g., heatmaps, parallel coordinates) of deployed VA system by considering all KPIs and 6 spatial variants (i.e., design alternative). Here, the green-red heatmap (upper section of Figure 4) denotes the degree to which certain variant (1-6) meets the set KPI requirements - red color indicating that such requirements are exceeded, and green indicating that these are met. Parallel variants comparison (lower section of Figure 4) provides a parallel analysis of all the variants while highlighting those where the set requirements are met. More specifically, by applying user-defined conditional selections (e.g., high GFA, low UTCI) to each of the investigated pillars (spatial, economic, climate), we identified the most optimal spatial variant given these specific framing conditions. Namely, spatial and climate requirements revealed variant 6 as the most optimal, whereby economic requirements identified variant 5 (Figure 5). More specifically, Figure 5 offers a comparative visual analysis of those variants that met the most of the set KPIs, further observed from the perspective of each of the considered pillars (spatial, economic, climate). In the following step, we conducted a deeper analysis of the two, while considering all KPIs simultaneously (Figure 6). Figure 6 thus provides a visual analysis of two isolated variants and the ways they respond to each of the KPI. This revealed a clear inversed trend and potential inter-correlations between multiple KPIs considered, further confirmed by conducting a correlational analysis, where we noted a positive correlation between, for example, GFA and construction costs. Such a comparative analysis indicated the height of decision complexity and a general inability to meet all set requirements.

Figure 4. Interlinked high-performance analytical VRVis Cockpits.

Figure 5. Most optimal variants as a result of the 3-pillar driven conditional selection.

Figure 6. Inversed trends in variants 5 and 6, with target KPI values marked in yellow.

4. Conclusions

There is an evident application potential of parametric design approaches for informed KPI-driven assessment of urban systems. Not only that, more urban alternatives may be simultaneously generated at very low computational costs, but these may be easily formulated within the existing building and zoning boundaries. Additionally, the key spatial metrics may be effortlessly derived from the resulting 3-dimensional representations of envisioned design alternatives. The added value to such a parametric approach is its enhanced environmental functionality that allows for the multi-dimensional assessment of climate and energy nexus. Complemented with exploratory data analysis workflows encapsulated within the Visual Analytics system, the entire framework becomes a powerful decision-support tool, invaluable to urban planners, architects, municipalities and other relevant stakeholders. In conclusion, this unifying framework allowed us to readily identify the most optimal solutions given the set of evaluative KPIs, however, it also uncovered the complexity behind decision-making and stressed the need for a certain degree of flexibility when trying to meet defined targets. Potential limitations to our approach relate to the confined consideration of only 3 pillars (spatial, economic, climate), where other aspects, such as accessibility, air quality, wind comfort, noise pollution, should certainly be integral to such appraisals. We are thus currently working on enhancing our framework to include a more comprehensive set of aspects.

References

"BKI: Baukostenindex." : 2020. Available from <www.statistik.at/web_de/statistiken/wirtschaft/preise/baukostenindex/index.htm> (accessed 21 October 2020).

"EnergyPlus" : 2020. Available from <https://energyplus.net/> (accessed 21 October 2020).

"EnergyPlus Weather" : 2020. Available from <https://energyplus.net/weather-location/europe_wmo_region_6/AUT//AUT_Vienna.Schwechat.110360_IWEC> (accessed 21 October 2020).

"Ladybug Tools" : 2020. Available from <https://www.ladybug.tools/> (accessed 21 October 2020).
"LGBI" : 2020. Available from <www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=LrW&Gesetzesnummer=20000006/> (accessed 21 October 2020).
"Rhino 3D" : 2020. Available from <https://www.rhino3d.com/> (accessed 21 October 2020).
"Stadt Wien" : 2020. Available from <https://www.wien.gv.at/flaechenwidmung/public/> (accessed 21 October 2020).
Chowdhury, S. and Schnabel, M.: 2018, An algorithmic methodology to predict urban form: An Instrument for Urban Design, *CAADRIA 2018*, China.
Fink, T.: 2018, *On urban planning and procedural modeling*, TU Graz, Graz, Austria.
Fink, T. and Koenig, R.: 2019, Integrated Parametric Urban Design in Grasshopper / Rhinoceros 3D, *eCAADe 2019*, Porto, Portugal.
Steinø, N. and Veirum, N.E.: 2005, A Parametric Approach to Urban Design: Tentative formulations of a methodology, *eCAADe 23*, Lisbon, Portugal.
Vuckovic, M., Loibl, W., Tötzer, T. and Stollnberger, R.: 2019, Potential of Urban Densification to Mitigate the Effects of Heat Island in Vienna, Austria, *Environments*, **6**, 82.
Vuckovic, M., Mahdavi, A., Tauber, C., Kiesel, K., Glawischnig, S., Heiderer, A., Pirstinger, I., Majcen, M. and Raudaschl, M.: 2017, Generation and evaluation of alternative urban densification scenarios, *15th IBPSA*, San Francisco, USA.
Vuckovic, M. and Schmidt, J.: 2020, Visual Analytics Approach to Comprehensive Meteorological Time-Series Analysis, *Data*, **5 (4)**, 94.
Zhang, Y. and Liu, C.: 2019, Parametric Modeling for Form-Based Planning in Dense Urban Environments, *Sustainability*, **11**, 5678.

PANDEMIC RESILIENT HOUSING

Modelling dormitory congestion for the reduction of COVID-19 spread

FREDERICK PETER ORTNER[1] and JING ZHI TAY[2]
[1,2]*Singapore University of Technology and Design*
[1,2]*{peter_ortner|jingzhi_tay}@sutd.edu.sg*

Abstract. In response to pandemic-related social distancing measures, this paper presents a computational model for simulating resident congestion in Singapore's migrant worker dormitories. The model is presented as a tool for supporting evidence-based building design and management. In contrast to agent-based or network-based building analysis, we demonstrate a method for implementing a schedule-based building simulation. In this paper we present the key functions and outputs of the computational model as well as results from analysis of a case study and its design variants. Learnings on the comparative advantages of schedule modification versus physical design modification in assisting social distancing are presented in a discussion section. In the conclusion section we consider applications of our learnings to other dense institutional buildings and future directions for evidence-based design for resilient buildings.

Keywords. Collective, collaborative & interdisciplinary design; Computational design research & education; Disrupted practices, resilience, and social sustainability; Simulation, visualization and impact projection.

1. Introduction

1.1. SINGAPORE'S RESPONSE TO COVID 19

Early in 2020 outbreaks of the COVID-19 pandemic intensified in areas of dense urban housing throughout the world. In April 2020, when Singapore saw a surge in COVID-19 cases in high-rise, high-density dormitories for migrant construction workers. In response, a series of safe-distancing recommendations (for example, maintaining at least one meter spacing between individuals) and de-densifying measures were passed by the Singapore government under the Infectious Disease Act (Ministry of Health, 2020). While these measures have been successful in reducing disease spread during periods of quarantine, worker dormitories are now reopening to normal function even as the global pandemic continues.

The design community has been called upon to support the return to a 'new-normal' where everyday activities resume, but with new safe-distancing measures. In the context of migrant worker housing in Singapore, the Ministry

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 589-598.

of Manpower concurrently released an advisory for existing dormitories to implement safe living measures and also a joint media release with the Ministry of National Development on improved standards for dormitory design (Ministry of Manpower, 2020; Ministry of National Development, 2020). The release of these articles show that the Singapore government is invested in finding a response to building management in the short term and building design in the longer term, with the implication that designers of urban housing and building managers must work together to develop a solution for pandemic resilient housing. We understand resilience in this context to refer to a capacity of socio-technical systems surrounding the built environment not only to recover from a disturbance, but to learn from, anticipate and adapt to these disturbances (Hassler, 2014; Hollnagel, 2014).

1.2. MIGRANT WORKER HOUSING IN SINGAPORE

Currently there are nearly 300,000 migrant construction workers living in Singapore (Ministry of Manpower, 2020). For the most part, they are housed in high-rise high-density worker dormitories. Ethical considerations for research on migrant worker housing are considerable. Dormitory residents in Singapore are often dependent on their employer to maintain their housing and immigration status (Moroz et al., 2020). Pandemic response measures, in particular quarantine, have recently limited their freedom of movement. The research in this paper has been developed in an effort to assist in increasing the safety of this housing environment during the period of the pandemic.

1.3. COMPUTATIONAL MODEL FOR PANDEMIC-RESILIENCE

To support an evidence-based design approach to pandemic related worker dormitory management and dormitory modifications, a knowledge gap exists: designers can not predict how de-densifying measures will impact patterns of social contact during the dynamic movement of residents. These daily movements create momentary peaks in congestion, where individuals arrive simultaneously in constrained areas like corridors, making 'safe-distancing' measures difficult to follow.

To address the knowledge gap on dynamic patterns of congestion in dormitory use we have developed a computational model of worker movements within a case-study dormitory. Our model is intended to support both building managers and architects as they seek to adjust building use schedules and building configuration to support safe-distancing measures during the pandemic. In our model, the building schedule supplements the rules and behaviors typically in a multi-agent model, using methods similar to a schedule-calibrated model (Goldstein et al., 2010; Goldstein et al. 2011). The use of a building schedule as a key input for our model presents value for building managers seeking to re-calibrate their schedules, and also permits us to generate close-to-reality scenarios for an environment where human movements have a degree of prescribed regularity due to safe-distancing measures.

2. Methods

Through our literature review we identified both building managers and architects as primary actors in the adaptation of dormitories to pandemic social-distancing measures. We designed our computational model to accept input from both of these actors: a building schedule adapted to building management and a building network diagram adapted to spatial configuration. Each key input is described in detail along with its associated function in the following methods sections. Our workflow, described in detail below, first generates a master schedule for all agents in the simulation via a *Scheduler* function, where each agent represents a resident. Based on the master schedule, a second *Pathtracer* function generates dimensionally accurate itineraries for each agent in the simulation. With the outputs from these two functions we conduct two forms of analysis: a global measure of use intensity for building spaces, and a congestion analysis which provides feedback on design variants. We have used the visual programming interface Grasshopper for Rhinoceros 3D in the creation of the model.

2.1. SCHEDULER FUNCTION

The first function in our computational model generates a master schedule for all agent movements in the dormitory simulation from a set of simple parameters provided by the user (figure 1). The user is prompted to input a set of data points for each defined activity taking place in the simulation. Examples of activities included in the current model include 'wake up', 'morning shower', 'morning departure,' etc. The list of activities is open to modification by the end user.

For each activity the following datapoint entries are entered: 1) name of the space; 2) earliest use; 3) latest use; 4) minimum visits; 5) maximum visits; 6) minimum stay; 7) maximum stay. The user also defines the number of agents in the simulation. Within the constraints defined by the above inputs the *scheduler* function randomly generates itineraries for all agents in the simulation. Randomness is constrained within the bounds defined by the user inputs. Commencement of each activity is allowed to vary randomly within the bounds of inputs 2 and 3. The number of repetitions of each activity varies randomly within the bounds defined by inputs 4 and 5. Duration of each activity is random within the bounds defined by inputs 6 and 7.

The *scheduler* outputs a color-coded time-sheet representing timelines for all agents in the simulation with each activity assigned a different color. It provides a visual feedback to the end-user on the distribution of agent activities over time. A .csv file data of the schedule is output and feeds into the *Pathtracer* function.

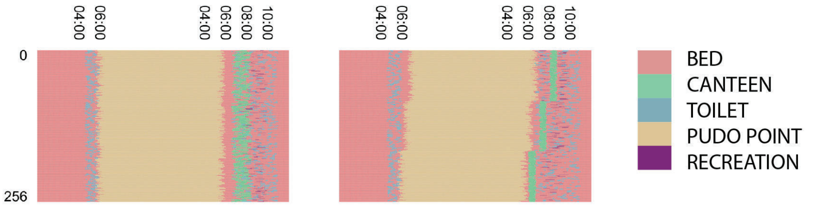


Figure 1. Baseline schedule (left) see section 3.2, staggered schedule from design scenario 1, (right) see section 3.3.

2.2. PATH-TRACER FUNCTION

The path-tracer function generates all paths traveled by agents in the dormitory based on the master schedule. The user input for this function is a network representation of the dormitory case study, as a list of labelled nodes and edges. Nodes represent functional spaces, like bedrooms, and edges represent spatial linkages, like corridors.This network representation is a three-dimensional, dimensionally accurate reflection of the building geometry, traced from the building floor plans. The creation of the network representation is a non-trivial manual activity which requires the assistance of an experienced design professional. The creation of this network representation is summarized in figure 2.

The *Pathtracer* function matches each agent to an available node for each of the activities/rooms within the agent's schedule. Bed nodes are 'checked-out' after assignment, whereas other nodes permit multiple simultaneous agent assignments. When there is a choice between available spaces for an activity, for example a toilet, the agents are assigned the node closest to their point of origin.

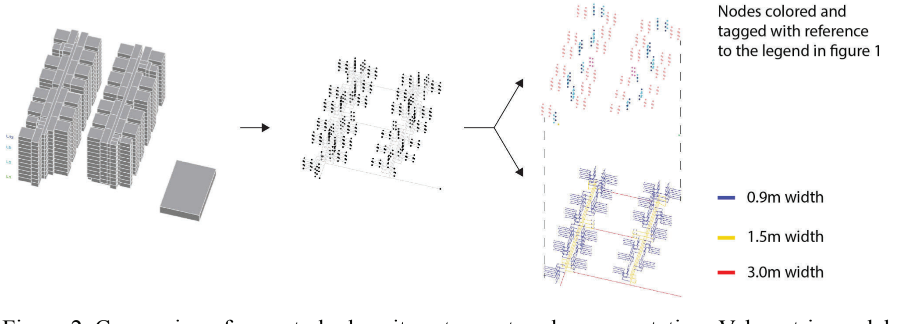


Figure 2. Conversion of case study dormitory to a network representation. Volumetric model (left) is extracted and converted to nodes and edges (middle), which will be tagged according to function (right top) and lateral dimension (right bottom).

Agent paths through the dormitory are generated using a shortest path algorithm to identify routes between origin/destination pairs. We have used the

A star algorithm (Hart, Nilsson, and Raphael, 1968). The time taken for the agent to move from origin to destination is calculated by dividing the path length with a constant walking speed. We account for the walking time by replacing the time spent by the agent at the origin, i.e. the agent leaves the origin space earlier and arrives at the destination exactly on time.

The function outputs the location of every agent for every second in the simulation period as a data tree of points where each branch contains a list of points representing a single agent's location at a given time interval. Simulations presented in this paper start from 00:00:00 and run till 23:59:59; for a total of 86400 seconds.

2.3. EVALUATION METRICS

We use two metrics to evaluate simulation outputs. A first metric, *Usage*, is defined as the total times an edge has been occupied by any agent over the course of the simulation period. A second metric, *Congestion*, is defined as the ratio of the total number of agents on an edge at a given time interval to the capacity of that edge as defined by its area and social-distancing guidelines (figure 3).

These two metrics will be familiar to readers of urban network analysis or traffic simulation. Usage is similar to betweenness though as explained above it is not an all-to-all calculation (Sevtsuk, A. 2017). Congestion in traffic simulation is defined as the ratio of traffic along an edge to the capacity of that edge, and is similar to the definition we provide for the purposes of our model (Poon et al 2004).

To compute congestion at a time t denoted as $C_i(t)$, we first compute the volume of traffic at edge E_i , denoted as $T_i(t)$. A_t represents an agent's position at time t in a given set S. is a constant representing the minimum area required per agent based on applicable social-distancing restrictions. In the case of Singapore, we are using a value of $1m^2$. $Area_i$ is the floor area of E_i.

```
def Congestion i ( E i , t ) :
        T i (t)  = count [ every A(t) in set S, if A(t) lies on E i ]
        C i (t) = T i (t)  x  α  / Area i
        return C i (t)
```

Figure 3. Pseudo code definition of congestion index .

2.4. VISUALISATION OF RESULTS

We visualize evaluated simulation outputs using both a 3-dimensional spatial representation and a two-dimensional temporal representation. The first two visualization outputs are three-dimensional views of the graph model, representing the Usage (figure 4 left) and Congestion (figure 4 right) metrics via the color and thickness of the graph edges. figure 4 shows results from our case study baseline scenario. The three-dimensional representation emphasizes spatial understanding of agent movement, highlighting areas where usage or congestion are relatively high.

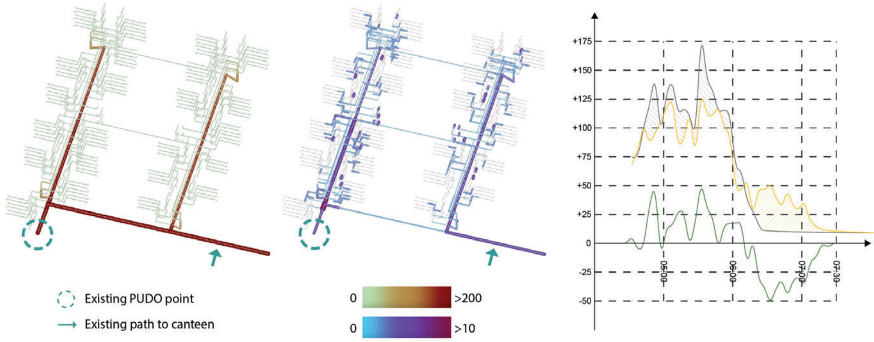


Figure 4. Usage diagram of baseline configuration (left). Maximum congestion diagram of baseline configuration (middle). Deriving deviation of cumulative congestion between baseline and and design scenario 1 during 4:30am to 7:30am (right) (see sections 3.2 and 3.3). .

The three-dimensional visualization, however, can not tell us when moments of high congestion happen. To understand congestion temporally we output a linear time-series graph showing cumulative congestion within the network over time. Cumulative congestion refers to the sum of congestion measurement for all edges in the network at a given time interval.

In our results we present comparisons between a baseline simulation run for a case study and a series of design variants. To better articulate this comparison the time-series graphs presented are the difference or deviation between the design variant and the baseline congestion. The method of calculation of this deviation value is shown in figure 4 on right: cumulative congestion for the baseline scenario and design scenario 1 are shown in grey and yellow respectively. The deviation between the two values is shown in green (see sections 3.2 and 3.3).

3. Results and Discussion

3.1. MIGRANT WORKER DORMITORY CASE STUDY

In this section we present results from applying our computational model to a worker dormitory case study and a series of design variants. We obtained an anonymous dataset of floor plans and images of our case study by liaising with a local industry contact. The dormitory consists of two twelve-story housing blocks and a separate structure for a canteen.

In all simulation runs described in this paper we have used 256 agents, constrained to the first three floors of the case study building, with agents further constrained to use only the vertical circulation core closest to their allocated bedroom. These constraints were imposed due to the computational cost of simulating the full building with its total population of 1024. Instead of simulating the full building with a sparse population, we chose to simulate a portion of the building with the full population.

3.2. BASELINE MIGRANT WORKER DORMITORY SCENARIO

In our baseline model we assigned a schedule corresponding to a typical work day in a migrant worker dormitory based on our review of literature (figure 1, left). The baseline schedule includes: morning preparation, transport to site, return from site, dinner at dormitory and other recreational activities within the facility. Agent start times fall in the range between 4:30am to 5:30am, with departure by 6:30am, as government regulated start and end time of work falls between 7am to 7pm (National Environmental Agency, 2007). Dinner timing between 7:00pm to 9:30pm is blocked out, with subsequent end of the day between 10:00 to 11:00 pm.

The usage diagram (figure 4, left) shows that the most heavily used spaces lie between the canteen and the pick-up drop-off point and the vertical circulation points on the ground level. The congestion diagram (figure 4, right) provides a more nuanced view, showing us that the vertical circulation areas at every level are points of higher congestion. The subsequent design scenarios presented in this paper are attempts to relieve congestion in these heavily-used spaces through changes in schedule and design interventions.

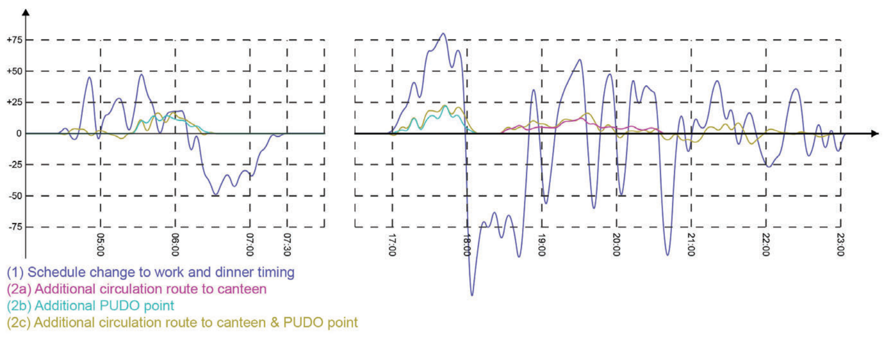


Figure 5. Cumulated congestion index deviation per minute generated for each design configuration.

3.3. SCENARIO 1: STAGGERED SCHEDULE

In a first scenario we simulated a modified schedule which splits the population of agents into three cohorts (figure 1, right). These cohorts are assigned a staggered work and dinner timing. A buffer time of 15 minutes between dinner timings is added to permit disinfecting of the tables between cohorts.

In the morning, before 6:30am, the deviation score is consistently positive for the variant indicating less congestion (figure 5). A negative score for this scenario occurs between 6:30am to 7:30am due to the fact that all agents in the baseline have left the dormitory by this point in time. In the evening as agents return to the dormitory, the advantage of a staggered arrival/departure schedule is again indicated by a consistently positive deviation score between 5:00 to 6:00pm.

Disadvantages of the staggered dormitory schedule appear during the evening meal time. The deviation score fluctuates widely between 6:00pm to 8:45 pm. This fluctuation can be broken down into 3 pairs of “dips” in the graph, occurring during each of the three dinner periods, caused by large numbers of agents moving in and out of the canteen over a short period of time. These peaks in congestion are the result of agents having a smaller range of possible entry/exit timings within the shorter 45 min periods.

3.4. SCENARIO 2: REDESIGN OF COMMON SPACES

In a second set of simulations we test if we can improve congestestion at shared spaces by adding an extra pickup-drop-off point and an extra path to the canteen. Configuration 2a adds an alternative route to the canteen. Based on a study of the existing floor plan, we find that there is a high possibility of constructing a second pathway to the canteen through the center of the residential block. Configuration 2b adds an additional pick up drop off point. The addition of a second PUDO point on the site would require the building owner to extend the driveway from the carpark to reach the proposed site, a possible design intervention. Configuration 2c combines both proposals together.

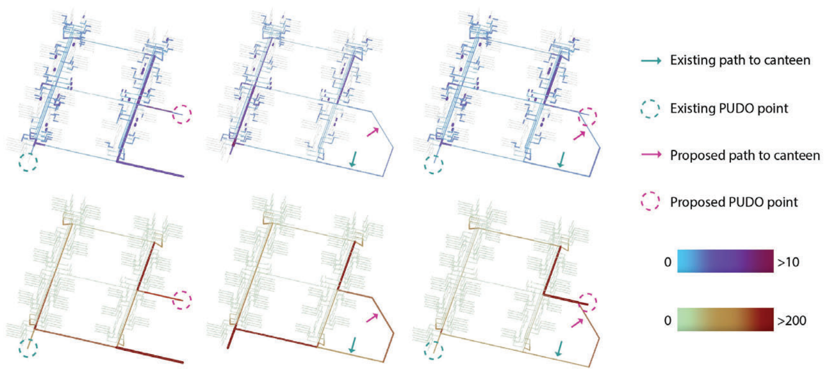


Figure 6. Usage index diagram (top row) and maximum congestion index diagram (bottom row) for configuration 2a, 2b and 2c (left to right).

Each design change improves dormitory congestion during the period it is in use as shown in figure 6. Creating an additional circulation route to the canteen (2a) creates a reduction in congestion during the meal time hours (18:30-20:30). The addition of a new pick-up drop-off point results in decreased congestion during the period when agents are departing from and arriving at the dormitory (5:30-6:30, 17:00-18:30).

While the combination of the two design scenarios (2c) resulted in a consolidation of the benefits of each, there are however some unexpected consequences of the combination. Combining the two scenarios results in an increase in usage and congestion of the area where the new PUDO point connects to the path to the canteen (figure 6). The ability to anticipate these unexpected add-on effects of combining design scenarios is one of the advantages our tool could provide end-users grappling with tradeoffs between means of implementing social distancing in worker dormitories.

3.5. DISCUSSION

Our dormitory congestion model has allowed us to demonstrate the comparative benefits of schedule changes and design changes with respect to a baseline configuration of a case study. By visualizing these benefits both spatially and temporally we are able to draw more nuanced conclusions about each scenario and compare schedule-based interventions and adaptations of physical design.

Our results show that while a staggered schedule does reduce average congestion over the course of the simulation, it also led to momentary but dramatic spikes in congestion as agents moved in and out of spaces (like the canteen) over short periods of time (figure 5). These results help us understand how staggered schedules lead to alternating periods of spatial over- and under-utilisation, and create obstacles to social-distancing measures. Future work could allow us to recommend adequate timings, additional flexibility, or additional space for socially distanced entry and exit to/from communal spaces.

Our results also suggest that implementing multiple design changes together will not necessarily have the same impact as implementing them in isolation. This is the case, for example, in configuration 2c where the combination of a new path to the canteen and an additional pick-up drop-off point has resulted in under-utilization of the initial drop-off point, as seen in the Usage diagram in figure 6. This result suggests that the model could assist end-users to plan for combinations of design interventions that complement rather than interfere with one another.

Comparison of the effectiveness of schedule-changes against physical design changes for social distancing is also permitted by our results. In figure 5 we see that while spatial changes (2a-c) have offered moderate decreases in congestion, schedule changes in contrast have resulted in a much wider amplitude of change with both greater reductions in congestion, but also moments of sharp increase. These initial findings suggest that schedule modification can be of great potential benefit in social distancing, but that it can lead to sudden crowding at spatial and temporal choke-points if not properly planned. Computational tools of the kind proposed in this paper can help anticipate these consequences and inform design changes to avoid choke-points.

4. Conclusions

In this paper we have presented a computational model for understanding population congestion in a dense institutional context, applied here to social distancing in the COVID-19 pandemic. This model presents a novel ability to allow for exploration of both spatial and temporal scenarios and compare tradeoffs between the two. The preliminary results shown here demonstrate the potential this approach has for facilitating informed decision-making across the building design and building management silos.

A limitation of the model as shown here is its reliance on approximations of dormitory schedules and operations instead of field-based measurements. Field data would permit the creation of a more accurate baseline model, as well as validation of simulation results relative to real-world values. Unfortunately pandemic controls on free-movement and access have prevented us from gathering these data as of this writing. We are continuing to pursue means of ethically and safely obtaining these data, and hope to present these findings in future.

Finally, beyond the horizon of the COVID-19 pandemic we believe that the methods and findings described in this paper can contribute to the creation of a more resilient urban habitat where building design/adaptive reuse and building management can be planned together. Beyond robustness of construction, we believe that a building's configurational capacity to limit congestion and adapt to new uses (like social-distancing) should be central in our understanding of its resilience. Computational methods, such as those presented in this paper, offer a path toward quantifying configurational resilience and incorporating it in an evidence-based design process.

References

"Construction Noise Control" : 2007. Available from National Environmental Agency Singapore<https://www.nea.gov.sg/>.

"Foreign workforce numbers" : 24 September 2020. Available from Ministry of Manpower Singapore<https://www.mom.gov.sg>.

"Infectious Diseases (measures to Prevent Spread of Covid-19) Regulations" : 26 March 2020. Available from Subsidiary Legislation Supplement Singapore<https://sso.agc.gov.sg/>.

"Advisory for dormitory operators on implementation of Safe Living measures in foreign worker dormitories" : 30 May 2020. Available from Ministry of Manpower Singapore<https://www.mom.gov.sg>.

"Joint MND-MOM Media Release on New Dormitories with Improved Standards for Migrant Workers" : June 2020. Available from Ministry of National Development Singapore<https://www.mnd.gov.sg/>.

Goldstein, R., Tessier, A. and Khan, A.: 2010, Schedule-Calibrated Occupant Behavior Simulation, *Proceedings of the 2010 Spring Simulation Multiconference, 1–8. SpringSim '10*, San Diego, CA, USA, Society for Computer Simulation International.

Goldstein, R., Tessier, A. and Khan, A.: 2011, Space Layout in Occupant Behavior Simulation, *Conference Proceedings: IBPSA-AIRAH Building Simulation Conference*.

Hart, P.E., Nilsson, N.J. and Raphael, B.: 1968, 'A Formal Basis for the Heuristic Determination of Minimum Cost Paths', *IEEE Transactions on Systems Science and Cybernetics, 4(2)*, 100–107.

Hassler, U. and Kohler, N.: 2014, Resilience in the built environment, *Building Research & Information*, **42**(2), 119-129.

Hollnagel, E.: 2014, Resilience engineering and the built environment, *Building Research & Information*, **42**(2), 221-228.

Moroz, H., Shrestha, M. and Testaverde, M.: 2020, Potential Responses to the COVID-19 Outbreak in Support of Migrant Workers, *World Bank Working Paper.*.

Poon, M.H., Wong, S.C. and Tong, C.O.: 2004, 'A dynamic schedule-based model for congested transit networks', *Transportation Research Part B: Methodological, 38(4)*, 343–368.

A. Sevtsuk (ed.): 2017, *Analysis and Planning of Urban Networks*, Springer.

Ulicny, B. and Thalmann, D.: 2003, Towards Interactive Real Time Crowd Behavior Simulation, *Computer Graphics Forum*, **21**(4), 767-775.

SECTIONMATRIX

Mapping Urban Form through Urban Sections

XIANGSHU GU[1], SHULIN TIAN[2], BAIHUI ZHANG[3], ZIYU TONG[4] and JINGWEN GAN[5]
[1,2,3,4,5]*Nanjing University*
[1,2,3]*{181870058|181870195|181870265}@smail.nju.edu.cn*
[4]*tzy@nju.edu.cn* [5]*736785302@qq.com*

Abstract. Most of the traditional studies on urban morphology are based on aerial views. However, the 2D plane model fails to describe the height information of buildings and the relation of buildings and the urban external space. An urban section is another map of an urban area. Through a series of continuous vertical urban slices, the city texture can be transformed into planar linear information containing height and width information. This paper proposes several indicators to describe a series of urban section slices and uses a three-dimensional coordinate mapping method Sectionmatrix to quantify and analyze the relation between the physical geometrical indicators and urban form from the section perspective. Through the case analysis of multiple residential blocks in Nanjing, China, the results showed that Sectionmatrix is convenient and efficient. Sectionmatrix relates the geometrical properties to the spatial characteristics of urban areas and provides a new way to classify, map and define building typologies. This new classification method reveals the tortuosity and complexity of residential blocks. By bridging the gap between quantity and form, the research also suggests other possible applications of Sectionmatrix as a control instrument and test framework for entire cities' planning and design.

Keywords. Urban Morphology; Urban Section; Sectionmatrix; Quantitative Analysis.

1. Introduction:

Morphological research in general has generated a useful body of definitions, as well as a common language for describing architectural and urban form, since the 1950s. In 1960, Conzen and Conzen (2004) regarded plane analysis as a basic method of urban morphological study and analyzed the structural elements of the urban fabric, such as block planes, plot planes and building planes, through its lane profile. In typomorphology, various classifications of buildings and open spaces are used to attain a more detailed description of urban form. Among the related methods, "Spacemate" proposed by Pont and Haupt (2004) provides a way to simultaneously reflect the physical properties and architectural morphological characteristics of a certain plot and relate to one another.

Spacemate is a charting tool that uses the coordinate mapping method to classify urban form. It relates three geometrical properties of buildings, including the density expressed as a floor space index (FSI), ground coverage, and number of stories, to the spatial properties. In addition, by understanding the relation between quantitative and spatial properties, Spacemate defines programmatic demands and spatial ambitions simultaneously without fixing a detailed program or a final image. By doing so, Spacemate bridges the gap between the density index and building typology. In addition, scholars have applied Spacemate in urban planning and urban design (Kickert et al. 2014, Steadman 2014).

However, at present, in the study of urban morphology, attention is given to "the two-dimensional figure-ground relation" rather than "the three-dimensional volume structure", which may inevitably cause limitations due to the lack of height, space and other information. The three-dimensional city model, as a type of simulation of reality, contains a great deal of information; and redundant information may hinder the clear and intuitive expression of urban form. In addition, 3D city modeling is still in the primary stage and has difficulty analyzing the complex urban form accurately. It is more effective to translate three-dimensional information into a flat diagram containing the characteristics of both the 2D plane model and 3D model.

Studies on urban morphology from the profile perspective have focused on the protection of historical cities at the end of the 20th century. Li and Du (2008) proposed the concept of urban sections in their study. The concept of a "city section" provides a new method for studying urban morphology and urban development. Other scholars have applied sections in various fields. Zhu (2017) applies the section method to mountainous city analysis. The results show that the "section" method well reveals the spatial characteristics and complexity of mountainous cities and compensates for the limitations of graphic design.

Most studies use the "section" method to analyze the relation of buildings and terrain but only analyze single or several slices of urban sections, which fails to describe urban form clearly and accurately. Liu & Ding (2012) proposed that through continuous vertical urban slices, the city texture can be transformed into planar linear information containing height and width information, which can reveal the tortuosity and openness of urban form. One vertical urban slice or several slices have limitations and difficulties revealing the real urban form. A series of urban slices not only contain height information and reveal the spatial features between buildings but can also reveal the characteristics of planes.

This research introduces the "series of section" method to the study of urban form and describes urban form through the section view. This research also proposes 3 section indicators to reveal the density, open space and other physical properties of urban form and generates multiple series of urban section slices. Inspired by Spacemate, which relates the density index to building morphology to describe urban form, this paper presents a new method to view the relation of physical density and urban form from the section perspective and proposes Sectionmatrix. Sectionmatrix is a three-dimensional coordinate mapping method that reveals the relation of density indicators and building typology. This section naturally reveals the spatial scale between buildings and provides the ability to analyze human perception in the space between different heights of buildings. We believe that Sectionmatrix will contribute to understanding cities from a human perspective, and the research also suggests possible applications of Sectionmatrix as a control instrument and test framework for entire cities' planning and design.

2. Materials and methods:

2.1. DEFINING AND CALCULATING QUANTITATIVE INDICATORS OF URBAN SECTIONS

Following plane analysis, a new series of indicators are defined to describe urban sections using basic parameters such as length, height and area (Dong 2019). Figure 1 demonstrates three important indicators: the length ratio (LR), the area ratio (AR), and the width ratio (WR). The LR presents the tortuosity of the urban section line. The AR represents the average height of the entire urban section. The WR represents the building density.

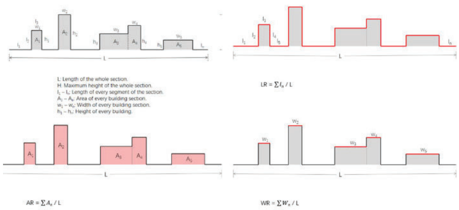


Figure 1. Definition of the quantitative indicators of urban sections (Dong 2019).

2.2. SERIES OF SECTIONS

A single section slice cannot thoroughly describe urban morphology, which leads to this research using a series of linear section slices to describe urban morphology. To obtain a series of section slices that accords to the actual building profiles as accurately as possible, this research uses the parallel cutting method. In this way, a series of section slices combined can reflect its 2D plane. According to the Chinese standard residential area planning textbook and handbook, the length of the space between low-rise buildings and multistory buildings should be at least 8 m; and for high-rise buildings, the length should be 15 m. Therefore, we first set the section distance as 5 m, 10 m, 15 m and 20 m for the experiment. When the section distance is set as 5 m, the large amounts of data are hard to process and the variations are rather small, which hinders further analysis. When the section distance is over 10 m, the geometrical shape of the area cannot be fully manifested. Thus, we set the span of the section line to 10 m, which can best reflect the morphological characteristics of the area. In this way, a series of urban section slices and the corresponding data are generated.

3. Case study

3.1. CHARACTERISTIC OF THE CASES

As a preliminary study, we chose residential blocks as the research object because residential buildings are not as complex as commercial buildings. In China, residential buildings can be divided into low-rise buildings (under 10 m), multistory buildings (10-20 m) and high-rise buildings (over 20 m) according to their height. In terms of form, residential buildings can be divided into parallel slab type, dot type, and enclosure type (Peng, Qin and Hu, 2018). However, in residential blocks, buildings with various heights and forms are often mixed, which makes it difficult to describe their characteristics only using planes.

Based on the characteristics of residential buildings, 60 residential blocks in Nanjing, China that clearly differ in terms of the degree of urbanization and the type of land development were selected to conduct the analysis. These residential blocks are located in different typical areas, including the old town, the suburban area, the old CBD, and the new CBD (Figure 2).

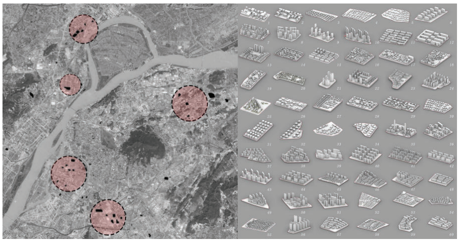
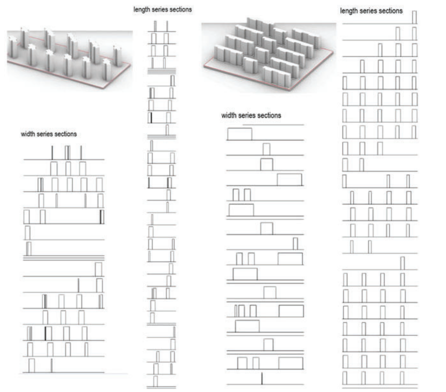


Figure 2. 60 residential blocks in Nanjing.

3.2. GENERATING URBAN SECTIONS

To investigate the degree to which a relationship exists between the physical indicators and the spatial characteristics of the blocks, we generate a series of sections of each block based on the parallel cutting method and calculate the corresponding 3 indicators through our program written in Rhinoceros Grasshopper. After processing the data of these 60 blocks and analyzing the corresponding urban sections, the results suggest that single slide parallel cutting can only present the geometrical shape of the buildings in one direction, and it cannot express the whole geometrical and spatial form of the block. In order to map the form of each building of the block more accurately, section lines parallel to the length and width of the building, respectively, are needed. In this way, each residential area leads to 2 groups of section slices and 6 sets of indicator data. 2 groups of section slices clearly show the different spatial arrangement and building height of each area while the indicator data indicates more detail information. Two different areas are selected to simulate the generating process. (Figure 3) Block 43 generates two kinds of series section slices, the width and the length and they are similar to each other. And LR of the length-average (2.150) is similar to the width-average (2.121). (Figure 3a.) As for block 41, the width series section is clearly different from the length series section and LR of the length-average (1.535) is as well quite different to the width-average (2.426). (Figure 3b.) Through the analysis of 2 groups of section slices and 6 sets of indicator data, it suggests that block 43 is a typical dot type high-rise area and block 41 is a parallel type multi-stories area.



	LR	AR	WR		LR	AR	WR
Len-aver	2.1499	7.4993	0.125	Len-aver	1.5351	7.1687	0.1991
Wid-aver	2.1213	7.5692	0.1262	Wid-aver	2.426	7.019	0.195
Aver	2.1356	7.5346	0.1256	Aver	1.9806	7.0939	0.1971

a. Block 43(high-rise tower block) b. Block 41(high-rise slab block)

Figure 3. Generating 2 kinds of series section slices and 6 sets of data.

4. Result analysis

The LR on the x-axis reflects the tortuosity of the urban section line, which indicates the height and density of buildings; and the AR on the y-axis presents the capacity of buildings. The WR on the z-axis represents the density of buildings. Combining these three axes leads to a three-dimensional coordinate, and the three section indicators give every block a unique “spatial fingerprint” and refer to different geometrical and spatial forms of the block.

In addition, the 2 groups of section slices and 6 sets of indicators result in two different ways to quantify the indicators and map the coordinates. The first is point coordinates, which take the average of the length indicators and width indicators as the measurement of each block. Point coordinates simplify data processing while blurring the geometrical and spatial characteristics of the area. The second is line coordinates. In this way, the values of the length and width indicators are both retained and thus produce two different points. By connecting the two points to a line, this unique line contains two variables, the angle and length, in three-dimensional coordinates. In addition, the line provides a way to describe the geometrical shape of the area more thoroughly. Sectionmatrix manages to separate residential areas in two different ways and find the corresponding relation between the physical indicators and urban morphology.

4.1. POINT COORDINATES:

Each residential block has its own distinctive density indicators; thus, each dot has its unique coordinate position. When grouping the different residential block points in the Sectionmatrix chart, obvious clusters are formed and divided by their similarities in terms of spatial structure (Figure 4). Analyzing the point positions in the coordinates and the corresponding spatial form of each area, we find that the chart has generated a kind of separation to naturally describe areas with different spatial attributes.

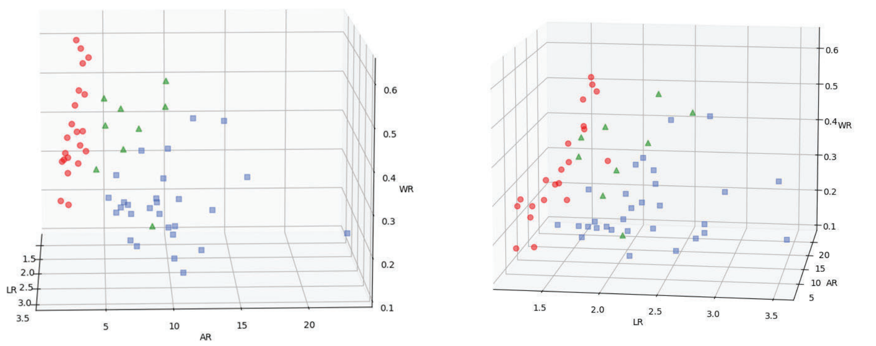


Figure 4. Point coordinate chart of the 60 residential blocks (Red circles represent low-rise blocks, green triangles represent multistory blocks and blue rectangles reflect high-rise blocks)

The point coordinate chart can first separate the areas by height. Low-rise areas are gathered together in one zone in the coordinates while multistory areas and high-rise areas are clustered in other areas. In addition, by analyzing the low-rise area, we find that Sectionmatrix can also separate the compact historical areas of the old town from spacious villas. When the LR ranges from 1.2 to 2.0, the AR ranges from 1.8 to 3.3 and the WR ranges from 0.3 to 0.4, the result implies a low-rise compact area. Otherwise, the result implies a low-rise spacious area. (Figure 5) The interaction between the variables appears to be more significant than their absolute values. For example, a high-rise area can have the same WR as an area with enclosed building blocks such as low-rise compact areas. The high-rise area is in fact built in a much less compact manner because of its height, so it has a higher AR. In Sectionmatrix, the position occupied by the high-rise areas is different from that occupied by the closed blocks.

Real urban forms are more diverse and complicated, and the values of the indicators also vary greatly. The point coordinates offer only a rough glimpse to describe and separate different types of buildings.

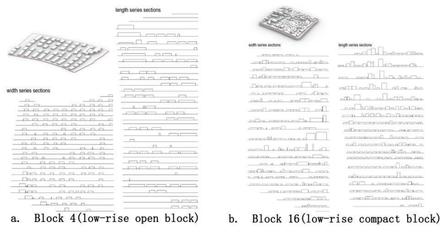


Figure 5. Low-rise block .

4.2. LINE COORDINATES

Lines in three-dimensional coordinates have two parameters: length and spatial position. In addition, in Sectionmatrix, the lines vary greatly. We arrange the blocks in length order and analyze their spatial positions.

A line is made of two different points that represent the average values of the section indicators along two slice directions. Thus, the longer the length is, the greater the difference between the two directions of the block (Figure 6). The lines can then be used to describe the parallel-slab type of buildings and the dot-type buildings.

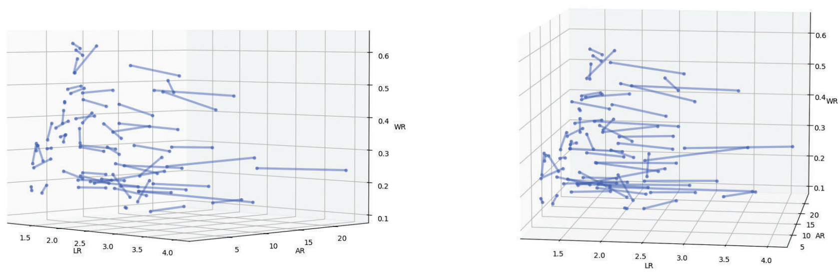


Figure 6. Line coordinates.

When the length of the line ranges from 0 to 0.50, it represents that the length of the buildings is similar to their width, which indicates low-rise even areas and typical tower-type high-rise areas (Figure 7a and b). It is difficult to separate these two types of areas only by length. By analyzing their spatial position in the line coordinates, these two different types of areas can be clearly separated. As the length increases, parallel slab type buildings and more diverse areas gradually appear. When the value is larger than 2, the area has great diversity and tortuosity, including both the characteristics of the parallel slab type of buildings and dot arrangement areas. In addition, this implies that the area has diverse functions (Figure 7c and d).

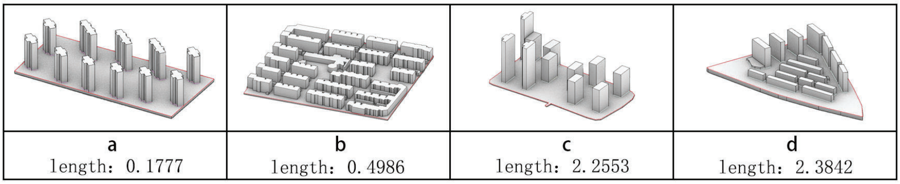


Figure 7. Blocks (length: 0-0.50) and blocks (length larger than 2.0) .

Through analysis, we find that the length of the line alone could only distinguish the spatial arrangements of the area in a rough manner and is insufficient. Only in combination with the spatial position and slope of lines can line coordinates describe urban forms more thoroughly.

Through analysis, low-rise areas have lines with relatively short lengths and steep angles while buildings with multiple stories often have longer lines with smaller angles. We find that when the length of the line becomes longer and the angle becomes steeper, it is due to low-rise areas often surrounded by other public buildings such as schools. In addition, the steeper the angle is, the more complex and tortuous the area is, which implies that the functions of the buildings in the area are more diverse (Figure 8).

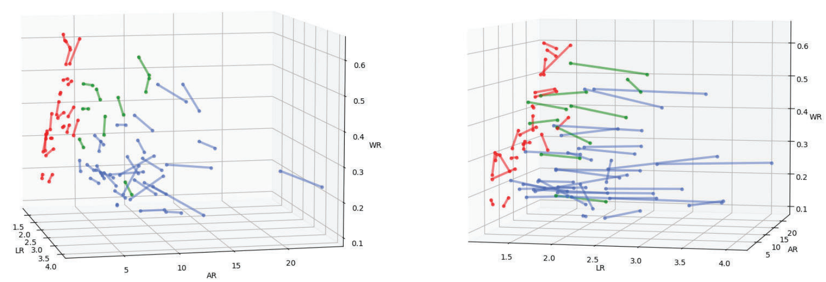
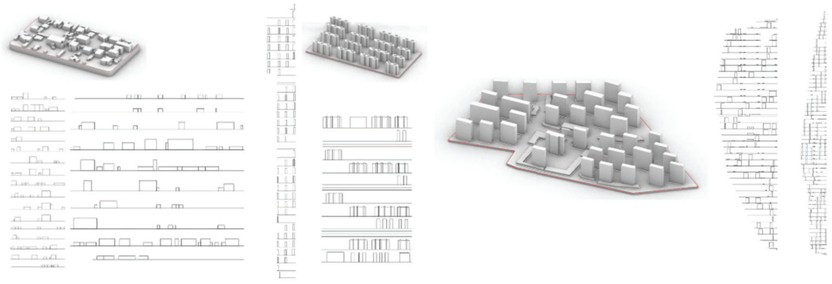


Figure 8. Red represents low-rise areas while blue represents high-rise areas.

We then take two extreme angles as examples: the area with the steepest angle (0.522) and the area with flattest angle (0.005) (Figure 9a). It is evident that the area with the steepest angle is a low-rise area while the other area is a high-rise area. We then take a high-rise area with a steep angle of 0.031 as a supplement (Figure 9b). This shows that the high-rise area with a 0.031 angle has rather diverse functions and a tortuous series of section slices. Furthermore, through detailed analysis, we find that line clustering in certain zones in the line coordinate chart is due to the building height, similar to the point coordinate chart. What truly makes line coordinates different from point coordinates is the angle and length that represent the diversity of functions and the tortuous series of sections. And it is obvious to see the tortuosity of the area from the series sections. (Figure 9)



a Low-rise area with the steepest angle (0.522) and high-rise area with flattest angle(0.05)

b high-rise area with a steep angle(0.031)

Figure 9. Comparison of areas with steep angle and with flat angle.

Areas are usually separated according to one factor: either the height or the spatial arrangement of the buildings. The proposal herein is quite a new way to describe urban form using the perspectives of height, spatial arrangement and even functions combined. In line coordinates, the parameters of areas contain abundant information and thus manifest various spatial arrangements. The angle, the length and the position of the line combined can describe the spatial arrangement, the diversity of functions and the geometrical shape of the area at the same time (Figure 10). The steeper the angle is, the more diverse and tortuous the area is. And with the length of line as a parameter, areas can thus be separated by height.

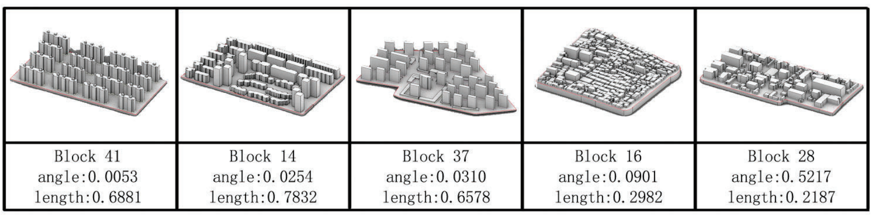


Figure 10. As angle increases and length decreases, area is more tortuous, more diverse and lower.

5. Conclusion and discussion

An urban section is another cognitive map of an urban area. In addition, a series of urban sections is a new way to map cities. The indicators of urban sections present the characteristics of urban form in a physical way and can be used to describe different areas of a city and different cities. A point coordinate chart uses the average value of indictors to describe and separate different spatially arranged areas. In addition, a line coordinate chart describes the functions and geometrical shapes of areas through the angles, lengths and spatial positions of lines in a further and detailed way. Through these two types of coordinates revealing the relation between density indicators and spatial form, Sectionmatrix provides a new way to understand urban morphology. Sectionmatrix can contribute to understanding a city from a ”section” perspective, and the results also suggest other possible applications of Sectionmatrix as a control instrument and test framework for entire cities’ planning and design.

The current research offers only a glimpse of some possibilities of using Sectionmatrix, and it only concentrates on the residential building scale in Nanjing. However, Sectionmatrix has not yet been fully exploited. With further discussion and analysis, other possibilities and functions of Sectionmatrix can be fulfilled. We hope that more attention will be given to Sectionmatrix and urban sections when mapping urban morphology.

Acknowledgement

This research was supported by National Natural Science Foundation of China (51578277) and Major Program of National Natural Science Foundation of China (51538005) and Student Research Training Program of China (202010284103).

References

Dong, J.: 2019, *Quantitative Analysis of Urban Form Based on Section Perspective.□in Chinese□*, Master’s Thesis, Nanjing University.

Kickert, C.C., Pont, M.B. and Nefs, M.: 2014, Surveying density, urban characteristics and development capacity of station areas in the Delta Metropolis., *Environment & Planning B: Planning &Design*, **41**, 69-92.24.

Li, X. and Du, J.: 2008, Analyses method and demonstration on city section, *Geograical Research*, **2**, 12-19.

Liu, Q. and Ding, W.: 2012, The Graphical Method and Its Significance in the Study of Urban Texture, *Architect*, **3**, 20-30.

M.B, P. and P, H.: 2004, *Spacemate: The spatial logic of urban density*, Delft University Press.

M.B, P. and P, H.: 2005, The Spacemate: Density and the Typomorphology of the Urban Fabric, *Nordisk Arkitekturforskning*, **4**, 55-68.

M.R.G., C. and M. P, C.: 2004, *Thinking about urban form, papers an urban morphology*, Oxford,.

PENG, D., HU, Y. and QIN, Q.i.n.: 2019, A Statistical Research on the Typical Patterns of Modern Housing Fabrics, Case Study of Nanjing, China, *Urban Form and Social Context: from Traditions to Newest Demands*, **3**, 573-583.

Steadman, P.: 2014, Density and built form: integrating ‘Spacemate’ with the work of Martin and March, *Environment & Planning B: Planning & Design*, **41**, 341-358.

Ye, Y.u. and Zhuang, Y.u.: 2016, The Raising of Quantitative Morphological Tools in Urban Morphology, *Urban Design*, **5**, 18-27.

Zhu, M.: 2017, Analysis Method of Mountain City Profile: Taking Chongqing Yuzhong Penisula as an Example, *Huazhong Architecture*, **3**, 56-64.

CITY CENTRES IN THE ERA OF SELF-DRIVING CARS: POSSIBILITIES FOR THE REDESIGN OF URBAN STREETSCAPES TO CREATE PEDESTRIAN-ORIENTED PUBLIC SPACES

SIU FUNG GEORGE LAU[1] and JEROEN VAN AMEIJDE[2]
[1,2]*The Chinese University of Hong Kong*
[1]*laugeorgelau@gmail.com* [2]*jeroen.vanameijde@cuhk.edu.hk*

Abstract. The forthcoming popularization of Self-driving Vehicles (SDVs) suggests a significant challenge in urban planning, as it enables new mobility patterns for urban citizens. While manufacturers have been developing visionary scenarios where cars become rentable mobile activity spaces, the impact of SDVs on the urban context is unclear. Through the analysis of the new social and technological functionalities developed by car manufacturers, and the projection of these functions into spatial scenarios of use within urban case study site, this paper explores the potential for the redesign of urban streetscapes to reclaim open spaces for pedestrian experiences and urban culture.

Keywords. High-density urbanism; Self-driving vehicles; Urban analytics.

1. Introduction

Since the advent of the Modernist doctrine, road infrastructure has dominated urban planning, in many cases segregating community fabric by wide roads (Flint, 2009). Car companies play an influential role in promoting the use of private vehicles, which undermines pedestrian's interests (Schwantes, 2003). As the auto industry plans to launch Self-driving Vehicles (SDVs) for the market by 2030, it is foreseeable that our urban environment will be impacted by another phase in the automotive revolution.

Despite the development of SDVs keeps accelerating in recent years, there is limited research on their impact to the urban environment. The main contributors to speculations about the impact on urban environments by SDVs are governments and car companies. An example is the 'Blueprint for Autonomous Urbanism', an urban design guidebook published by a governmental organisation to suggest pragmatic policies solutions to accommodate the arrival of SDVs (NACTO, 2017). This publication suggests a mild revision of existing street designs, by widening street space for pedestrians and cycling, and reducing space for vehicles. It assumes that large scale public transport, such as buses and trams, will continue to play a significant role in future cities. However, the usage of ride-sharing services with sedan size vehicles may dominate the majority of local transportation (Fehr&Peers, 2018). The Blueprint explores to a small extent the

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 609-618.

potential of designing flexible and dynamic urban spaces, but largely promotes the categorisation of different transport modes into lanes, while SDVs would not need these. On the other hand, publications by car companies explore future usage scenarios surrounding SDVs, visualising innovative uses of vehicles but without exploring the impact on the urban environment. A project from Ford titled 'The City of Tomorrow' with SDVs was subsequently criticised by urban planners as it depicts future cities with Modernist urban planning elements such as elevated walkways and wide road sections, resulting in low walkability (Speck, 2020).

The possibilities of autonomous vehicle systems, as they have been announced by car developers, point to the emergence of new urban mobility systems that extend beyond the scope of the vehicles themselves, as they inform issues such as ownership, management and spatial distribution across urban areas. The technical features of self-driving vehicles, such as sensor-based responses, route coordination in relation to other vehicles and real-time user inputs through mobile applications, allow conceiving traffic management in urban areas as a computationally controlled eco-system which can be adjusted dynamically to satisfy collective interests. Their capacity to improve pedestrian safety, road efficiency and function as an adaptive form of public transport, allows for the radical rethinking of urban streetscapes and of the use of urban open spaces. The possibilities for self-driving vehicles to function as mobile offices, shops, restaurants or hotel rooms open up new scenarios for the distribution and mixing of activity patterns of urban residents across urban centres and throughout the day.

The aim of this study was to explore a possible future scenario for the reshaping of urban open spaces, based on evidence of the new functionalities as they have been presented by self-driving car manufacturers. It adopted a research-by-design approach, using a case-study site in Tuen Mun New Town in Hong Kong to explore processes of urban transformation, public space planning and a data-driven distribution system for SDVs that prioritises human agency and collective social engagement.

2. Self-driving Vehicles' Opportunities Beyond Transportation

SDVs have advantages over conventional modes of transport, as they do not require driver's input and secure safe travelling thanks to controlling systems and the real-time analysis of the route environment. The possibility of conducting activities other than driving during travelling has been addressed by car designers in various speculative visualisations and prototypes. For instance, Toyota is developing its SDV system 'E-palette' with different modules like shops, restaurants, offices and hotel rooms (Toyota Motor Corporation, 2018).

Besides accommodating different interior activities, the overall anatomy of self-driving vehicles is also likely to change. Israeli startup Ree revealed a flat electric vehicle platform in 2019 that can be combined with different modules (REE Automotive, 2019). These SDVs enable efficiency gains, allowing to swap different types of cabins depending on demand, and for the separate charging of platforms and batteries.

These examples indicate that SDVs could enable productivity while transporting passengers, but could also be used as temporary stationary spaces to introduce additional functions into open urban spaces.

3. Possibilities for Changes to Road Infrastructure

There is a range of technical innovations for controlling the movement of SDVs, either individually in response to their environment or as a collective system, by coordinating movements across multiple cars. Car companies have been developing a 'platoon' mode of travelling, where SDVs can travel in clusters at high speed to minimize road occupation and also wind resistance. This functionality implies that road capacity and efficiency can be significantly increased, resulting in narrower and fewer lanes for expressways and trunk roads (Zhang, et al., 2020).

SDVs' ability to detect obstacles with sensors and manoeuvre safely around them, allows for the adoption of shared road systems. This principle allows for the removing demarcations between vehicles and pedestrians at low-speed sections, which benefits pedestrians' freedom of walking. Originally introduced by Hans Monderman in The Netherlands, well-known examples of the Shared Space principle are Exhibition Road in London and New Road in Brighton. Research on the traffic movement in both sites indicates that shared road systems create the flexibility to give priority to different users groups in different traffic conditions (Anvari, et al., 2016).

According to researchers, the shift from private ownership to on-demand ride services will reduce the demand for parking facilities between 67% and 90% (Zhang, 2017). Meanwhile, charging facilities can be placed on the outskirts of urban centres to avoid interference with public spaces. Due to their lower cost and flexibility, on-demand ride services could also replace conventional transportation such as minibuses and light rail. Subsequently, related infrastructure including stations and stops can be removed, releasing a significant amount of urban space for pedestrian-oriented planning.

4. Traffic Problems and Opportunities in Existing Urban Centres

To explore the changes to urban environments made possible by SDVs, a central urban site in Tuen Mun New Town in Hong Kong is selected as a case study area. The site represents 'high-income, dense cities' in Asia that are predicted to have the highest level of adoption of self-driving vehicles by 2030 (McKinsey&Co, 2016).

As almost 70% of the working population in Tuen Mun commute to work in other districts (Census and Statistics Department, 2016), the quality and experience of daily travel greatly impact people's quality of life. Wide roads with limited and difficult crossing, high footbridges, congestion and inefficient public transport connections contribute to a negative travel experience. Barriers caused by road infrastructure reduce public space usage by the community as a whole, and people with limited mobility in particular.

While Tuen Mun Highway experiences limited congestion during rush hour periods, minor roads around the town centre are congested for most of the time.

This is caused by a considerable amount of traffic flow to retail destinations, where traffic lights and limited parking and drop-off locations cause delays to an oversupply of private cars. This congestion does not only lengthen travel times but also affects pedestrians through the added noise, pollution and safety risks.

There is a wide range of literature advocating for well-designed streets. Jacobs and Appleyard established the values of public spaces and streets as platforms for 'good city life': "Liveability, identity and control, access to opportunity, imagination and joy, authenticity and meaning, community and public life, urban self-reliance, an environment for all" (Jacobs & Appleyard, 1987, p. 115). A recent publication titled 'Streets for People' offers that streets should perform well in both as a link and as a place. 'Link' refers to the directness of street connection, which is expressed in time, based on an average walking speed. 'Place' refers to a street that has activities that allow pedestrians to spend time, such as parks and shops. This parameter is quantified by measuring the number of activities on street sections (South Australian Active Living Coalition, 2012).

To assess the impact of traffic infrastructure on the walking experience in Tuen Mun, several routes from residential districts to popular places in Tuen Mun were assessed according to the 'Streets for People' method. Most of the routes are not performing well as both link and place, due to the many crossings or footbridges, and sections that do not have any active street frontage programming. Traffic lights at intersections cause waiting times in unpleasant conditions, and routes forced along seven-meter-high footbridges do not contain any additional functions that would animate the spaces (Figure 1).

The urban planning of Tuen Mun prioritizes vehicles over pedestrians, where wide roads and traffic lights contribute to the unpleasant walking experience. In the subsequent research-by-design section, the potential of SDVs will be explored to maintain traffic volumes yet offer improved urban environments for pedestrians.

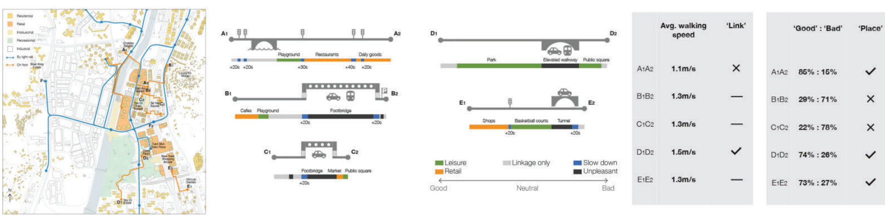


Figure 1. Street Quality Analysis, showing pleasant in orange and green colours and unpleasant sections in blue and grey colours.

5. Tuen Mun Town Centre: An Epitome of Urban Problems

A 1 x 1 km area was chosen for a speculative redesign, which contains the approximate area of Tuen Mun Town Centre. The site contains many of the urban experience issues described above, including wide road sections and poor ground-level walking experience. Walking routes within Tuen Mun Town Centre are obstructed by ground traffic, as the ground level serves as a large transport hub for public transport, including minibuses and a local light rail system (Figure 2). As a result, the majority of the people flow is at the first upper floors, where a public plaza and the main entrances to the town hall and library are accessible via an elevated pedestrian level and several footbridges. This elevated system, however, lacks the clarity of orientation, animation and freedom of route choice, and a majority of it consists of privately owned public spaces controlled by retail mall operators.

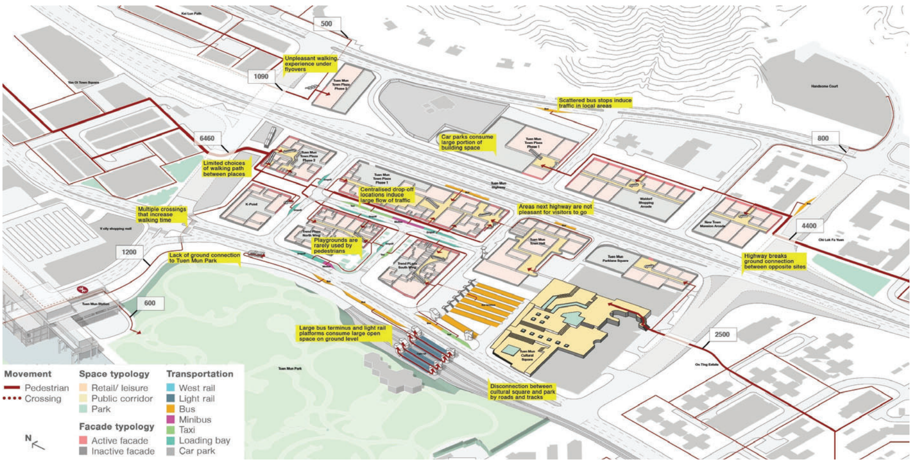


Figure 2. Current pedestrian flow at ground level in Tuen Mun Town Centre.

6. Adaptive Traffic Management Based on Self-driving Vehicles

The large-scale adoption of SDVs offers the opportunity to redesign urban streetscapes based on the cars‘ integrated technologies for improved safety, control and management. This research-by-design study explores the possibility of removing road infrastructure, pedestrian barriers and parking spaces, to create a shared road space that prioritises pedestrians’ freedom to navigate and socialise. Urban trunk roads such as Tuen Mun highway would continue to facilitate high-speed traffic, and therefore should retain barriers for safety reasons. Local distributor roads could be transformed to allow SDVs to plan routes freely at low speed used the ‘Shared Space’ principle, without fixed lane demarcations of pedestrian intersections.

Within these shared spaces, the movement coordination of all cars in the area would be controlled through a centralised computational system, allowing cars cluster together to free up space and time intervals for pedestrians (Figure 3). During peak hours when there are many vehicles, SDVs can be programmed to travel at moderate speed along planned paths, giving priority to the vehicles and instructing pedestrians to cross paths at specific locations or time intervals. During off-peak hours when demand for using SDVs is less, the cars can be programmed to prioritize pedestrian movements, slowing down or diverting routes to allow pedestrians to walk uninterrupted (Figure 4).

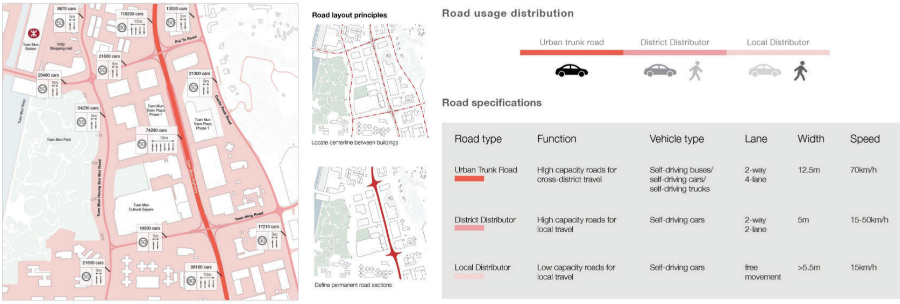


Figure 3. Road system in the future with shared roads (pink) as major public spaces.

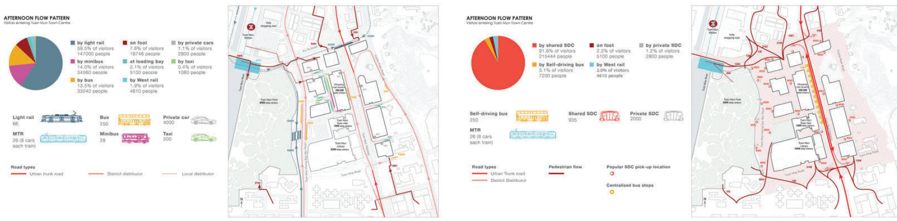


Figure 4. Types and volumes of different transport movements currently (left) and in the predicted future system (right) during off-peak hours.

7. The Introduction of On-demand Mobile Functions in Shared Spaces

On the case study site, the introduction of SDVs and the associated restructuring of transport systems would free up an open ground of approximately 10 hectares for public use. In order to maximize the opportunities for social processes on this common ground, there should be a system utilizing shared data to allocate space, which would encourage spontaneous activities at different periods during the day, and a new walking experience for people passing through the area.

This projection points to an important aspect around the control of these new types of dynamic spaces, that this should be managed as a public open space rather than allowing it to be dominated by commercial interests. ‘Public space’ refers to the ownership of the spaces, but also to assure that people from all layers of society are welcome to use the space. ‘Open space’ in this context would refer to the principle that the decisions about the materialisation of urban spaces are open to input from all citizens. Following the principle of ‘The Right to the City’ (Lefebvre, 1968; Harvey, 2008), the amounts and functions of SDVs in urban centres should be subject to governmental oversight for the purpose of enhancing collective interests and the quality of urban spaces.

A reference to support the idea of ‘common ground’ proposed in this case study is the open structures explored by Archizoom. In the 1969 project ‘No-Stop City’, an infinite grid of sheltered space is provided for people to choose freely where and how they would like to inhabit the space. While basic facilities such as bathrooms were provided, actions and activities were all determined by the users (Branzi, 2006). Similarly, the idea of common ground in this project is to aim for minimal intervention on open space usage and let users decide and negotiate.

8. Dynamic Adaptation of Public Space

This research-by-design proposal reveals the opportunities of a large and flexible public open space, keeping the area free of permanent fixtures to maximise the potential of a dynamic configuration of activities enabled by SDVs (Figure 5). Similar to current on-demand services such as Uber, functions can be allocated based on real-time user input, using geolocation data and electronic payment systems. Functions could be physically located near areas where there is a higher number of (anticipated) requests, opening the configuration of the space up to a democratised or market-driven system of dynamic demand and supply.

The project explores the possibility for a control system of SDVs that is not just based on the number of vehicles allowed in a certain area perimeter, but that is spatialised within the open spaces of the city. Using interactive maps accessible to both providers and users of mobile services, a spatial negotiation can take place based on proximity, cost, and attractiveness or quality of the service. To facilitate temporary static functions enabled by SDVs such as food trucks, mobile meeting rooms or grocery shops, public spaces can be subdivided into grid-based plots, where each plot can document real-time and statistical data on current and past uses. This data system, which is similar to current Google Maps functionalities, should be accessible to all stakeholders to facilitate an equitable allocation of space and services.

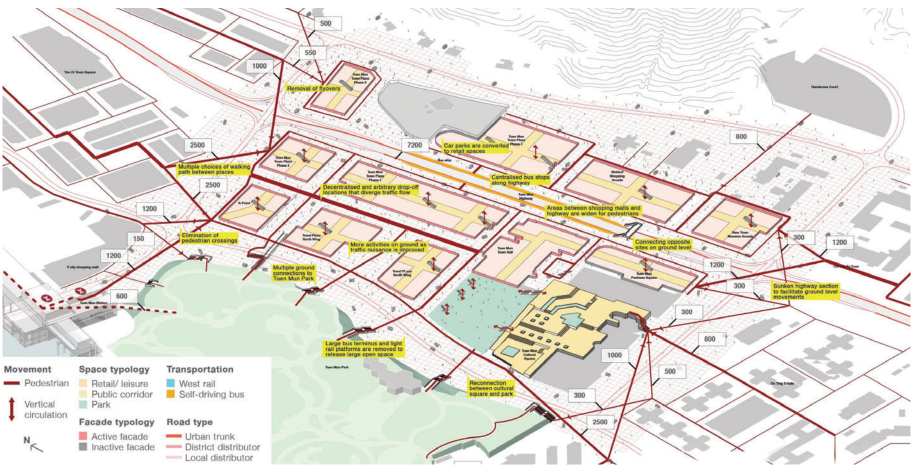


Figure 5. Future scenario of ground level pedestrian flows, following a comprehensive redesign of traffic systems and public open spaces in the area.

9. Case Study Scenario Simulations and Visualisations

To test how the choreographies of SDVs could result in more open space, dynamic configurations of functions and improved social processes, several scenarios of vehicle distributions and flows were modelled using animation software. This exercise allowed to verify the capacity of the road spaces and the urban area as a whole, modelling the same number of trips as in the current situation, based on government data on road traffic volumes and public transport usage. Three periods of a day were chosen to play out different scenarios for SDV movements, including the morning rush hour, mid-afternoon, and evening periods.

For the morning is rush hour period, the large number of commuters travelling between residential locations requires SDVs to be prioritised over pedestrians. The shared road systems are switched to district distributor road protocol, organising vehicles in compact clusters with 200 m distance gaps in between, to enable 20 seconds pedestrian crossing opportunities at one-minute intervals. Dynamic signals assure pedestrian safety while the maximum speed is capped at 50 km/h. It is assumed that a percentage of residents will prefer to use privately owned SDVs, and the majority of commuters will use public transport for cross-district commute, in the form of self-driving buses and the MTR. People living further than 10 minutes walking distance from a regional transport station would use shared self-driving shuttle vehicles, while the improved walking environment invites local people to walk to stations. Along the main walking routes, catering vehicles are stationed to provide breakfasts, informed by real-time data on people concentrations and demand. Local companies can position mobile office vehicles in the most convenient locations to bring collaborators together for meetings or events, while other spaces in the common ground are reserved for social services to serve different groups within the local population. Functions such as health and exercise programmes, education and elderly support are enabled by specialised vehicles distributed near target audiences (Figures 6.1, 6.2, 6.3).

During the afternoon, local pedestrians and street activities are prioritised, and SDV movements in the area are limited in number and to a maximum speed of 15 km/h. This allows vehicles to dynamically avoid pedestrians who can walk freely in the shared road spaces. Existing retail malls can be expanded with retail and social activities at neighbouring public spaces, using stationary shopping vehicles to configure outdoor market areas. As the current retail malls are organised around elevated pedestrian corridors, these markets help activating the neglected ground-level shopping experience. Similar to the morning scenario, part of the public space is reserved for cultural programs and social services (Figures 6.4 & 6.5). At night, the public spaces are used for parked vehicles that function as mobile homes or micro-apartments, to address the shortage and unaffordability of housing in the local area (Figure 6.6).

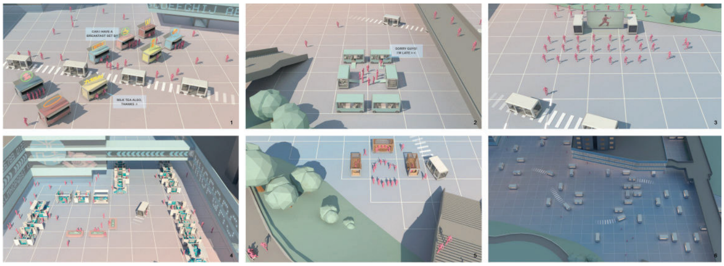


Figure 6. 1)SDVs with food truck modules arranged for commuter pedestrian flows. 2)Mobile workspaces cluster for company employees. 3)Morning exercise area for elderly residents. 4)Temporary market arrangement with additional seating to activate public spaces outside the existing retail mall. 5)Street performance surrounded by seating provided in parked vehicles. 6)SDVs stationed as additional micro-apartments to alleviate the housing shortage in the area.

10. Conclusions

The introduction of SDVs at large scale into urban centres offers several opportunities as well as potential challenges. This paper argues that in order to avoid the over-congestion of urban streetscapes by wide range of commercially operating vehicles, the amount and spatial distribution of SDVs should be controlled according to criteria that ensure public spaces that are pedestrian oriented and inclusive. The technologies that ensure coordinated, safe and responsive vehicle movements allow for the removal of traditional safety measures that limit walkability such as pedestrian crossings, barriers or footbridges. The increase in road use efficiency and the reduced need for parking allows for a reduction in road space, freeing up vital space for better quality pedestrian spaces. Shared space principles in low-speed traffic areas can be managed to prioritise pedestrians during most periods of the day, while platooning protocols during rush hour periods can still allow for opportunities for same-level crossing, which increases the walkability of urban centres.

The additional functions of SDVs allow for the merging of travel and productivity time for commuters, and also for choreography of temporary spaces stationed around urban space to serve pedestrians. This ability suggests new urban space experience and management, where the real-time negotiation between supply and demand produces dynamic fluctuations of vehicle and people flows.

The case study design and simulation exercise in Tuen Mun Town Centre has produced a vision on how future cities could operate, bringing changes to the physical urban landscape as well as to the social and cultural facilities of the area. Commercial operators are welcomed to bring additional vibrancy and customised services to local residents, but it will be necessary to assure that a proportion of the space and services is reserved for vulnerable groups.

While this study has aimed to speculate on the general organisational, spatial and social consequences of introducing SDVs into urban centres, several different types of studies could be undertaken to further develop the traffic and urban planning concepts explored here. While many of the technical possibilities will likely be developed by the industry, we argue that urban designers and city authorities have the urgent task to envision policies for the management of SDVs, to maximise on the positive benefits that these can bring and to support the expansion of vibrant, supportive and inclusive urban spaces.

References

"Streets for People: A Compendium for South Australian Practice" : 2012. Available from South Australian Active Living Coalition<https://intermethod.com.au/portfolio_page/streets-for-people-a-compendium-for-south-australian-practice/> (accessed 1st December 2020).

"Working Population by Sex, District Council District, Place of Work, Year and Working Age" : 2016. Available from Census and Statistics Department<https://www.bycensus2016.gov.hk/en/bc-mt.html?search=C209> (accessed 1st December 2020).

"Automotive revolution – perspective towards 2030" : 2016. Available from McKinsey and Company<https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/disruptive-trends-that-will-transform-the-auto-industry/de-de> (accessed 1st December 2020).

"Blueprint for Autonomous Urbanisms" : 2017. Available from National Association of City Transportation Officials<https://nacto.org/publication/bau2/> (accessed 1st December 2020).

"Toyota Launches New Mobility Ecosystem and Concept Vehicle at 2018 CES®" : 2018. Available from Toyota Motor Corporation<https://global.toyota/en/newsroom/corporate/20546438.html?_ga=2.214637207.1857995100.1607826198-706742117.1607826198> (accessed 1st December 2020).

"The Annual Traffic Census 2018" : 2019. Available from Transport Department<https://www.td.gov.hk/en/publications_and_press_releases/publications/free_publications/the_annual_traffic_census_2018/index.html> (accessed 1st December 2020).

"What are TNCs Share of VMT?" : 2019. Available from Fehr and Peers<https://www.fehrandpeers.com/what-are-tncs-share-of-vmt/> (accessed 1st December 2020).

"Ree Cooperates with Hino Motors to Showcase New Flatformer Concept Vehicle at the 46th Tokyo Motor Show" : 2019. Available from REE Automotive<https://ree.auto/press-release/ree-cooperates-with-hino-motors-to-showcase-new-flatformer-concept-vehicle-at-the-46th-tokyo-motor-show/> (accessed 1st December 2020).

Anvari, B., Bell, M.G.H., Angeloudis, P. and Ochieng, W.Y.: 2016, Calibration and Validation of a Shared Space Model: Case Study, *Transportation Research Record*, **2588**, 43-52.

Branzi, A.: 2006, *No-Stop City*, Hyx.

Flint, A.: 2009, *Wrestling with Moses: How Jane Jacobs Took On New York's Master Builder and Transformed the American City*, Random House Trade.

Harvey, D.: 2008, The Right to the City, *New Left Review*, **53**, 23-40.

Jacobs, A. and Appleyard, D.: 1987, Toward an Urban Design Manifesto, *Journal of the American Planning Association*, **53**, 112-120.

Lefebvre, H. 1996, Writings on Cities, *in* E. Kofman and E. Lebas (eds.), *The Right to the City*, Blackwell, Cambridge, Massachusetts, 158.

Schwantes, C.A.: 2003, *Going Places: Transportation Redefines the Twentieth-Century West*, Indiana University Press.

Speck, J.: 2020, "Ten rules for cities about automated vehicles" . Available from <https://www.cnu.org/publicsquare/2020/02/27/ten-rules-cities-about-automated-vehicles> (accessed 1st December 2020).

Zhang, L., Chen, F., Ma, X. and Pan, X.: 2020, Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research, *Journal of Advanced Transportation*, **2020**, 1-10.

Zheng, W.W.: 2017, *The Interaction Between Land Use and Transportation in the Era of Shared Autonomous Vehicles: A Simulation Model*, Ph.D. Thesis, Georgia Institute of Technology.

OPTIMISING HARBOUR TYPOLOGY IN THE FORM FINDING PROCESS USING COMPUTATIONAL DESIGN: A CASE STUDY OF A GREENFIELD PORT FACILITY

SEOW JIN KOH[1], CHIEW KAI MOK[2], RACHEL TAN[3] and EDMUND CHEN[4]
[1,2,4]*Defence Science & Technology Agency*
[1,2]*{kohseowjin|mokchiewkai}@gmail.com*
[4]*chen_mingyie@yahoo.com*
[3]*Sembcorp Architects & Engineers*
[3]*rachel.tanwx@gmail.com*

Abstract. The bulk of computational design strategies and research have been focused on issues related to architectural form and building systems. This is done by employing computational tools to optimise architectural forms, building performance and generally, improve quality of living. Many of these methodologies are based on the concept of form finding - varying geometric elements to generate and evaluate options to derive optimised solutions. However, beyond building designs, the concept of form finding can find its relevance in other design applications too such as engineering, landscape, and in our case, the design of ports, or more specifically harbour typology. In most building scenarios, the plot of land earmarked for development is typically selected beforehand, hence little exploration have been done to optimise land topology, when in fact the profile of land is the governing feature in most designs. For performance driven facilities like ports with high economic and political impact, there is value in optimizing topology to maximise throughput. Through the multi-disciplinary and collaborative effort of stakeholders and specialists, our project explored optimizing harbour topology via performance-based approach using computational design. The phenomenon, including impact and effects of trade-offs, are discussed and presented in this paper through a case study of a Greenfield port facility.

Keywords. Form finding; form optimisation; port masterplanning; harbour typology; computational design.

1. Introduction

1.1. USING GENERATIVE DESIGN FOR LAND USE MASTERPLANNING FOR PORTS

Looking beyond architectural form and building systems which the bulk of computational design strategies are focused on (Belesky, et al. 2012), the concept of form finding and form optimisation (Colakoglu 2005;2010;2011) which many

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 619-628.

of these computational designs are based on, may also find relevance in land use master planning, especially for performance driven facilities like marine ports where its productivity is driven by its capacity and efficiency (Ligteringen 2017). In other words, shape of land (and sea) directly affects performance of ports in terms of vessels' manoeuvrability and port capacity, as generation of land restricts sea space affecting port throughput, and generation of more sea space impedes land workflow and efficiency. Restrictive conditions like these act as interacting variables, defining a design space that sets the boundaries for any speculative explorations (Bunster 2013). Even as designing of ports is not new, harbour typology have not evolved significantly and little have been explored on the relationship of land and sea spaces in computational design, presenting much opportunities in this area.

1.2. CASE STUDY

The development is a real-world case study where the client seeks to construct a multi-purpose port facility on a Greenfield site in Singapore. The study consists of front-end planning, and if assessed to be favourable, to lead up to detailed design and land reclamation for construction of the harbour. In such early stage of planning, the client finds computational design useful for investigating the solution trade space, with the objective of finding the best harbour profile optimised for their port operations. This is the first time computational design is used for developing harbour profiles in Singapore. To help computational designers who are not familiar with the port planning process understand better, the client had arranged for them to participate in the user-engagement workshops held with various stakeholders as part of the study for understanding the port planning requirements better. The workshop seeks to develop the overall strategic plan and outlining functional and performance requirements. This helps to establish spatial needs and sets the plan up towards stakeholder driven instead of only expert driven to improve quality of the plan (Kunze & Schmitt 2010). The computational designers will later work with the port planners to scrutinise and translate the requirements into computational parameters.

2. Methods and Results

2.1. OVERALL DESIGN PROCESS

The design process takes reference from established master planning guides for port facilities, which are guidelines used widely in the marine industry (MarCom WG158, PIANC 2014). Guided by the conventional port planning process as well as requirements established by the stakeholders, the overall computational process was then set up to expand the solution space (i.e. form finding) and then optimizing generated solutions (i.e. form optimization) to distil the best performing profiles. The steps include (1) setting requirements, (2) generation of harbour profiles, (3) testing feasibility of options, and (4) sense making of results. This process fundamentally replicates the conventional port planning process but is tweaked to adapt to computational design methodology. This is to help stakeholders draw parallel to the process they are familiar with, an important consideration when employing computational techniques through a collaborative effort to gather meaningful inputs.

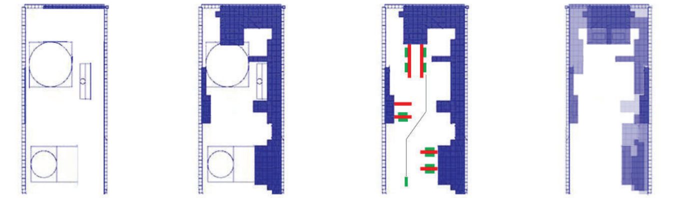


Figure 1. Overall Design Process.

2.2. STEP 1: SETTING REQUIREMENTS

In early stages of port master planning, spatial requirements are set at high level, relating mainly to navigation, berth orientation and location, hinterland connections and stakeholder requirements (MarCom WG185, PIANC 2019). In the computational design process, these requirements are set as initial parameters and are used for generation of options in the form finding process and evaluation of options in the form optimization process. For this port facility in Singapore, the client has focused mainly on navigational requirements for driving the harbour design.

- Spatial Requirements. The client intends to set aside 60% of the plot for sea and 40% of the plot for land, with the possibility of ±10% variation in space allocation. Sea spatial requirements were gathered at this stage where clients require adequate sea space for maintenance yard and small craft facility. These requirements are later used as key criterion in the computational model as part of the form finding process, where the land area is used as upper limit during the generation of harbour profiles.
- Design Vessels. The client provided a list of vessels planned to be berthed in the facility, with the largest vessel expected to be received at the port facility to be 200m, length overall. To cater for flexibility, the computational model was set to optimise profile edges towards 200m in length to create "modular berths" to allow the vessel the ability to berth anywhere.
- Turning Circle. Within the basin, it is required to cater clear sea space for vessels to manoeuvre safely during directional change. This translates to a minimum clear turning circle radius within the sea basin. In the computational model, this was used as one of the criteria for generating harbour profiles.
- Berth Orientation. Based on the land parcel, port planners have derived various berth orientations that were viable. These orientations are used for generation of piers in the computational model for berthing of vessels. Ideally, vessels navigating within the harbour should not deviate too much from the original path to travel to assigned berth, especially for larger ships. This consideration was coded in the algorithm for testing the feasibility of profiles in step 3.

2.3. STEP 2: GENERATION OF HARBOUR PROFILES

To maximise solution space, two methodologies with varying degree of freedom were employed for generation of profiles. (1) Parametric Modelling, and (2) Grid-Based Generative Approach. These approaches are part of the form finding process to generate as many different profiles as possible, prior to testing these options in the form optimisation process.

2.3.1. Parametric Modelling

In parametric modelling, the form finding process was performed by modelling interface between land and sea (i.e. the shore) as parametrically defined associative geometry, and varied to generate profile options. In this case, the parametric variables of the model are based on land depth, and by varying the land depth on the parcels to its North, East and West to generate land profiles. The algorithm considered total land and sea area of the profiles, where profiles beyond the requirement (i.e. 60% sea, 40% land) are not shortlisted.

2.3.2. Grid-Based Generative Approach

In grid-based generative approach, discrete grid cells are used in the form finding process and optimised using genetic algorithm based on performance criteria to obtain top performing options. Firstly, "obstacles" representing the sea spatial requirements are assigned on random within the boundary. These include the maintenance yard, turning circle, small craft facility etc. Then, land parcels represented by modular grids (i.e. 40m x 40m) are "spawned" on random to form the land mass. The intent behind assigning "obstacles" prior to generating the profiles is to increase the fitness of the options, as the grid-based generative approach methodology could generate indefinite number of options and to filter the best performing options would take up too much computing power and too much time. This is as shown in Figure 2, where "obstacles" are assigned in random positions and land mass are generated around these obstacles to form the profiles.

Figure 2. Land Mass Generated around "Obstacles" to Form Profiles.

The profiles generated will then form the initial population to be optimised using genetic algorithm. These profiles are optimised based on evaluation criteria developed together with the client, set as genomes in the algorithm, including "clear basin area", "land edge length", "land contiguity" etc. This is to favour profiles with open basin spaces for manoeuvring and longer edge length for higher utility of shoreline such as allowing wharf berthing of vessels. The weightage for the evaluation criteria were ranked based on Analytic Hierarchy Process (AHP), a technique client find fitting for such multi-criterion complex problems, as they were able to breakdown the requirements in a structured manner to organise their priorities. In the application of computational design, the technique was also useful for contextualising priorities to develop numerical weights for single-objective optimisation to derive a final fitness score.

Top performing options are then shortlisted for feasibility testing. Figure 3 shows the profiles generated using the two approaches organised by fitness scores in early optimisation stage, whereas Figure 4 shows the profiles as more optimisations are employed. It is worthy to note that with more generations, the grid-based profiles improve in performance over the parametric profiles, and gradually converge to a common profile across the top performing profiles.

Figure 3. Profiles Generated using Parametric Modelling and Grid Base Generative Approach.

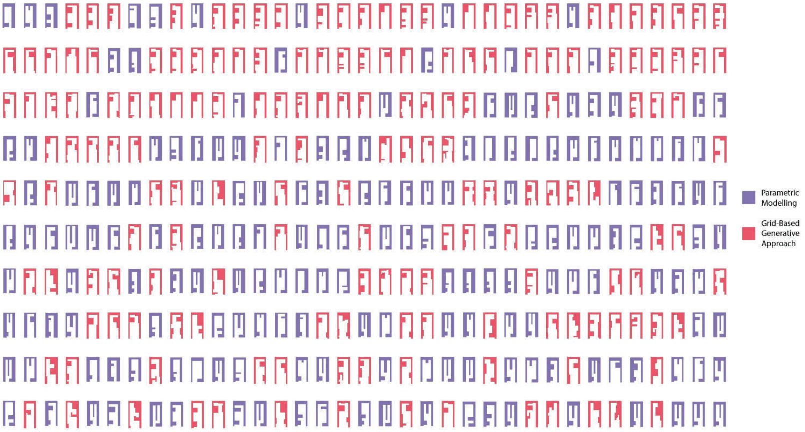


Figure 4. Optimised Profiles with More Generations.

2.3.3. Adapting Computational Models for Client's Understanding

While the Grid-Based algorithm was set up to also generate profiles similar to Parametric Modelling, it was observed that the client had difficulties in drawing parallel between the algorithm and conventional port landuse planning process and was unable to associate the profiles for actual port use. Hence, the Parametric Model was set up to provide that half step as the algorithm mirrors the port landuse planning consideration more closely, where the depth of land was normally used as a key parameter. This is an important consideration especially for clients engaging computational designers for the first time. Where computational design is normally considered to be more relevant in academia, these considerations could help clients understand the subject better and achieve better 'buy-in' to the methodology.

2.3.4. Comparison of Approaches

The key difference between the two approach is in the form optimisation process. In Parametric Modelling, the form optimization process take place in step 3 during the feasibility testing to sieve out non-performing options. In Grid-Based Generative Approach, the optimisation process was intrinsically built within the algorithm, where genetic algorithm was employed to iterate the options to derive good performing profiles. As the discrete nature of Grid-Based Generative Approach sets the algorithm up to produce large number of non-performing options which could increase computational time in later steps, it was ideal to optimise the solutions up front in step 2. By employing genetic algorithm, higher population of phenotypes could also be set to further expand the solution space and be more exhaustive in considering all options using the same computational power. Employing the two approaches, the options were then brought into step 3 for feasibility testing.

2.4. STEP 3: TESTING FEASIBILITY OF OPTIONS

The next step of feasibility testing involves generating seaward facilities to simulate vessel approach to determine vessel manoeuvrability within the basin. This sieves out non-performing options that does not meet the operational requirements. The testing is a two-step process, including (1) generating piers of various orientation and (2) assigning vessels to the berths. For each option, calculation for the berthing length and angle of approach for each vessel assigned was recorded as its fitness score to determine the good performing profiles.

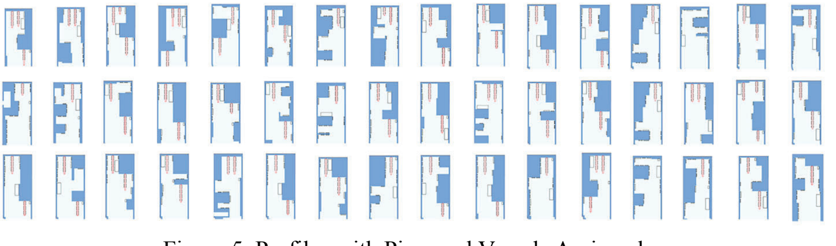


Figure 5. Profiles with Piers and Vessels Assigned.

2.5. SENSE MAKING TO DERIVE HARBOUR TYPOLOGY

Due to the extent of variability that is inherent with employing multiple layers of computational techniques, employing suitable methods for filtering data types was important to derive meaningful insights. For this case study, two methods of classification were applied, including (1) visual-based and (2) performance-based.

2.5.1. Visual-based Classification

As with conventional building typology, visual classification is a powerful tool for determining harbour typology. This was employed after Step 2 in the generation of harbour profiles, in an attempt to identify the most favourable type of land profile based on client's requirements. The profiles were categorised by location of land mass, with four main archetypes being identified: Inverted 'F', 'M' Mass, Multiple Mass and 'F' Mass. This categorisation effectively defines the vessels' navigational profile in the basin, one of the key considerations in master planning of ports. The profiles in each archetype were further superimposed to derive a common profile.

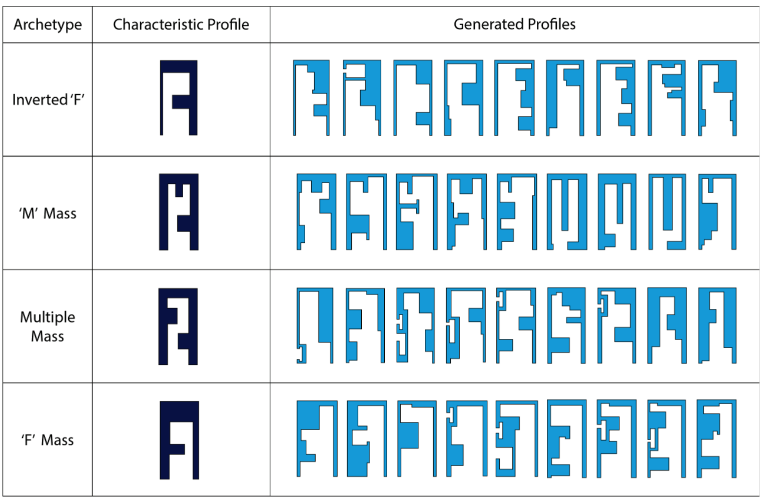


Figure 6. Harbour Profile Archetypes.

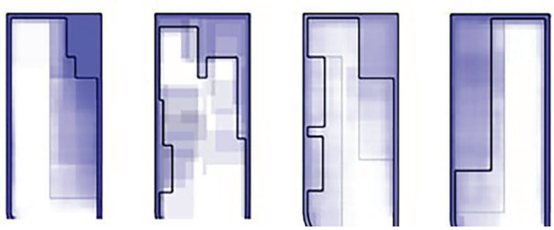


Figure 7. Heat Map to Identify Common Profile.

2.5.2. Performance-based Evaluation

The performance-based evaluation criteria were based on the AHP hierarchy developed earlier, but expanded to include criteria for vessel manoeuvrability from step 3. Tabulating the fitness scores computed at each stage, the final performance scores were derived. These scores were then used to shortlist the high performing profiles.

2.5.3. Sensemaking of Results

The two techniques were not used exclusively but in conjunction to draw insights from the results generated. After classifying the profiles by archetypes, we further ranked the profiles based on the fitness scores to examine which archetype performed better, and how changing the criteria weights would change the scores of the profiles. An average score for each archetype to represent the performance of the common profile was also tabulated. Client was able to see how changing their prioritisation would favour the type of profiles, and find this computational study useful to outline the flexibility of the land profiles to further validate their decision before conduct of any physical reclamation work, when it may already be too late. It was interesting to note that results were not always consistent, and profiles that looked similar visually could have very different scores. Understanding the logic and performing sensitivity studies would require more elaborate data crunching, as further discussed in Tan et. al (2020).

3. Discussion

The extent of complexity of the model and how harbour profiles generated led to diverging conclusions was fascinating. However, conflicting results and overload of data also led us to scrutinise and refine the process more, trawling through every parameter and constraint put in the algorithm to ensure meaningful results. Where required, we deliberately took a few steps back and adjust the algorithm to infuse more variability and filter better performing results quicker. For novel methodologies like this, there are no similar data to benchmark against to give clients the confidence they need (Tan, et al. 2020). Hence, it is useful to highlight trade-offs from varying priorities to aid clients in making informed decisions. This was well illustrated with the methodology.

Besides generating best performing options, the computational methodology also generated technically feasible but unconventional profiles which would not have been designed manually. For example, the model generated options such as dedicated small craft basin and multiple basins design, which when we presented to the client, thought were all feasible ideas that are worth exploring. This highlighted the degree of depth and breadth of solutions that computational models were able to bring to the table which deeply impressed the clients.

While the algorithm may be complex and challenging, we found most difficulties in Stage 4, as some of the results were found to be conflicting and we could not rationalise the behaviour behind. Therefore, there were multiple iterations with client on presentation of the results, and even just to agree on the best approach to move forward and conclude the study. Amidst the discussions, we also observed how clients were starting to lose trust in the methodology and how computational designers were losing their patience. Hence, mutual understanding is important in such collaborative efforts and both parties must manage their expectations.

Through the results, we could quantify how interacting variables between the spaces affected overall performance of the port. In this regard, the two spaces may be described as a 'cross-disciplinary' system with an interdependence directly impacting the outcome. By employing generative design methodology, it effectively simplifies the complex multi-level, multi-criterion form finding problem to distil insights and optimise spaces, even generating feasible profiles that presents different perspectives to bring about opportunities that could be missed if designed by hand.

For operational facilities like ports, our work on harbour typology is only the first step forward to outline the spatial needs. In early Masterplanning stage, it is important to provide maximum flexibility in laying out spatial geometric requirements to avoid excessive early investment (PIANC WG185 2019). To truly optimise operations for downstream activities, it is valuable to develop the computational methodology further to go beyond conceptual planning and include other considerations such as land operational workflow (e.g. land access, storage area, movement of goods), marine operations (e.g. berth turnaround time, tug operations), and environmental factors (e.g. harbour basin resonance, wave heights), of which are all directly influenced by the shape of harbour and basin.

4. Conclusion

Up till today, port master planning has been extremely tedious. Being a specialised trade involving high economic trade-offs, port designers and master planners are typically engineers with hydraulic training (Ligteringen 2017). They often are not exposed to computational design methodologies, which are more widely employed in architectural domain. What is presented here is only one case study. However, the methodology presented here is not limited to port facilities. These considerations captured are scalable for other complex operational infrastructure with interacting stakeholder requirements and clear throughput, including facilities such as airports, maintenance depots or production factories.

Just like in landscape design (Belesky, et al. 2012), there is a gap of unfilled potential for computational design techniques in port master planning, or even operational infrastructure altogether. Developing and distributing such techniques will empower designers and planners, leading to large payoff both economically and socially.

Acknowledgements

We would like to thank Angeline, Jun Rui, Kai Qi, Eng Hua, Cheng Hua, Eddie, Jing Zhi and all who supported the team throughout the study.

References

MarCom WG 158, P.: 2014, “Masterplans for the Development of Existing Ports (2014)” . Available from <https://www.pianc.org/publications/marcom/masterplans-for-the-development-of-existing-ports> (accessed 26 November 2020).

MarCom WG 185, P.: 2019, “Ports on Greenfield Sites – Guidelines for Site Selection and Masterplanning (2019)” . Available from <https://www.pianc.org/publications/marcom/wg185> (accessed 26 November 2020).

Belesky, P., Monacella, R., Burry, M. and Burry, J.: 2012, A Field In Flux: Exploring the Application of Computational Design Techniques To Landscape Architectural Design Problems, *[Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture*, Cincinnati, 194 - 201.

Bunster, V.: 2013, How to Customize Architecture under Heavily Prescribed Design Conditions? Principles and Prospects for an Evolutionary System, *Proceedings of the 17th Conference of the Iberoamerican Society of Digital Graphics*, Valparaiso, 319 - 323.

Colakoglu, B.: 2011, Introduction to Architecture Studio: Geometry, Rules and Patterns, *29th eCAADe Conference Procedings*, Ljubljana, 745 - 750.

Colakoglu, B. and Dionyan, S.: 2005, A Parametric Form Generator - ConGen, *23rd eCAADe Conference Procedings*, Lisbon, 623 - 628.

Colakoglu, B. and Keskin, G.: 2010, Form Generator: A CAD tool for conceptual design developement, *28th eCAADe Conference Proceedings*, ETH Zurich, 411-417.

Kunze, A. and Schmitt, G.: 2010, A Conceptual Framework for the Formulation of Stakeholder Requirements, *28th eCAADe Conference Proceedings*, ETH Zurich, 697 - 705.

Ligteringen, H.a.n.: 2017, *Ports and Terminals*, Delft Academic Press, Delft.

Tan, R., Patt, T., Koh, S.J. and Chen, E.: 2020, Exploration & Validation - Making sense of generated data in large option sets, *Proceedings of the 38th eCAADe Conference - Volume 1*, Berlin, 653-662.

INTERACTIVE VIRTUAL SAND TABLE

A theoretical review on its application towards Urban Planning

YAO CHEN[1], TIANTIAN LO[2], XIANGMIN GUO[3], RUIJIE DU[4] and XINCHUANG HU[5]
[1,2,3,4,5]*Harbin Institute of Technology (Shenzhen)*
[1,3,4,5]*{1280519315|24904404|262854714|1051246725}@qq.com*
[2]*skyduo@gmail.com*

Abstract. The sand table is a tool of expression of urban planning.With the development of computer science and technology,virtual reality technology is playing an important role in many aspects of urban planning and design,as well as,the virtual sand table.This article analyzes the limitations of the current urban planning sand table from designers‘ and other participants’ perspectives. It analyses the advantages of applying interactive technology in a sand table for urban planning and proposes using such interactive technology in the future. This paper will also investigate three aspects of interactions: human-computer interaction technology, collaborative interaction technology, remote visual interaction technology. The application of interactive technology on the virtual sand table, on the one hand, can carry out a multi-angle forward-looking analysis of the problems of urban construction and improve the efficiency of planning and approval, and development; on the other hand, it can increase public participation in urban planning and design.

Keywords. Interactive technology; urban planning; urban planning sand table; electronic sand table.

1. Introduction

Urban planning refers to design and direct the harmonious development of Spaces to meet social and economic needs.The focus of the design process is to fully consider the public interest and balance various contradictions□Li□2020□. In traditional urban planning and design, a physically scaled sand table model is usually made first (Li, 2013). As a result of the time-consuming model-making process and laborious modification, the cost of having such a model is very high yet it has considerable limitations with information that is not very accurate. In recent years, remote sensing and telemetry technology (Cai, 2013), 3D modeling technology (Li & Jia, 2018), and computer graphics (Yu & Zhang, 2007) have been gradually introduced into the research methods and means of urban planning, providing improved technical means for design planning and development.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 629-638.

Urban planning model as the final form of expression, can systematically express the planning and layout of the city.With the comprehensive application of computer technology,urban planning uses geographic information systems (GIS) and other infrastructure platforms to combine urban information resources uses three-dimensional (3D) visualized technology(Liu, 2020) and urban digital twin(Dembski et al, 2020) to assist design. But this tools are still presented through a screen.It is not as easy for users to adapt to the new interactive mode even though it allows users to control the model more flexibly. Users still prefer the traditional interaction method of the sand table where they can intuitively interact with the model to better understand urban planning and design. The arrival of VR offers an opportunity to restore that connection.

VR is a comprehensive technology that combines several technical achievements, using computer technology and the latest sensing devices to simulate a brand new environment (Liu & Zhang, 2018). It enables the observer to walk in it arbitrarily, making him feel like he was in the scene. As a new attempt,the use of Interactive Virtual Sand Table to assist design.It can express timely and accurate feedback on the work and put forward comments.And designers of urban planning can use computer technology to make changes in seconds to meet the needs of observers.

This paper analyses virtual reality technology’s interaction capability and compares it with urban planning and design needs. It explores the theory and possibility of an Interactive Virtual Sand Table (IVST), discusses its potential to makes up for the relatively unintuitive interaction of the current urban planning sand table, and analyses how IVST could improve the urban design process.

2. Background

Research into virtual reality human-computer interaction (HCI) has been going on for years to see how humans interact with computers and digital technologies, from interface visualization to functional control, from keyboards and mouse to touch screens to tracking sensors. Although virtual reality hardware is still considered a “computer,” the interaction is very different. Because users are immersed in a virtual world environment, interaction has gone beyond the traditional scrolling of a mouse. However, all of these interactions and communication can only work well when the experience is intuitive and enjoyable. It is necessary to understand the development of VR and Virtual Sand Table before exploring the interaction modes in-depth for the research direction of IVST.

2.1. VIRTUAL REALITY TECHNOLOGY

VR integrates computer graphics, image processing, and pattern recognition, intelligent technology, sensing technology, voice and sound technology, and many other sciences (Lo, 2020). It changes the digital information processed by computers into multidimensional information with various forms of expression that people can interact with. As a comprehensive high and new technology in graphics and images, the advantages of VR technology provide possibilities for the construction of new and more efficient interaction of urban planning and design.

In the 1993 World Electronic Annual Conference, many scholars proposed the "3I" feature for virtual reality technology. It expresses three key elements of the virtual reality system, namely, Immersion, Interactivity, and Imagination.These "3I" features inform how virtual reality technology is rising to a new height. It is distinguished from the simple traditional two-dimensional picture and three-dimensional modeling,forming a new media art form. Using VR in urban planning can also have these immersive aesthetic characteristics bringing people closer to the digital content for their imagination. But they have a different need in how the content is interacted with for its information.

Further development of digital technologies and immersive interaction technologies, such as virtual reality (VR), augmented reality (AR), and emerging mixed reality (MR), provide opportunities to better understand the design of cities and urban planning. In addition to the mixed visual effect of the virtual and reality, virtual technologies also provide the means to realize real-time interaction between users and the virtual model, providing the necessary conditions for the generation and development of IVST.

2.2. USING SAND TABLE FOR URBAN PLANNING

In Urban Planning there are four important issues: it is for and about people; the valueand importance of the "place"; operates in the "real" world; and the importance of design as a process. It is about building a scenario for urban evolution,imagining the conditions of transformation and proposing a process capable of incorporating new experiences in the human-environment relationship.

The traditional physical sand table is a model made of sand and other materials according to a certain proportion of the topographic map, field terrain, or aerial map. It has the characteristics of a strong three-dimensional sense, allowing multiple users to feel directly from any angle and have certain physical interactions at the same time. The interaction method is through direct contact with the physical model, moving them around with props since the size is usually quite big.Although the interaction is very limited, it is in line with people's physiological and psychological habits which enable efficient communication.

With computer hardware and software and virtual reality technology, the electronic sand table has replaced the physical sand table for many application fields. An electronic sand table (Li & Han, 2010) has a three-dimensional, dynamic, and interactive realistic environment simulated and displayed in digital display equipment. They can cover geographic information, graphics, and images of the urban environment, and some form of human-computer interaction. The electronic sand table improves the disadvantages of the limited interactive mode of the physical sand table.

VR provides an opportunity for more interaction to be added to urban planning electronic sand tables. Instead of just a touch screen and infrared remote control for users to complete some simple interactive operations to the electronic sand table, VR enables much richer interaction with sand table content. VR's immersive-ness will let the users feel like the virtual sand table model is in front of them. Using the controller, which usually comes will a "laser pointer," allows accurate interaction by pinpointing the sand table's specific part to work with. However, observation has shown that the fact that the immersive environment is so "real," users tend to reach out to "grab" the virtual objects, only to realize they will still have to use the button operation mode of the controller, which makes the visitors lose the sense of manual interaction naturally. It is necessary to look into other interactive technology that can be integrated into the virtual sand table to develop IVST.

3. Interactive technology for urban planning sand table

The sand table represents the art of urban planning in the form of physical miniaturization. The aim is to represent both the spatial structure and the combination of urban components clearly and expressing the process of urban planning.In addition,the relationship between the different stakeholders in the planning process can be enhanced with the development of virtual technology (THOMPSON et al. 2006).The future of the application of IVST in urban planning mainly has the following three directions: human-computer interaction,collaborative interaction, remote interaction.

3.1. HUMAN-COMPUTER INTERACTION

Human-computer interaction (Diao, 2020) is a process in which the system responds to the interactive information received. The electronic sand table mainly uses a touch screen, infrared remote control, and other technologies to control the sand table; it does not conform to human interaction habits, resulting in a low interaction rate. The display of electronic sand table is rich and colorful multimedia, mainly realized using audio-electronic integration and multimedia interpretation, which lacks immersion (Tan et al., 2007). To improve the communication efficiency between designers, virtual reality technology is introduced into the electronic sand table. The virtual electronic sand table can realize seamless interaction and natural communication between single or multiple people. Still, the research done on the organizational structure and system operation mode of the electronic sand table by relevant researchers is quite limited and did not relate much to VR. The current electronic sand table is still a distance away to satisfy the necessary interaction for urban planning purposes (Figure 1).

To improve user engagement and motivation, it is proposed that urban planning sand table should implement interactions, using simple, intuitive, and natural gestures, the line of sight, and voice to interact directly with the sand table. Using natural gestures instead of the mouse and keyboard to complete some functions in the virtual environment so that the HCI in IVST does not need other intermediary media. Users can define proper gestures to control the operation of the virtual contents more naturally. In the past, during the scheme's discussion, the designer could only create or destroy virtual buildings on the sand table using mouse and keyboard operation. The introduction of such HCI to the virtual sand table allows users to change the sand table's content through gestures in real-time to explore various urban planning and design schemes.

The development of interactive gadgets has gradually developed to interaction through wearable devices allowing more natural ways of interaction such as body movement, hand gesture, and voice. The interactive interface has also developed from the difficult-to-understand professional text to the easy-to-understand graphical interactive interface. For example, users can adjust the spacing of buildings for daylight, the height of excessively high building objects in a certain area, the position and size of roads, etc. In the process of planning, the sand table can demonstrate some more complex, novel and cool, and more fluid urban acoustic environment system, light environment system, and wind environment system. This enables the general public to really participate in the presentation process, improve their sense of involvement.

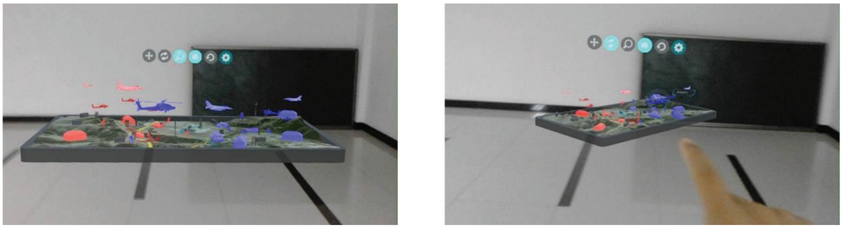


Figure 1. Human-computer interaction(Yao, 2018).

3.2. COLLABORATIVE INTERACTION

Collaborative interaction (Wang, 2018) is the communication between different professions, and different digital contents that usually comes from different software. It is necessary for them to be closely coordinated for effective design and research and development. The main advantage is that the key designer and other stakeholders can simultaneously discuss within the same digital model. The information can be operated interactively, and any problems can be pointed out collaboratively. The improved model can be organized and communicated again in a timely and convenient manner.

Urban planning involves land use planning, environmental planning, rail transit planning, and so on, and at the same time takes into account landscape, architecture, municipal and other disciplines. Urban planning involves the intersection of multiple disciplines and requires the coordination of multiple elements. It is difficult for planners themselves to make correct decisions timely based on their individual experience. Therefore, numeral professions are needed to provide effective information collaboratively and assist planners to make decisions quickly. In this case, horizontal and vertical communication needs to be emphasized. For example, on the one hand, information sharing among various professions and departments to put forward design requirements; on the other hand, planners need to design in accordance with the planning guidelines and standards, visually see the design constraints using the virtual sand table.

For professionals to collaborate in the design, local collaboration enables multiple designers to overlay and synchronize professional information in the sand table through scene sharing. Local collaboration also allows multiple designers to manipulate, mark, browse, and so on the virtual buildings in the sand table. In other words, any changes made by one person operating the sand table are synchronized in real-time to the other person's view. For example, planners mark urban plot functions in sand tables, and architects can see and change building types simultaneously to achieve the function of multi-person collaborative planning design.

The traditional idea of urban planning is people-oriented, but this idea is not fully reflected in the implementation of urban planning assessment. Urban planning will have a disadvantage if it lacks the necessary bottom-up subjectivity. Due to the lack of communication between planners and citizens, urban planning has become a one-way, dominant, and rational planning. In addition, the quality of the evaluation results depends on the subjective assumptions of experts and scholars. For example, the content of the evaluation is not public, which makes it difficult for the public to participate in the evaluation and even harder to know the quality of the evaluation results. Therefore, it is necessary to provide a simple and quick way for the public to participate in the urban planning assessment and for the planners to receive the feedback of the assessment content in time (Figure 2).

For the public to participate in the assessment, the sand table enables the local coordination with intuitive feedback of many people simultaneously. The planners can then report the main problems to the government agencies through public information feedback. For example, the public prefers to see more parks, squares, and other public places in the city. The public will mark the information on the sand table, and the planner will adjust the urban planning and design after seeing the marks and understanding the public intention. On the one hand, local collaboration builds a bridge of communication between the public and planners and their governments. On the other hand, collaborative interaction improves the operability, scientificity, and fairness of urban planning and urban planning implementation by enhancing public participation.

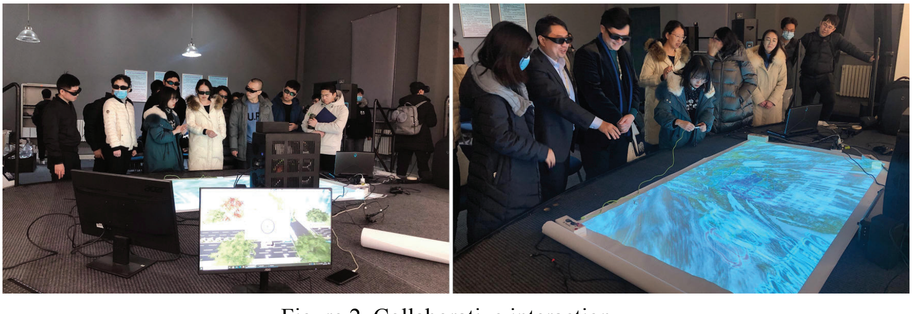


Figure 2. Collaborative interaction .

3.3. REMOTE INTERACTION

Remote visualization collaborative interaction (Bao, 2014) brings together geographically scattered experts and working groups in various fields to interactively carry out research or design of a project and complete a specific project with the support of information technology. Remote visual interaction emphasizes that designers, decision-makers, and stakeholders from different locations to participate in the design, decision making, and evaluation in a unified and coordinated environment.With the current pandemic situation, it can be seen from these advantages that a long-distance visualization is an efficient form of communication and exchange of views, enabling people to communicate "face to face" because they have to work from home.

Urban planning and design require the extensive participation and collaboration of experts in various fields. Because different people are located in different regions, it is necessary to depend on the network platform for collaborative communication to reduce carbon footprint. However, different people use different platforms and there is no same standard, which makes the way of collaboration somewhat limited. In addition, the model used for discussion between the stakeholders needs to be guaranteed to ensure the consistency of the information.

For professionals to interact in different places, remote designers are projected locally in VR in the form of virtual avatars. Designers can jointly manipulate the 3D model on the same display environment to display the 3D model's different details. They can communicate with each other through "face-to-face" dialogue and record the problems found through the 3D model at the common annotation layer. All parties' collaborative work can be accomplished without the need for personnel travel and without the disruption caused by waiting for documents to arrive. (Figure 3).

Urban planning advocates open design, and the public as a third party should have the capability to provide feedback to the design scheme. But there is no straightforward way for the public in different areas to participate in the design, and the process usually takes quite a bit of time. As a result, the public has no strong enthusiasm to participate in the planning process. Usually, only a small number of persons or interest groups will be represented by the general policy implementation assessment results. The evaluation results of implementing the general plan should combine the expert opinions with the public feedback to infiltrate the public enthusiasm into the evaluation process of the implementation of the general plan.

To enable the public to react to the design schemes, remote visualization enables the public to conveniently participate in all urban planning stages and conduct scientific and fair supervision and evaluation on the implementation effect of planning. The public can directly see the designer's design and renovation of the city and give their opinions on the design scheme through a "face-to-face" dialogue. Virtual sand tables can clearly translate specialized language into a form that the public can understand to provide feedback.

Figure 3. Remote visualization collaborative interaction(Yao, 2018).

4. Discussion

By examining the various interaction needs of urban planning above, this paper proposes integrating the three interaction needs into IVST. The application of IVST can improve the efficiency of the planner of the collaborative design (Shi, 2019), and the visual feedback for planning can also help the planners after by absorbing the opinions of the public feedback to adjust the design (Yao, 2019).

IVST is a tabletop virtual display in which the virtual content is projected on any horizontal surfaces and can be viewed with 3D effects simply with specific glasses. They are a tool that will greatly aid the field of urban planning and urban construction. It is open source and can connect with different professional software to carry out information superposition so that urban managers can carry out traffic dredges, emergency management, and other management of the city, and become the display window of the smart city. The reasons why IVST is more suitable for urban planning are as follows:

- Unlike a traditional electronic sand table or virtual sand table, IVST does not require interaction with a mouse, keyboard, or wearable devices. IVST can interact through the body, gesture, voice. The users do not need to wear heavy headsets and just put on a pair of specific glasses, just like in a 3D cinema. This allows the general public to participate in urban planning and design and provide feedback in an interactive manner consistent with their habits.
- Unlike VR immersive interactions, which lose the sense of isolation from the real environment, IVST has a fixed viewing perspective, and planners will design from a global perspective. Planners meet operational requirements by quickly placing, moving, zooming, rotating, marking information, and browsing. It is not easy for the general public to even rotate the model. Therefore, IVST's fixed perspective duplicates the traditional physical sand table and simply makes it virtual and interactive.
- IVST is more intuitive in displaying information. The professional information from various stakeholders in urban planning can be presented intuitively at the same time. Also, multiple people can view and communicate simultaneously, and the marked information can appear in everyone's vision, satisfying the integration of professional information in urban planning.
- Different from the traditional physical sand table, suggestions can only be recorded on the side and revised back to the paper file. Users can directly add text comments, draw red lines and circles, and sign within the IVST. These marks can also be viewed with the original document at any time, such as the

change content, date, modifier, etc.
- The cost will be reduced compared with the physical sand table. IVST can appear in three-dimensional form on any plane, which can not only meet the design needs, but also reduce the threshold of use.

Although there is a great potential for IVST to be applied in urban planning, there are still some deficiencies that need further research and development:

- Technical aspects: the scope of planning area is too wide, and the demand for 3D model data is too large, which makes the workload of 3D modeling and data processing too heavy.
- Software and hardware: The 3d modeling software in the current market is mainly good at building 3D models, while there are few suitable products and software for building a large number of existing 3D urban landscape models. In addition, the virtual interactive sand table is very demanding for the hardware and software environment of the computer.
- Interaction gadgets: The connection between the interaction and the content is still not perfect. There is still a short lag time, which causes the interaction to feel unnatural.
- Standard system: Standardization has become a major bottleneck restricting the construction of digital projects such as “digital city”. Due to the lack of unified standards for project-related data management, it is difficult to realize the update, data sharing and exchange between virtual reality systems established under different circumstances.

The shortcomings of the above four aspects limit the use of IVST in urban planning. Simultaneously, due to the limitations of equipment, planners have become more difficult in the design process. In other words, how to reduce the cost of working in a virtual interactive sand table is a key issue. Also, interacting with users in the same virtual space is another technical problem that needs to be solved.

5. Conclusion

This paper summarizes the application direction of IVST in future urban planning and illustrates how IVST can help professionals and non-professionals better participate in urban planning and design. The feature of IVST is very suitable for solving the problem that urban planning needs cannot be met. Users can interact using the body, gesture, and voice to place, move, scale, rotate, mark information, and browse the sand table to achieve the collaborative design. The next step of this research will be to explore richer, more intuitive interactions within the current technologies’ constraints by improving the way the virtual content is generated and how they can be interacted based on its information. With the development of IVST, there are more opportunities for both professionals and non-professionals to participate effectively and immersion in the design process, making the urban design more possible. A comprehensive consideration of the city’s problems will lead the city in a better direction.

Acknowledgements

The authors would like to acknowledge that this paper was financially supported by The Iater-stage funded project of the National Social Science Foundation(No. 19FXWB026),The Science Research Project of Guangdong Province(No. 2017A020220011) and National Natural Science Foundation of China (No.51908158).

References

Bao, J.: 2014, *Design of Distributed Collaborative Design's Platform in CTMC*, Ph.D. Thesis, HU.

Cai, N.: 2013, The role of remote sensing and telemetry in ecological environment impact assessment of highway construction projects, *Technology Wind*, **1**(19), 158.

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M. and Yamu, C.: 2020, Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany, *Sustainability*, **12**, 2307.

Diao, X.L.: 2020, *Research and development of intelligent sand table human-computer interaction system*, Ph.D. Thesis, HIT.

Fan, C.W.: 2016, *Design And Implementation of The Interactive Electronic Sand Table*, Ph.D. Thesis, AU.

Hu, C.G.: 2016, *RESEARCH ON THE COLLA BORTIVE PROBLEM OF "MULTI-R EGULATION" POLICY IN URBAN PLANNING OF NANNING CITY*, Ph.D. Thesis, GUN.

Li, L.: 2013, *VIRTUAL REALITY TECHNOLOGY APPLICATIONS IN THE ART OF URBAN PLA NNING* ., Master's Thesis, HNU.

Li, M. and Han, F.: 2010, Overview of Virtual Reality technology, *Software Guide*, **3**(06), 142-144.

Liu, X.: 2020, Three-Dimensional Visualized Urban Landscape Planning and Design Based on Virtual Reality Technology, *IEEE Access*, **8**, 149510-149521.

Liu, Y. and Jiao, X.R.: 2018, The Application of 3D Information Technology in Urban Planning Management in the New Era, *Planners*, **6**(12), 73-78.

Liu, L. and Zhang, p.w.: 2018, The design and implementation of training system based on virtual reality technology, *Dianzi Jishu Yingyong*, **4**(10), 102-105.

Lo, T.T. and Gao, X.R.: 2020, From HCI to HVRI - How different will the interaction of digital architecture design be?, *CAADRIA*, Chulalongkorn University, Bangkok, Thailand, 253-262,2.

Shi, J.: 2018, *Research on gesture Interaction technology of augmented reality electronic sand table*, Ph.D. Thesis, NUST.

Tan, S.R., Zhang, M.J., Cheng, G. and Lou, J.T.: 2007, Study on Augmented Reality Electronic Sand Table and Key Technique, *Journal of System Simulation*, **4**(20), 4727-4730.

Wang, Q.L.: 2018, *Design and development of city planning platform based on online collaborative technology*, Ph.D. Thesis, SRE.

Yao, S.M.: 2018, *Research and Implementation of Augmented Reality Electronic Sand Table Cooperative Interaction Technology*, Ph.D. Thesis, NUST.

Yu, Z. and Zhang, H.: 2007, DIGITAL MODEL OF CFD SIMULATION DESIGN IN URBAN PLANNING, *Urban Planning*, **4**(06), 52-55.

Zhang, L.: 2018, *Evaluation of urban overall planning implementation from the perspective of public participation– Taking Chengdu as an example*, Ph.D. Thesis, SJU.

AUGMENTING COMPUTATIONAL DESIGN AGENCY IN EMERGING ECONOMIES

RAPHAËL ASCOLI
[1]*Collaborator*
[1]*raphael.ascoli@blue-temple.com*

Abstract. This /practice-based design research/ investigates the possibility of computational design to increase agency and impact in emerging economies through real-world projects. By cultivating a new kind of relationship to issues in development and local untapped resources, they inspire for more public engagement and resource-based conversations within a spatial framework. The topics that were addressed in this research are the democratization of data and affordability of construction. These two on-going early-stage initiatives have used computational design tools at specific areas in the project's development, therefore optimizing the parts where low-tech tools weren't sufficient. This demand driven design process explores ways in which different levels of technology can augment each other.

Keywords. Space; resource; housing; myanmar; optimization.

Although architectural design tools are advancing, their inclusivity is questionable. Digital fabrication often requires expensive machinery or advanced digital literacy in coding. It could therefore be seen as a luxury instead of a progressive initiative to expand the industry as a whole. Applications of such tools strive to push the boundaries of what is currently possible to build without necessarily questioning their purpose. Complexity isn't the end, but in a specific scenario, the means to an end. While the vast majority of architects in Myanmar still use Autocad and Sketchup to design; what can computational design bring to the table in a time of political, economic, health, and social instability? What kind of new disruptive processes can be created during a time where futures seem to be going back in time and repeating the past? This research does not pretend to bring a solution to an overly complex situation, but, internally, start addressing issues such as remote community development through architecture's multicultural and cross-disciplinary nature. This 'practice-based design research' investigates ways to expand computational design's agency and impact across the board, targeting different areas in society, at different scales and geographical locations in Myanmar. All of which are data-driven designs that respond directly to discrepancies between need and supply. These two on-going early-stage initiative projects have an aspiration for large scale rural development in Myanmar. Within the entire scope of these two projects, very specific steps have been optimized using computational design. The use of the tool is not holistic to the project, it is specific to a key area. In order to integrate real-world workflows, digital

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 639-648.

fabrication, implementation, and dissemination should be considered contextually using the appropriate tools. The methodology that was followed in both projects are replicable in other parts of the country, and perhaps in other parts of the world, however, the implementation is unique to a specific context. Both aspects have been developed in the following projects, defining a clear methodology of work and real-world applications in a target region. The topics that were addressed in this research are the democratization of data and affordability of construction.

1. Chin State mapping

Following up on the on-going military coup, many executive orders will be approved to enable targeted sanctions in Myanmar. Development-related budget spendings will need to be very carefully monitored to avoid leaks and achieve tangible results. This mapping pilot project is a prototype in exploring new data-driven approaches in site analysis and in computing projections for budget-allocation scenarios intended for development. This approach is bringing to the table a new perspective and insight, that formerly was either inexistent or done at a very basic level.

Today, data is being collected everywhere, there are many initiatives in creating dashboards for dynamic visualization. However, the impact is very questionable because accessibility is monitored with different levels of security allowances. Data visualisations are often oriented at a technocratic, policy-making class instead of being for the general public and more specifically for marginalized communities. This prototype investigates decentralized mapping, that qualitatively, allows for different kinds of engagement and non-government-complicit decision chains. Looking at Asia Foundation's Township Development Indicators (TDI) database that was published in 2019, some important measures were taken to prevent the data from being overly revealing. The precision of the data was intentionally reduced from the village track level to the township level. This decision also reflects on which level of decision-making the data is intended for, in this case, it seems to target a higher and macro-level. Explicit data visualizations, when publicly shared, can create public insecurity, ressource grabbing, commercial manipulation, and finger-pointing. This prototype was intentionally not designed to visualize the geographical location of ressources but to visualize where to tackle specific problems using colour gradients that highlight different levels of needed interventions throughout the target region. The data is therefore mobilized to start a conversation about on-going development-related issues, anomalies, discrepancies and inequalities within a spatial framework without jeopardizing and putting at risk ressources and communities. Therefore, the data harvesting process was carried out in order to obtain the highest accuracy and precision of information. A holistic approach is established, which considers all steps of the process from data acquisition, analysis, visualization, and dissemination.

People-led data collection processes can lead to some degrees of inaccuracy, incompleteness, and scarcity within the set. In physics, for example, significant figures are ways to remediate to the difference in precision between different numbers in an equation. However, this logic conforms the output to the smallest level of precision amongst all the inputs. In order to get a higher level of precision, the least precise inputs need to find more digits after the decimal point. This research explores ways to fully utilize every data set to its full potential without culling out levels of precision. Instead of digits after the decimal point, the data is previewed as geographic points or pixels within the spatial framework.

Myanmar Information Management Unit (MIMU) released in 2017 *P-Codes*. This new system created a distinct and ordered classification of all Districts, Townships, Towns, Wards, Village Tracts, and Villages throughout the country, allocating to each geographical data point a specific code of reference. This initiative revealed itself as a major improvement for data collection and in facilitating mapping projects. Referencing villages by name is extremely difficult, as translations can be slightly different from one person to the other and some of the villages have the same name as other villages or townships. However, P-Codes cannot be assumed to be 100 percent reliable either; in Chin State, for example, villages very regularly move from one place to another, their documented geographical location is seldom updated on the Open Access Database. Furthermore, many remote villages have not been documented yet as they are difficult to access. Even though this documentation could be considered one the most reliable in Myanmar, not everyone uses this system in their own datasets, collaboration is not always perceived as positive, many companies would rather ignore this tool rather than use it. Therefore, some sets of data were not used to their full potential during this research, all translated village names that were not corresponding to the MIMU translations or had the same spelling as other villages were therefore culled out from the set before being operated on. A portion of data was therefore lost during the formatting process.

During the course of this pilot project, we collected data from a wide variety of sources, some of which were simply downloaded from existing Open Access Database, others were collected through more unconventional methods. In order to collect data from local Myanmar tourism agencies that record roads and tracks during their guided tours in the country using GPS tracking devices, we had to sign a Non-disclosure Agreement (NDA) that specifically mentioned the fact that the final map would not preview the data but use it exclusively for analysis. Similar processes of data acquisition were used to get government data from the Ministry of Construction (MOC) and the Ministry of Hotel and Tourism (MOHT) in Chin State. Other processes in data collection we went through required the use of a motorcycle and a USD stick in Hakha, the capital of Chin State.

Prior to data analysis, the acquired data sets were graded in terms of accuracy, this grading can be seen as a benchmark to build a trustworthiness indicator for each individual set. In this way, all data is usable, their aptitude in influencing the output map is relative to the perception of their accuracy. This perception is based on the format of the data, the uniform spread of the data throughout the target region, and a personal judgment. For example, if it is a GPS route recently collected by a trained guide on a motorcycle, the accuracy of these geo-localized recordings is high and should therefore be able to influence the analysis in a more thorough way compared to a hand-drawn road on a printed map for example.

The wide range of add-ons for Grasshopper allows us to import many different data formats into the same file, should they be excel spreadsheets using GHExcel; SRTM HGT, OSM, and GeoTiff files using Elk; SHP files exported GPS coordinates through Google Earth using Heron; JPEG images through Rhino. Each format has different types of output, some are points with attributes, others are polylines, meshes, pixels; furthermore, each data set has a unique level of precision. In order to start analyzing the imported data, we changed them to the same format. During this research, topography meshes were chosen as a common format because they are light to compute and are easy to work with. This technique allowed us to layer on top of each other many different imported data sets from various sources. By calculating the height difference between different topographies, we created indicators based on the distance ratio. These indicators do not have units, they indicate densities that can later be used to create new topographies that can visually represent them.

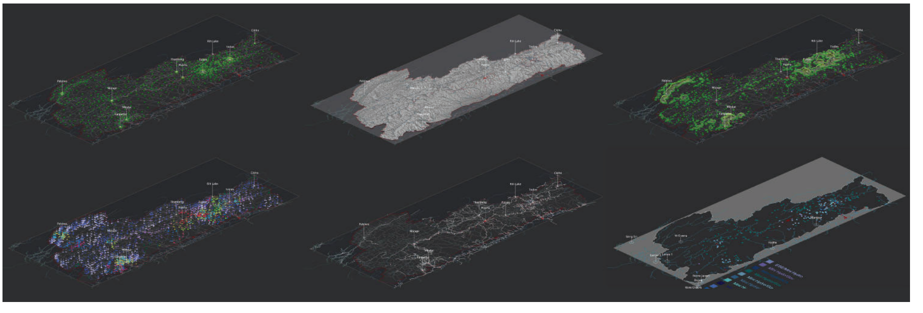


Figure 1. Development related data visualizations from Chin State (NGO activities per sector, energy harvesting, topography, population density, road networks, water resources) by Blue Temple Co., Ltd.

Through the use of the HERON add-on for Grasshopper we were able to import the geolocalized target region we wish to base the analysis on in Rhino. This frame was then used as an input in the Elk topography component that contains *Geospatial Data Abstraction Library* to better read GeoTiff format images. The high-res GeoTiff image was downloaded from the Earthobservatory NASA website. The output is a 3D topography mesh of the target region that visualizes the observable nightlight in the region from the Suomi NPP satellite. The highest point of the mesh shows the brightest area of the region.

The created maps collect a large amount of information in a small format. In just a look, we can understand thoroughly an incredibly dense amount of data. Where the spreadsheet is scattered, the map is condensed, this allows the viewer to understand data in a relative way, comparatively speaking. Data is no longer an individual, isolated piece of information, it is a point within a cloud. Observing the cloud itself instead of the individual data releases the visualization from possibilities of inaccuracy. The viewer is no longer reading information but trying to read between the lines, to find patterns within the database. The ability to reveal patterns was therefore a priority. The jpeg image conceals all data sets in an unhackable format, a JPEG image. This also guarantees compliance with NDAs.

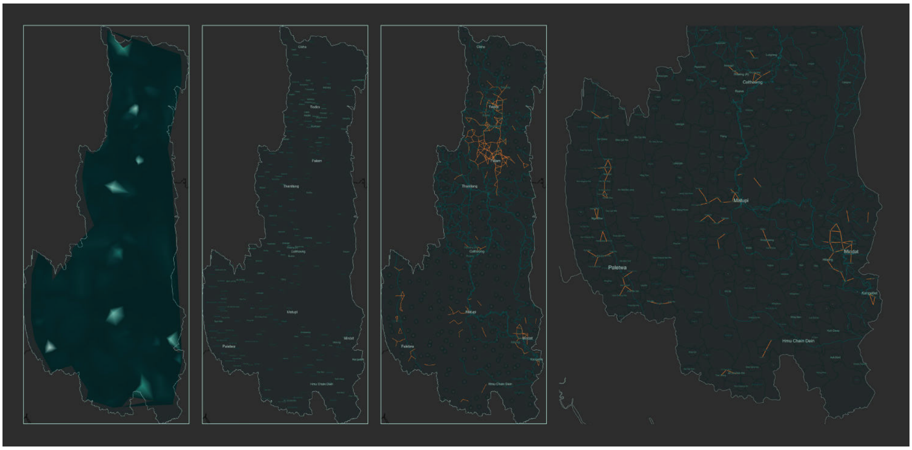


Figure 2. Map of Chin State emphasizing on towns with the greater population with the least access to energy supply as well as possibilities of mini-grid implementation by Blue Temple Co., Ltd.

The high-speed mobile internet coverage in Myanmar has recently improved dramatically, mobile service providers have built towers across the entire country that serve 80 percent of the national population. Furthermore, 70 percent of the connections are made through smartphones. The dissemination of our maps was presented through an app for smartphones, accessible to everyone without any levels of security allowances. Making raw data accessible to a wide audience through open data platforms does not necessarily entail the democratization of data because a large portion of the population does not have enough digital literacy or the tools to read them. By using color gradients instead of text, the data becomes apparent and readable.

The app was inspired by ‘Draw Something’, it is an intuitive interface where users can sketch on top of a base map. This social media connects through the use of *Discussion Rooms* the users together. All the way until this third national lockdown in Myanmar, traveling has been banned throughout the country. Online communication has become a real challenge to organize the decision-making process, Zoom has revealed itself not to be the best performing tool. More specialized and practical tools are needed to quickly and efficiently connect people. This app also allows for more transparency to happen and get stronger citizen participation. It is a conversation starter instead of a decision-making tool. People can vote for each conversation to go up or down, the more popular topics therefore appearing the most visible at the top of the list.

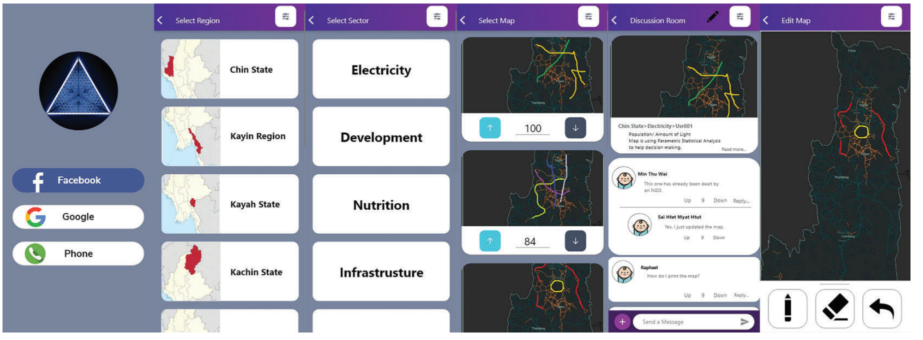


Figure 3. Phone application prototype, developed within the Blue Temple proposal with Min T. Wai and Sai Htet Myat Htut during the 2019 Data4Change Hackathon organized by Asia Foundation at Phandeeyar (Phandeeyar is a community tech hub that is fostering Myanmar's technology & innovation ecosystem) in Yangon.

Mapping is just one element of representation, decision-making processes shouldn't exclusively rely on maps, there are many more factors, non-measurable and intangible variables that can influence decision-making in much more practical and often greater ways. Such kinds of data are essential to render a much more accurate representation of a site, such as political instability, historical events, internal conflicts, religious beliefs, land ownership, language, local culture. In this manner, mapping is not enough, it is just one part of a complex puzzle. The combination of both mapping and public engagement can increase community empowerment.

2. Optimized Bamboo Frames

There is a major discrepancy in the affordable housing market in Myanmar between very high demand and very low supply. A big percentage of the total national population does not have access to decent housing and does not have access to safe microfinancing options to afford it. The demand for affordable housing in Yangon is 100,000 housing units per year, the public sector was able to supply 9,200 units in 2016, while the private sector supplies between 7,000-9,000 units, although none of them were targeted for *low to lower-middle-income households*, they were exclusively targeted to the high-end markets. While the demand for affordable housing continues to rise due to the effects of rapid urbanization; internal migrations because of climate change, poverty, and violence; the need for house replacement because of damages; the supply is heavily lacking. The effects of this lack of supply generate an increase in households having to resort to informal settlements as a solution.

One of the main perpetuating factors of poverty, ironically, is housing in Myanmar. According to the 2014 Myanmar Population and Housing Census, up to 42.7 percent of housing units in rural areas are constructed from bamboo, and 23.6 percent in urban areas. Bamboo is the cheapest building material in Myanmar, therefore the most common because of widespread poverty. Low-income households cannot afford long-term solutions, therefore, the house gets damaged due to lack of proper maintenance, the lack of proper treatment of the bamboo, the lack of proper footings to protect the bamboo against exposure to water during the rainy season, flooding, high winds, and more. Every year, they need to rebuild the house but don't have enough money to do so, therefore they borrow money from non-regulated shark loaners around the village, they become unfairly indebted but still don't have access to decent housing. If the payments are not done in time, some households can find themselves in dangerous situations. This vicious circle keeps them in a state of poverty, perpetually owing money to others, and not having decent living conditions.

There are more than 350 species of bamboo in Myanmar, only 7 of which are used in construction because of their load-bearing capacity. They grow in particular areas in Myanmar and are in high demand; therefore the cost per pole is relatively high. The supply of bamboo is inconsistent, even though bamboo grows everywhere in the country, the species used for construction are in reality not abundant. The price of this kind of bamboo fluctuates, it, therefore, adds another risk for businesses that strongly depend on their exploitation. Finding a way to use the abundant and cheapest species of bamboo on the local market would radically lower the cost of construction. Smaller bamboo has a high bending capacity that allows for more complex designs. Bundling together sets of bamboo subsequently makes the structure more resilient to damage compared to a structure made from single large diameter bamboo poles. The structure's integrity is therefore no longer subjected to its weakest link, it is a composite material within a monolithic structure. Computational design tools can therefore be used to reassess materials that are commonly non-commodifiable, create a new utility, and mobilize abundant and untapped resources that are often beyond the realm of marketization. Using locally found materials and low-cost simple construction techniques inspired by vernacular architecture integrates digital fabrication into ordinary real-world workflows. This proposal explores a different form of application, resolving the conflict between the complexity of design and affordability of construction.

The designed structural frame is made out of cheap small diameter bamboo combined with locally found recycled and everyday materials. The bundling makes it possible to use commonly non-structurally performing materials in a structurally performing way. Its modularity allows for prefabrication where quality control of the whole assembly chain is more easily monitored. The combination of both, a large scale production, and an optimized building process over time will reduce the price of the structural frame units every year. Once the structural frames are put into place; the walls, floor, and roof are built locally by workers from the village using the construction materials of their choosing. Additionally, in case of damage, the frames are easily replaced with new ones without the need to dismantle the entire house. Therefore specializing the production specifically on the structural elements of the house, which is the most complex and costly, will reduce the price of the entire house, while still ensuring its durability.

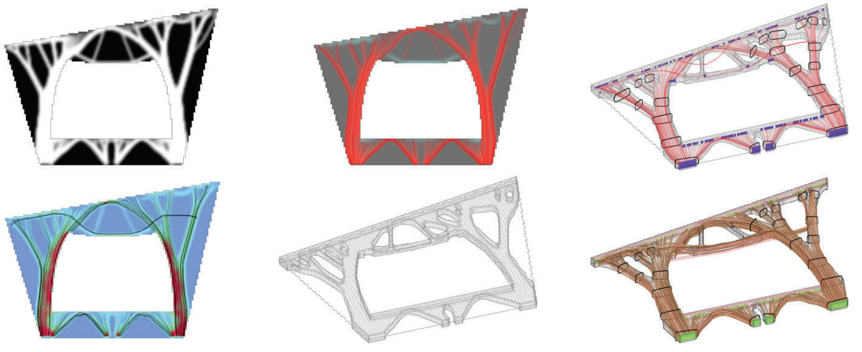


Figure 4. 2D topology optimization by Blue Temple Co., Ltd.

Calculating the structural integrity of the frame is incredibly difficult because it is a complex composite material made of many small non-isomorphic parts. Instead of working with real loads using Fusion 360 by Autodesk for example, we choose to use Millipede on Grasshopper. Its ability to compute 2D topology optimization was also a plus. The overall shape where we allowed the software to work was defined according to local regulation such as the overhang distance of the roof, local context such as the raised floor as a form of protection during the rainy season, the overall dimensions of the interior space. The 2D mesh result based on a stiffness factor shows an optimized overall shape that responds to the sets of loads we predetermined, such as live load, dead load, and three footings for support.

In order to start 3D modeling the frame for visualization purposes and quotation preparation for prototyping, we needed to interpret the results of the program. This interpretation resulted in simplifying the overall shape, and according to the color gradient extracted from the principal stress 2D result mesh, create different densities of polylines. To do so, we extracted the iso-curves from the stress pattern by creating different densities of seeds according to the color gradient.

We created a virtual 3D mold and used Kangaroo 2 collider component to evenly spread out the contained polylines in order to mimic the bundling of the bamboo. The entire frame is made out of 350 small diameter bamboo poles. In order to create the smallest file size, we used the MeshPipe component of Ameba instead of the usual nurb piping component. The metal strapping was placed at the start and end of each branch segment.

According to the exchanges we had with Sebastian Kaminski, an Associate Structural Engineer at ARUP specialized in bamboo shelter construction processes, engineering, and materials in refugee camps, specifically for the Kutupalong refugee camp in Cox's Bazar, Bangladesh; he advised us to test the structural performance of the frames until demolition at least ten times per variation (choice of bamboo specie and slight variations in design) in order to get the most accurate data and assessment. Prototyping, testing until demolition, and assessment is another essential part of the design process. While computational design is essential in obtaining a preliminary blueprint of the frame, it is not enough to successfully carry out a final product onto the local market. The combination of both processes expands the agency of the architecture by making it more affordable and structurally performing.

A mockup prototype was tested for a structural column in a shelter in Yankin Township. The freshly cut green color bamboo called ‘Theik wa’ (Bambusa tulda Roxbo) was bought in Rhakine Yoma (Rhakine State mountain). These were the top part of the plant, the most bendable and cheapest part that is not in high demand because of their lack of load-bearing capacity. One hundred bamboo poles cost 4,000 Myanmar Kyat (3.06 USD). Moreover, this bamboo species has low sugar content, insects are not naturally attracted to it, which makes it more durable; also simpler, and less costly to treat. We tested different types of strapping for the bundling (coconut rope, post mounting straps, galvanized steel strap, and galvanized tie wires), the steel strap revealed itself to be the most suitable candidate. The prefabricated component of the footing, using a recycled 20L water bottle filled with concrete for a stronger and solid base, was very promising and cheap. A much more detailed assessment would need to be made in order to optimize and plan each step of the bundling and assembly process.

Figure 5. Mockup prototype as a structural column for a shelter in Yankin Township by Blue Temple Co., Ltd.

Inspired by the *The Grameen Bank Housing Programme* in Bangladesh, the structural frame would be brought to the local market together with a micro-loan. Today, we are currently working with brokers specialized in microfinance in Myanmar to conduct inverse auctions with official and regulated financial institutions in order to get the most affordable financial package that will be coupled with the sales of the structural frame. Our target end-users are low-income households in remote urban and rural areas in the lower 3 deciles of revenues. This strategy will allow the end-user to own at an affordable price, a quality, and long-lasting housing option.

3. Conclusion

During this period of great change in Myanmar, resources have become a major topic of conversation. Looking at The Belt and Road Initiative (BRI), most of the proposed infrastructure projects are resource-oriented whether is it in regards to rivers, jade, natural gas, and wood. Computational design can provide additional tools for designers to address this issue in creative ways, and explore the possibility of utilizing resources that are commonly outside the realm of marketization. This reassessment of resource utility can provide new design solution space in the housing sector, in specific regards to affordable housing, making accessible to marginalized communities new construction techniques that can take advantage of local abundant and cheap materials. Similarly, looking at a more macro level of intervention, computational design also addresses remote community empowerment through mapping. By re-orienting the typical target end-user from the technocratic policy-making class to remote communities, the maps allow for better public engagement. By revealing patterns of development, they can better understand their location within the spatial framework, and access a tool of communication that is a conversation starter. The combination of different levels of technology within the same project augments the agency and impact of the design. Each step is optimized using tools that best respond to the need. It is a demand-driven design process.

References

"Composite image of Asia and surrounding region at night" : 2016. Available from <https://earthobservatory.nasa.gov/features/NightLights> (accessed 2019).

"Myanmar mobile leaps along" : 2016. Available from <https://www.mmtimes.com/business/technology/19801-myanmar-mobile-leaps-along.html> (accessed 2019).

"The installation is conceived and designed for Dimensions of Citizenship, the US Pavilion at the 16th International Architecture by Diller Scofidio + Renfro" : 2018. Available from <https://dsrny.com/project/in-plain-sight?index=false&section=projects> (accessed 2019).

"In Myanmar, soaring numbers of smartphone users present business opportunities - and frustrations" : 2018. Available from <https://www.todayonline.com/world/myanmar-soaring-numbers-smartphone-users-present-business-opportunities-and-frustrations> (accessed 2019).

"Financing Affordable Housing in Yangon by Asian Development Bank (ADB)" : 2019. Available from <https://www.adb.org/sites/default/files/publication/504671/financing-affordable-housing-yangon.pdf> (accessed 2019).

MASS PRODUCTION

Towards Multidimensional, Real-time Feedback in Early Stages of Urban Design Processes

MAORAN SUN[1], PENGCHENG SUN[2], YUEBIN DONG[3] and JOSE LUIS GARCIA DEL CASTILLO LOPEZ[4]
[1,2,3,4]*Harvard University Graduate School of Design*
[1,2,3,4]*{msun|psun|yuebin_dong|jgarciadelcasti}@gsd.harvard.edu*

Abstract. Urban design, especially in its early stages, focuses mainly on massing studies rather than architectural detail or engineering. Traditional urban design workflows involve a mix of sketching and modeling. However, the back and forth between the sketching-modeling loop is typically fairly time-consuming, resulting in a reduced capacity to iterate efficiently over design concepts, even in their digital form. In this paper, we present a workflow for producing digital massing tests from hand-drawn sketches. The goal of Mass Production is to help quick iteration on volumetric design enhanced by real-time feedback on quantitative and qualitative parameters of the model, thus helping designers make better informed decisions on early stages of urban design processes. The architecture of the proposed workflow consists of three main elements: a tangible user interface (UI) for designer input, a real-time dashboard of diagrams and models for massing analysis, and an augmented reality (AR) environment for enhanced feedback on design form and shaping. In this research, Mass Production is tested in different design scenarios, a discussion about the future and its impact is presented, including emerging technology while keeping traditional workflows.

Keywords. Urban Design; Massing Study; Augmented Reality.

1. Introduction

Due to the scale and goals of urban design, massing study is often the start point and key of the whole urban design process. The process of massing study, both in academia and in practice, features a linear protocol: conceptual sketching on paper, allowing quick but rough illustration of design ideas, followed by 3D digital modeling, offering more precise volumes with quantitative examinations, and physical 3D modeling providing a sense of scale on site. Although each step aims at specific design goals, the back and forth between sketching and modeling is generally time-consuming, slowing down the pace of design iterations. Numerous efforts have been devoted to optimizing this process.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 649-658.

We present a workflow for producing digital massing tests from hand-drawn sketches. This project aims to help quick iteration on volumetric design enhanced by real-time feedback on the model's quantitative and qualitative parameters, thus assisting designers in making better-informed decisions on early stages of urban design processes.

Firstly, sketching is the native language of designers. It allows the most freedom of expressing design ideas, but at this stage, designers can only imagine an incomplete picture of how the 2D sketch looks in volumetric form. We present a graphical input interface on tablet devices where sketching's freedom and fluidity are mostly maintained. The 2D sketches can be 'translated' into geometry data for 3D digital models in modeling software. In this workflow, quick sketch and precise massing feedback happen simultaneously, facilitating more accuracy in sketching and providing evidence for selecting the most suitable massing typologies (tower, courtyard, slab, mat building, etc.) for specific projects. While most computational urban design tools aim at optimizing statistical parameters such as FAR, open space ratio, density, sunlight, etc., this real-time correspondence between 2D sketches and 3D digital modeling only assists designers to quickly experiment with their own design ideas instead of developing the massing form from a dataset and making decisions for designers. In this sense, we try to preserve designers' dominant role in the design process and encourage them to determine the massing form with real-time massing parameters only as a reference.

Furthermore, massing study in urban design is not only about qualifying for objective specifications but also pursuing a subjective sense of scale and form, which is traditionally studied by physical models. The time delay between early sketches and physical model presentation considerably slows the design iteration. What if designers can perceive on-site massing volume and get the sense of scale in the most initial stage possible? The recent mobile Augmented Reality (AR) technology "has the potential to offer new opportunities for co-designers as a new design platform where the physical and visual models are superimposed during the architectural massing study" (Gül, 2017). The geometry data gathered from tablet sketches is also "translated" into augmented massings that can be inspected by the designers while they are sketching. This AR on-site volume helps designers study how the design fits into the context in a more visible and "tangible" manner. In conclusion, the connection we build between the sketching and modeling removes the time delay between the two steps. With objective and subjective modeling feedback at the earliest design stage, both the efficiency and experience of massing study are improved.

2. Background

Existing digital design tools can be described under three main categories. The first one is the parametric model and information modeling. It is possible to have a developed rule-based computer-aided urban planning and design platform with an implemented theoretical model. It can formulate urban programs, generate design according to urban grammar, and evaluate the generated design (Duarte et al. 2012). The second is developing urban form from a parameterized dataset. In this sense, Shen et al (2020) and Jinmo et al (2020) have for instance experimented with the generation of urban patterns with machine learning. The third is visualization, collaboration, and interaction. Work in this direction involves exploring tools to enable visual management of strategies and risks, assisting decision-making with knowledge models, and enhancing participatory design by evaluating stakeholders' needs (Kunze et al. 2012).

While computer applications provide designers with extensive pre-defined functionalities in high precision and sufficient details, traditional tools are preferred because of their flexibility, speed, and intuitive interaction. In practice, many design works are drafted by traditional tools in the early stages and then completed by digital ones in later stages (Aliakseyeu, Martens and Rauterberg, 2006). Based on these ideas, we propose to rethink the role technology plays in our design process, from fully automated, data and computer-driven to human dominant with computer-assisted and data-informed.

AR technologies are reliable and can be deployed on mobile devices. Such technologies support the visualization of building on-site and aid design and construction design in the architectural domain (Billinghurst and Henrysson, 2009). The study also proved the benefits of using AR in landscape education. AR can offer individuals a new learning experience by demonstrating the theory on a real-world site (Jeremy and Lawson, 2020). It helps reduce the time and effort of building real physical models but conveys similar if not the same sense of scale.

Compared to existing 3D modeling software often used by architects and urban designers such as SketchUp (SketchUp, 2021) and Rhinoceros 3D (Rhinoceros 3D, 2020), Mass Production aims to build a more intuitive workflow for designers, focusing more on the massing stage of urban design, and with less functionalities. It allows a more intuitive way of input by sketching on touch screens of tablets and makes it easier to perceive building volumes in AR. Though Mass production does not support complex operations on massing, the digital model it produces could be exported and modified in other 3D modeling softwares.

3. Methodology

Mass Production consists of three main components: a graphical user interface that takes user's input, a bespoke geometry-processing unit for translating user's input to a 3D digital model and producing necessary diagrams to provide statistical design feedback, and a mobile Augmented Reality section letting user test the massing in physical model scale and get a sense of aesthetic design feedback (see Figure 1).

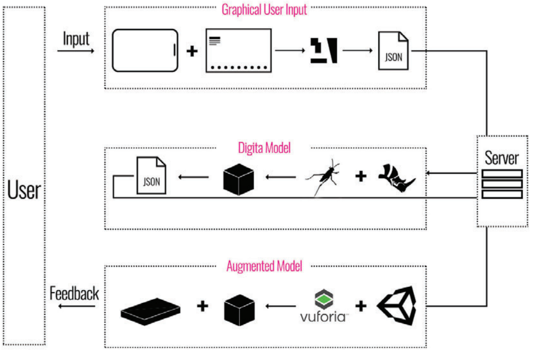


Figure 1. Diagram of workflow, integrating Graphical Input Interface, Digital Model and Augmented Model .

3.1. CONNECTION

The three elements of this design framework communicate via WebSockets (WebSocket, 2020), a standard network protocol, allowing users to connect multiple devices over local or world networks, opening the possibility for team collaboration. By setting up the three parts of our tool as WebSocket clients and connecting to the same server, information is stored in JSON format (ISO/IEC 21778:2017, 2017) and transmitted among them. The geometry-processing unit is implemented using Rhinoceros 3D, a NURBS-based 3D modeling software, and its plug-in Grasshopper 3D (Grasshopper 3D, 2020), a visual algorithmic modeling tool. This component receives messages from the graphical input interface about the user's input and sends 3D digital model information to the AR component. The details of this communication will be presented in the next sections.

3.2. GRAPHICAL INPUT INTERFACE

A digital sketching interface was developed for a tablet device for the user input, with drawing tools targeting specifically urban design parameters. The technology stack for this UI is platform-agnostic and can be run on any touch-capacitive device. We try to keep the feeling of the way urban designers sketch on trace paper, intuitive, low cost, and easy to use, but enhance it to be editable and responsive. To make our tool simple and let users concentrate more on design, the elements are kept as simple as possible: a canvas that allows users to sketch on, some buttons taking urban design parameters and a display area to inform users what they're drawing.

The canvas is organized by layers. A base site plan is displayed on the bottom layer, with the site boundary outlined by red lines. Users can add as many layers as desired and draw on them, except the base one. Layers can be toggled on and off to make it convenient for users to test massing in batches. Users are able to draw two kinds of shapes: quadrilateral and free forms. In quadrilateral mode, users are required to draw four lines, then a quad polygon will be generated automatically based on our calculation of intersections. While in free form mode, every continuous move of the pen will close automatically and be recorded as a polygon. In both modes, a void shape could be created to subtract it from other buildings. This allows more flexibility in massing combination. After a shape is formed, we could drag it to different locations or delete it to revise the design according to the feedback we received from other parts of this tool. As rectangles are one of the most common and essential shapes in urban design, we offer an orthodiagonal mode that constrains users to draw purely vertical and horizontal lines only.

The other input information needed is urban design massing parameters. Users are required to provide two parameters. As we draw sketches building by building in plan, height is necessary to translate it to 3D model. Three height options (low, middle, high) are provided per the user's selection. These are considered enough for the early stages in urban design. A building program is also requested, allowing users to choose from retail, residential, and office buildings. This will be used in statistical calculation and visualization steps later and may be useful in further development. Figure 2 shows the Graphical Input Interface.

Figure 2. Graphical Input Interface, Upper Left: Tower typologies, Upper Right: Simple urban design plan sketches, Lower: Courtyard typologies sketch with toggling void layers for design comparison.

After each operation is complete, our user input interface will broadcast information of all current active buildings to the server. The message will then be echoed to the geometry-processing component. Operations are defined as a shape being formed, deleted, or dragged, or a layer being toggled on or off. Where applicable, messages contain points for each shape, corresponding height, layer, and building program.

3.3. DIGITAL MODEL

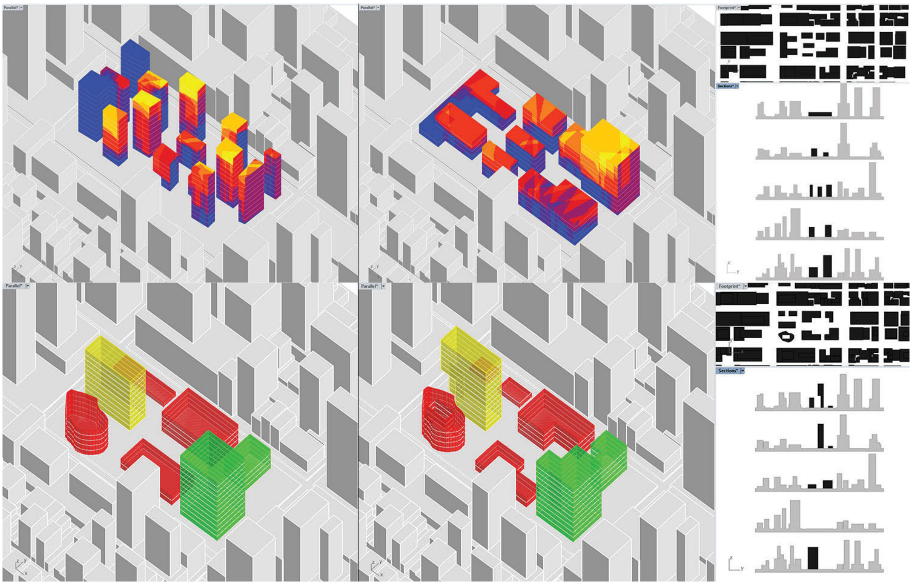


Figure 3. Digital Models and Analysis, Upper Left: Tower typologies with sunlight analysis, Upper Right: Simple urban design massing with sunlight analysis, figure and ground and serial sections, Lower: Courtyard typologies massing with toggling void layers for design comparison.

The aim of this work is to translate the sketches into 3D models for further detailed development and provide statistical figures and analytical diagrams for feedback. As both models and diagrams should allow further development, modification, and visualization, the Rhinoceros and Grasshopper platforms were chosen for their wide usage. This setup enabled performing advanced geometry manipulations, such as complex Boolean operations, creating buildings in different layers, and making the tool compatible with many existing analysis extensions.

Polygons of each building and void footprint are created from points with messages fed through our server. The footprint then is extruded according to the height option the user selected. Height is initially randomly chosen from 1-3 floors, 4-6 floors, and 9-12 floors, corresponding to low, medium, and high, respectively. This randomness happens within a small range and is intended for making the massing visually appealing, not affecting the production to a significant degree. The tool then computes Boolean operations and subtracts void spaces from buildings of other programs. Buildings belonging to different programs will be displayed in different colors.

Once the 3D models are ready, the tool analyzes the massing and provides design feedback. Pitts's (2012) work concentrates on statistical figures such as FAR, GFA and density. Guthrie (2003) highlights IBC (International Building Code) that "all services provided by an Architecture office include: Programming, Space Diagrams, Site Development Planning, Site Utilization Studies, Utility Studies, Environment Studies, and Zoning". We combine existing research and tools, as well as our own experience as urban designers, and propose the following diagrams to be our output: figure and ground diagram showing how the massing pattern co-exists with the context, serial sections to illustrate if the massing fit into surroundings in the vertical dimension, and sunlight analysis to provide environmental studies feedback (see Figure 3). We also annotate statistical parameters (FAR, building density, and GFA) in our tool to let users be informed if the site is being fully used.

Information of 3D models is delivered to the AR part through the server. Model of each building (Vertices, Triangles, and Normals) and its height are stored in JSON format. Below shows an example of a message.

```
{
  "objectType": "geometryCollection",
  "data": [
    {"objectType": "mesh",
     "faceIndice": [1, ..., 4],
     "vertexCoord": [251.0, 414.7, ..., 420.3, 0.0],
     "program": "office"},
  ]
}
```

3.4. AUGMENTED MODEL

Traditionally, urban designers and architects make physical models to get a sense of scale, how proposals would fit into the context and get visual feedback from the design. Shin et al (2013) discuss how virtual 3D models and AR are both expected to support the scene imagination, while "the AR representation for non-existing buildings in an existing environment presents the seamless scene of the 3D models combined with the real site on the display". Our tool tries to utilize the power of AR technology to replace the role of traditional physical massing models. We choose Unity (Unity (game engine), 2020), a cross-platform game engine, and Vuforia (Vuforia Augmented Reality SDK, 2020), an augmented reality software development kit, as platforms for AR deployment for its easy implementation and wide use.

A physical site model is required as the existing environment to help users build a sense of scale and site conditions. The model should be scanned and set as the target object within Unity. Unity also serves as a WebSocket client and receives messages from the Digital Model section about massing. Our own script will reconstruct the massing and in designated locations within the scanned site in real-time. With an AR device connecting to Unity, when the device detects physical site models, user's design proposals will pop up where the physical site is located. Similar to the digital model, massing will be colored according to their program (see Figure 4).

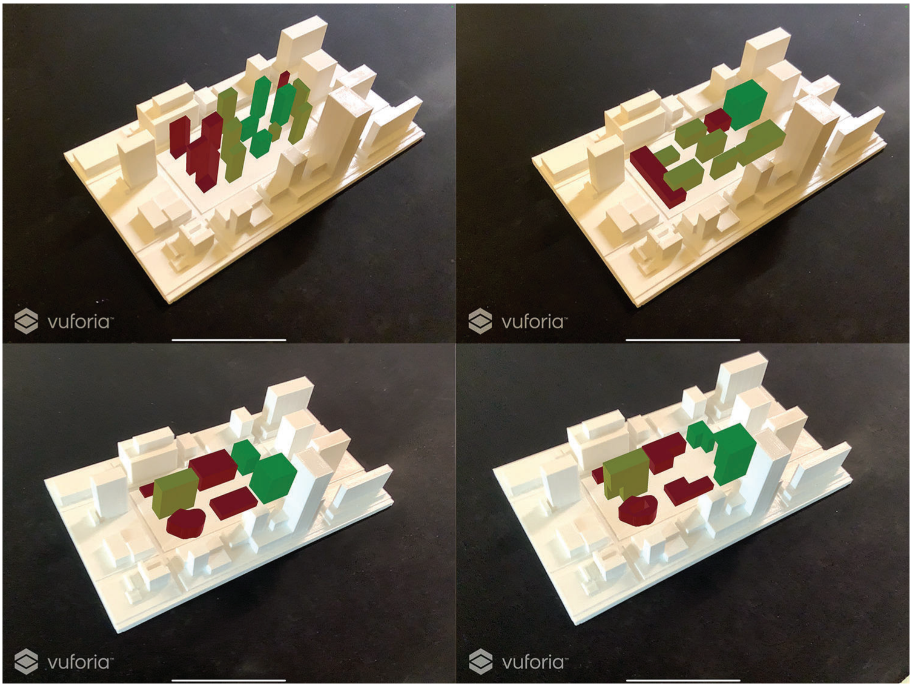


Figure 4. Augmented Models, Upper Left: Augmented tower typologies in physical model, Upper Right: Simple urban design massing, Lower: Courtyard typologies massing with toggling void layers for design comparison.

4. Results

With all three parts assembled together, Mass Production is an effective tool to translate urban designer's sketches into digital models, diagrams, and AR models in real-time and provide seamless visual and statistical feedback about urban design massing. The framework was showcased at an interactive exhibition (see Figure 5) under the theme of Computational Design at Harvard University Graduate School of Design to audiences from different fields such as urban design, community design, design technology, and data science in both academia and industries. Mass Production was also tested by authors' cohorts at school who major in architecture and urban design.

Figure 5. User Demonstration during the exhibition.

The feedback was generally positive, while some suggestions were inspiring. Users working on community engagements suggest that Mass Production could be used in participatory design as it's friendly to local residents who have no experience in design software. They only have to use tablets and pens after technical specialists set up the devices and software. The limitation users suggested was that some designers are not familiar with the programming and tools we used. They suggested Mass Production to be further compacted to avoid unnecessary setups and limit the software.

5. Discussion & Future Work

Along with algorithms, machine learning and VR/AR are widely applied in urban design fields, as urban designers, it's essential to understand these technologies and what advantages they could bring to our design with a critical view. Mass Production's goal is to keep the good and old way we practiced over the past decades but accelerating it by introducing computational and AR tools into this process. With mixed physical site models and urban design massing in augmented reality, the traditional sketching-modeling loop's feedback time has been reduced to almost zero. Mass Production makes the whole process faster and better as it makes both drawing and modification on sketches more convenient and accurate. It allows remote cooperation because of the networked communication, which could have an increasingly important role in contemporary contexts of social isolation. Mass Production is economical and environmental friendly as it helps to make the process consume less paper and model materials while it doesn't require expensive devices. We hope this tool could help designers concentrate more on the design itself by rapidly producing massing tests.

We plan to continue developing this tool to incorporate new techniques, equipment, and software mainly in two aspects: improving the user experience and adding more functionalities. While this tool aims to replace and accelerate traditional sketch-model loops, we try to make the interface, setup and experience as simple as possible. Our tool currently involves three software and at least two devices, which makes it sometimes cumbersome to switch between devices/software. By integrating some available software such as Fologram (Fologram, 2020) or developing our own app, the workflow will be more rational and fluid.

We also envision the completion of our feedback loop. Currently, the sketch interface changes could influence the final AR model, while users can’t manipulate the AR model directly. We are considering adding features that allow users to modify AR models directly with hand tracking or other available technologies. The program, the input parameter users choose for each building, is not fully utilized right now. Instead of pure visualization purposes, different features could be visualized such as architectural style, facade design, or typologies to push this tool a step further into urban design phases.

References

“Information technology — The JSON data interchange syntax” : 2017. Available from <https://www.iso.org/standard/71616.html#̃::text=JSON%20is%20a%20lightweight%2C%20text,portable%20representation%20of%20structured%20data> (accessed 9th December 2020).

“Grasshopper 3D” : 2020. Available from <https://en.wikipedia.org/wiki/Grasshopper_3D> (accessed 9th December 2020).

“Rhinoceros 3D” : 2020. Available from <https://en.wikipedia.org/wiki/Rhinoceros_3D> (accessed 9th December 2020).

“WebSocket” : 2020. Available from <https://en.wikipedia.org/wiki/WebSocket> (accessed 9th December 2020).

“Vuforia Augmented Reality SDK” : 2020. Available from <https://en.wikipedia.org/wiki/Vuforia_Augmented_Reality_SDK> (accessed 9th December 2020).

“Fologram” : 2020. Available from <https://fologram.com/> (accessed 9th December 2020).

“Unity (game engine)” : 2020. Available from <https://en.wikipedia.org/wiki/Unity_(game_engine)> (accessed 9th December 2020).

“SketchUp” : 2021. Available from <https://en.wikipedia.org/wiki/SketchUp> (accessed 7th February 2021).

Aliakseyeu, D., Martens, J.B. and Rauterberg, M.: 2006, A computer support tool for the early stages of architectural design, *Interacting with computers*, **18**, 528-555.

Billinghurst, M. and Henrysson, A.: 2009, *Mobile Architectural Augmented Reality*, Springer Netherlands.

Duarte, J.P., Beirão, J.N., Montenegro, N. and Gil, J.: 2012, *City Induction: A Model for Formulating, Generating, and Evaluating Urban Designs*, Springer Berlin Heidelberg.

Guthrie, P. and Guthrie, J.P.: 2003, *Architect’s Portable Handbook*, McGraw-Hill Professional Publishing.

Gül, L.F.: 2017, Studying Architectural Massing Strategies in Co-design - Mobile Augmented Reality Tool versus 3D Virtual World, *Proceedings of eCAADe 2017*.

Kerr, J. and Lawson, G.: 2019, Augmented Reality in Design Education: Landscape Architecture Studies as AR Experience, *The international journal of art & design education*, **39**, 6-21.

Kunze, A., Burkhard, R., Gebhardt, S. and Tuncer, B.: 2012, *Visualization and Decision Support Tools in Urban Planning*, Springer Berlin Heidelberg.

Pitts, G. and Luther, M.: 2012, A Parametric Approach to 3D Massing and Density Modelling, *Proceedings of eCAADe 2012*.

Rhee, J., Veloso, P. and Krishnamurti, R.: 2020, Integrating building footprint prediction and building massing - an experiment in Pittsburgh, *Proceedings of the 25th CAADRIA Conference*.

Shen, J.Q., Liu, C., Ren, Y. and Zheng, H.: 2020, Machine Learning Assisted Urban Filling, *Proceedings of the 25th CAADRIA Conference*.

Shin, D.H., Park, J., Woo, S. and Jang, W.S.: 2013, Representations for imagining the scene of non-existing buildings in an existing environment, *Automation in construction*, **33**, 86-94.

P2P URBANISM

Collaborative Generation of Spatial Plans Through Paper Cutting

DEREK PUNG[1] and PATRICK JANSSEN[2]
[1,2]*National University of Singapore*
[1]*derek.pung@u.nus.edu* [2]*patrick@janssen.name*

Abstract. This research presents a vision-based Tangible User Interface that was designed to facilitate the investigation of urban spaces. The analogue-digital process made use of inexpensive paper material and commonly accessible technology like a modern camera-enabled phone. Citizens will use a paper-cutting approach to shape the urban space within an urban block and use the phone as the processing agent communicating with a server in the cloud. A three-dimensional visualisation of the urban block may then be viewed on the phone or the computer. A prototype implementation has been developed that allows simple urban massing to be generated. Preliminary tests with groups of users showed promising results. Instead of a conventional design workshop engagement, participants were able to set up the tool in their own time and space and work collaboratively in small groups to developed diverse types of urban layouts.

Keywords. P2P Urbanism; Tangible User Interface; OpenCV; Human-Computer Interaction.

1. Introduction

Participatory Urban design is an effective method for engaging citizens in the design of the urban environment. Several papers reported that the designed spaces at the end of the process often better fulfil the wishes and aesthetic preferences of the citizens (Crewe, 2001). Citizen involvement in the design process could also directly contribute to their wellbeing and the frequent utilisation of the designed space (Anderson & Baldwin, 2017). In a traditional participatory urban design using the physical medium, participants would undergo active discussion and mediation in a workshop setting where people interact face-to-face. Modern web technology has transformed the way people work, engage with a tool, and with one another. The Peer-to-peer(P2P) urbanism movement (Salingaros, 2010) argues for a network-based planning process that incorporates citizen participation and co-design. It proposes an informal environment supported by Information and Communication Technologies (ICTs), where people can contribute to planning decisions through their collective knowledge.

Numerous researchers have been investigating how co-designing by citizens can be facilitated through different visualization methods (Mueller et al., 2017).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 659-668.

Typically, such methods and tools will rely on a digital modelling approach, often within a web-based environment. Compared to the physical medium, digital visualization tools are often able to communicate more complex solutions and provide a platform for citizens to quickly iterate and compare with past designs (Al Kodmany, 2001). However, digital environments tend to discourage collaborative discussions between multiple people in real-time. Furthermore, for non-experts, creating and modifying digital models is often seen as a frustrating process.

Tangible User Interface (TUI) is an active research field that looks at coupling digital computation with human interaction in the physical space. This research posits that TUI can combine the benefits of both traditional and digital mediums. Participants in a TUI-enabled design engagement will be able to discuss and evaluate complex designs in real-time.

For instance, the Walter Segal Model was a tool created by Frazer and his team to involve the self-builders in the design process. The tool featured acrylic sheets that served as an abstraction of the panels used in Segal's timber framing construction method. Users fitted the processor pins attached to each sheet into the sockets of a gridded circuit board. Each embedded acrylic sheet contained information of the material and form of the panel, allowing a three-dimensional model to be generated on the computer, along with necessary construction drawings and metrics that evaluated the cost. This tool served as a substitute for the Architect and presented a case where an architect's intelligence had been successfully transferred to the tool. Without the presence of the architect, participants were able to successfully generate, visualise, and evaluate their models with the digital tool. Prior to the tool, the architects would be involved in the translation of the matchstick abstractions and sketches into architectural drawings, while explaining the design concerns (Frazer, 1982). MIT's CityScope allows participants to interact with a digital urban model through physical LEGO blocks. Each LEGO module was tagged with a unique grid pattern that is representative of its type. After capturing the layout using computer vision technologies, complex simulations are calculated and projected onto the table in real-time (Hadhrawi & Larson, 2016). These projects used complex algorithms to provide an environment for citizens to collaborate and create spaces. However, the chip-based and projection-based technologies often require elaborate set-up and are often very costly. They may not be deployable at the community scale and would limit the number of citizens that can participate in the design process.

A web-based co-design platform would allow for a broader reach while keeping the set-up time and cost relatively low. For example, the Quick Urban Analysis toolkit was developed as a tool for presenting and manipulating urban geometries on the web (Mueller et al., 2018). On the platform, citizens place modules from a library of geometries onto a map. The geometries represent urban features and may be published and viewed by other participants on the platform. The project has shown how a web tool may be beneficial for active participation in the design and evaluation of urban environments. However, beyond rating submitted designs, such environments tend to discourage collaborative discussions between multiple people. Multiple participants do not have the option to collaborate on the same map at the same time. The strengths and weaknesses of the digitally-enabled projects are consistent with the analysis presented by Al-Kodmany.

This research aims to develop a web-based participatory tool that combines the benefits of both traditional and digital mediums in its design. It evaluates the use of a web-hosted, paper-based tangible user interface as a cheap and accessible method for participatory urban design. The next section discusses the tangible operations possible with paper modules, followed by a section that discusses the digital algorithms and methods for processing the paper modules. A prototype was implemented and tested with two groups of participants. This paper concludes with the results and a discussion of future work.

2. Paper-based TUI

This research proposes a hybrid analogue-digital approach that allows citizens to generate urban proposals using paper cut-outs, a mobile phone app, and a web-application. The paper cut-outs are placed on a print-out of the site plan and are used in various ways to define either urban massing or urban spaces. The thin planar nature of paper makes it very malleable to different forms of expression. It is also a very accessible material and may be bought from any stationery shop at an affordable price. Paper can vary from one another in its density, texture, and colour. As a TUI powered by vision-based technologies, this research posits that colour may be used as rule indicators for generating a 3D model. Participants will directly manipulate paper and create cut-outs shaped to their desired spaces. The colour of the paper will inform the digital processing agent which rule to use to generate the model.

2.1. COLOUR OPERATIONS

Two basic relationships have been identified as colour operations. In an additive colour operation, paper cut-outs are generated as physical objects. For subtractive colour operations, the cut-outs are used to carve out or subtract spaces. Different colours can be used to define different colour operations. More complex relationships may be defined when multiple colour operations are used in combination.

2.2. PAPER OPERATIONS

Paper shapes may be rotated, flipped, or moved around on a printed site map. They may also be cut down into smaller shapes. These basic operations either transform the paper module on the site map or directly changes the shape of the module. They are straightforward as the nature of their transformation is not affected by the change of material colour. On the contrary, folds, and overlays with different coloured paper open more opportunities for expression (Figure 1).

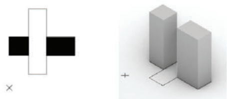
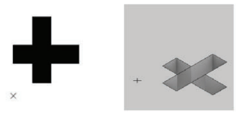
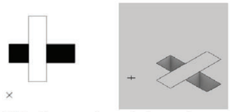
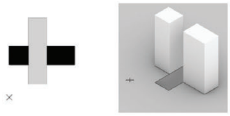
Paper Operation	Colour Operation	Same Colour	Different Colour
 Overlay	Addition		 Overlaid has the same colour as background
	Subtraction		 Overlaid has the same colour as background
	Combination	**Not Applicable** Different Colours are used to represent different operations	 Grey: Subtraction; Black: Addition
 Fold	Addition		 Back face has the same colour as background
	Subtraction		 Back face has the same colour as background
	Combination	**Not Applicable** Different Colours are used to represent different operations	 Grey: Subtraction; Black: Addition

Figure 1. TUI Paper Operations.

2.2.1. OVERLAYS

Two modules of the same colour overlaid on one another may be perceived as a single module. Overlaying a module of another colour effectively splits the lower module. In other words, the overlay operation may be operated similarly to the "union" and "difference" operations found commonly in conventional CAD environments.

2.2.2. FOLDS

When a module with different colours on each side is folded, the size of the original module is reduced. Folding a module of uniform colour mirrors and unions itself on the folded axis. In other words, the folding method may perform similarly to the cut and overlay method. However, folding allows for convenience as the operation directly operates on a single piece of paper.

3. Proposed P2P Urban Design Method

The focus of the proposed method is to get feedback from citizens on the types and configurations of urban spaces that are desired. For the proposed method, a platform is envisaged for citizens to select urban sites anywhere in the city and to create massing proposals that incorporate public spaces for various purposes.

The proposals were to incorporate desirable urban spaces, while at the same time meeting the required gross floor area (GFA) targets. Citizens can provide suggestions for the type of urban space that would serve the community. Developers will receive a variety of solutions that will inform the citizens' desires and preferences. Ultimately, citizens will gain awareness of the new development and benefit from a more inclusive urban space inspired by the collaborative efforts.

The steps are as follows:

1. **Location:** Citizens gather in small teams, with access to a laptop, a mobile phone, a printer, and a set of coloured papers. This could be at people's homes.
2. **Preparation:** The teams print out the design materials on various coloured papers, consisting of the site plan and a library of 2D shapes that can be placed on the plan. The colours represent the rules used for generating a design. The teams cut out the library of shapes.
3. **Analogue Exploration:** Teams proceed to make urban design proposals by arranging the shapes on the printed urban plan. Since this process is totally analogue, the team can sit around a table and discuss different options, moving around the cut-out shapes.
4. **Digital Generation:** The mobile phone is used to take photos of the design proposal and upload them to the web application running on the server. The photos are converted to vector drawings using the OpenCV library. For each photo, a 3D urban model is then generated, together with various analysis results, using a series of parametric models. Within a few seconds, the 3D model with analysis results is visible on the laptop.

Computer Vision (CV) and Geographic Information Systems (GIS) are the key supporting technologies.

OpenCV is an open-source computer vision library. The library contains a collection of optimised algorithms ranging from basic image processing to advanced machine learning processes. Although the core library only supports non-browser programming languages like C++, Python, and Java, the recent development of Web Workers allows the library to be precompiled into WebAssembly modules and be run on a web browser.

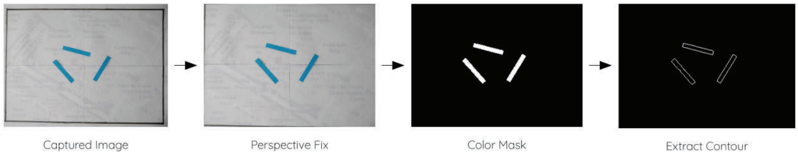


Figure 2. A captured image goes through resizing, perspective fix, colour fillter, and contour extraction.

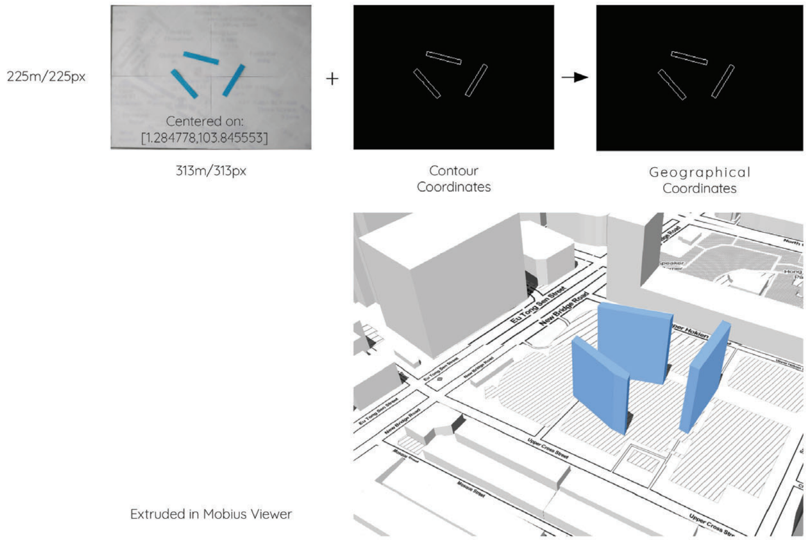


Figure 3. Contour to GIS parametric model.

The captured image goes through the following steps in the digital generation process (Figures 2 & 3):

1. **Resize and Fix Perspective:** The map boundaries are detected from the image and the defined area of interest is then stretched and skewed to fit the image canvas.
2. **Colour Layers:** Participants may define different colours to be extracted from the image. The colours will be separated into layers which may be used to define different operations.
3. **Contours:** Filtered shapes from the same colour layer are converted into contours. The closed poly-line shapes are simplified to reduce the number of coordinates.
4. **Geospatial Context:** The geolocation, image resolution, and dimensions of the printed map are known. The coordinates of the 2D polygons can therefore be automatically converted into geospatial coordinates (Figure 3).

5. **3D Model:** To generate 3D models, an existing web-based parametric modelling tool was integrated into the generation pipeline. The tool is called Mobius Modeller (Janssen, 2016). Parametric scripts may be set up to process the geographical output of the different colour layers.

4. CtySketch Web Application

A tool named CtySketch was developed. Additive paper operations were explored in the first version of the tool. The paper cut-outs represent building footprints that were generated as simple extruded forms. In future versions, the repertoire of modeling operations will be expanded, to allow a greater variety of forms to be generated.

CtySketch is a web application written using the React JavaScript Framework and is hosted on the Amazon Web Services cloud. Users will only require readily accessible technologies such as laptops, mobile phones, and desktop printers (Figure 4).

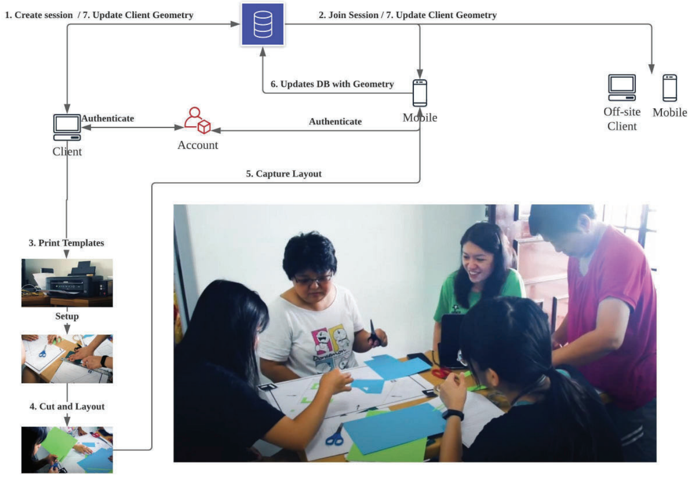
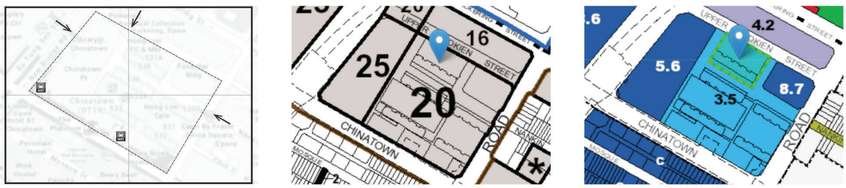


Figure 4. CtySketch Workflow.

1. A new user may create an account and start a design session for a selected site.
2. A unique room number is administered for the session, which may be shared to other off-site participants to view the design as it changes live.
3. Participants on-site will then print out the site drawing and scaled modules.
4. The modules are cut out and arranged to the site drawing to the desired design.
5. The room owner may also access the same room using a portable device to easily take a photo of the prepared site.
6. The image is processed, and the identified geometries are then updated on the database.

7. All participants may view the generated design layout on the computer screen, discuss, change the layout, and regenerate with the same process.

A specific site in Singapore was chosen to provide a controlled environment for testing and evaluation. The Hong Lim residential estate in Central Singapore was constructed in the 1970s to provide housing for squatter residents displaced by the renewal developments. This research posits a scenario where the entire urban block will be cleared for redevelopment due to age and operational inefficiencies. The block was chosen for its size, existing program, and proximity to a variety of historic and financial developments in central Singapore. By keeping the site size to the bounds of an urban block, we constrained the investigation to a scale familiar to untrained residents



Provided site map (1:750) | Height Limit (storeys) | Plot Ratio

Figure 5. Existing Site Constraints.

Two basic building functions have been identified for the plot: Commercial and Residential. Participants were to relate to the neighbourhood and provide urban layouts that satisfy the required Gross Floor Area (GFA) of the block. GFA was calculated following the land use and plot ratio guidelines in the Master Plan. A different colour was assigned to each function and participants placed the different coloured paper cut-outs on an A2 sized plan (Figure 5). Surrounding context such as key circulation paths and transport nodes were provided on the site map. Footprint templates printed on a 10x10m scaled grid were also provided to the participants to enable a better sense of the scale. A Mobius Modeller script was created to generate the building massing. For each polygon detected and processed from the captured image, a simple extrusion was generated on the location.

5. Pilot Test

Two voluntary groups of 5 to 6 people participated in the pilot test. The two sessions were independent and explorative. They serve to report on the successes and insufficiencies of the application. Participants were tasked to create layouts that satisfied their design goals and the required GFA. Two different coloured paper were used for the test. Blue was used to represent commercial footprints while green was used to represent residential footprints. Often, the participants were quick to get started. They would each pick up a sheet of gridded coloured paper and start to simultaneously develop small parcels of the map with their individual coloured cutouts. The application would then inform the participants of the computed GFA for each coloured function. By making quick and simple organisations at the start, participants were able to quickly familiarise themselves with the technology. However, disagreements quickly arose as the group had not agreed to a clear organisation strategy for the entire block. In their following discussions, participants were able to quickly shift the paper cut-outs around, or pick one up and make non-destructive operations like overlaying and folding. Some participants were also quick to tear their creations to trim them into smaller shapes. The short waiting time between capturing a photo and the result showing on the shared computer screen allowed participants to better visualise their ideas and come to a consensus.

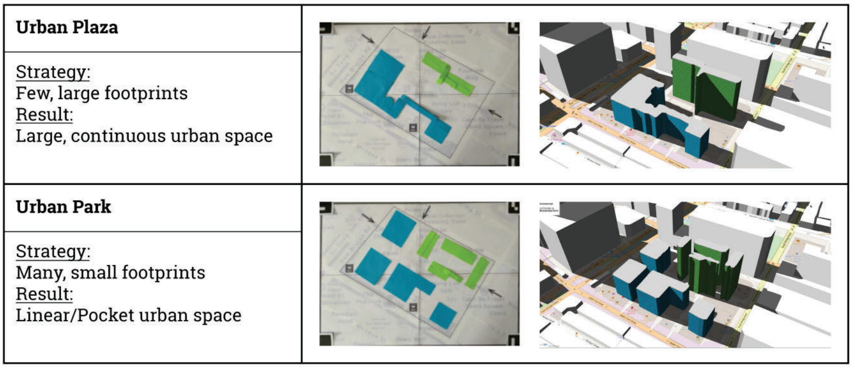


Figure 6. Urban Plaza: Large Footprints; Few Buildings.

Over the course of the sessions, more than twenty layouts were collected from the users' experiments. In all of the designs, participants took into consideration the key East-West circulation directions and the access locations to the nearby public transport nodes. We have classified the generated urban spaces into two types (Figure 6). Generally, participants created layouts with many, small footprint cut-outs, or few, large footprint cut-outs. The former had the tendency to generate linear and pocket urban spaces, which we classified as "Urban Parks". The latter created large and continuous urban spaces, which we classified as "Urban Plazas". In the featured Urban Park example, participants also pointed out their intention to create an enclosed space within the residential cluster.

Feedback was also obtained from the groups:

- **Simple:** Most of the participants were unsure of how to start on a design. However, they got the hang of it after going through the full workflow a couple of times: cutting, arranging, and generating. The printed templates allowed participants to get started quickly and visualise their results.
- **Enjoyable:** Participants felt that the nature of the activity was quite fun
- **Inexpensive:** Participants were amazed that the generated result was derived from paper cut-outs.
- **Relatable:** Most of the participants felt that they were able to relate to the context well and the circulation arrows and transport nodes marked on the map

were helpful.

- **Comprehensible:** Participants were able to understand to the effects of changing the size of the cut-outs on the extruded height.
- **Collaborative:** Participants enjoyed developing ideas in a collaborative face-to-face group setting in the comfort of their own home, with discussions focusing on both the decisions about paper cutouts and the results generated by the computer.
- **Limited Flexibility:** Some issues surfaced during the generation. Participants had attempted to make holes and bridges which the algorithm was currently unable to account for.

6. Conclusion

An inexpensive TUI prototype was developed to enable citizens to contribute to the creation of urban environments using simple paper cut-outs. In the spirit of P2P Urbanism, the prototype was also enabled by accessible ICTs, allowing participants to contribute from the comfort of their own homes. Experiment results have shown that participants were able to create of conventional urban spaces like urban plazas and parks while meeting the maximum GFA of the site. Using paper and a portable phone camera, participants collaborated to express their ideas, and to visualise relatable extruded models on screen.

The TUI prototype coupled an analogue planar material with digital generation algorithms that were defined by the material colour. Further research will look at more complex relationships and algorithms. A framework will be developed to provide a guide for the decision-making support necessary for this new remote collaborative design process. Augmented Reality may also be explored to provide more active interaction between participants and the generated model.

References

Al-Kodmany, K.: 2001, Visualization Tools and Methods for Participatory Planning and Design, *Journal of Urban Technology*, **8**(2), 1-37.

Anderson, J. and Baldwin, C. 2017, Building well-being: Neighbourhood flourishing and approaches for participatory urban design intervention, *in* R. Philips and C. Wong (eds.), *Handbook of community well-being research*, Springer, 313-337.

Crewe, K.: 2001, The quality of participatory design: The effects of citizen input on the design of the Boston Southwest Corridor, *Journal of the American Planning Association*, **67**(4), 437-455.

Frazer, J.: 1982, The use of simplified three-dimensional computer input devices to encourage public participation in design, *Computer-aided Design*, **14**, 143-151.

Hadhrawi, M. and Larson, K.: 2016, Illuminating LEGOs with Digital Information to Create Urban Data Observatory and Intervention Simulator, *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems*, New York, NY, USA, 105-108.

Janssen, P., Li, R. and Mohanty, A.: 2016, Mobius: a parametric modeller for the web, *CAADRIA 2016*.

Mueller, J., Lu, H., Chirkin, A., Klein, B. and Schmitt, G.: 2018, Citizen Design Science: A strategy for crowd-creative urban design, *Cities*, **72**, 181-188.

Salingaros, N.A.: 2010, “P2P Urbanism” . Available from <https://www.researchgate.net/publication/214822806_A_Definition_of_P2P_Peer-To-Peer_Urbanism>.

RESEARCH ON SELF-FORMATION WIND TUNNEL PLATFORM DESIGN BASED ON DYNAMIC GRIDDING MECHANICAL DEVICES

YANAN SONG[1], KEKE LI[2], YUQIONG LIN[3] and
PHILIP F. YUAN[4]
[1,2,3,4]*Collage of Architecture and Urban Planning, Tongji University*
[1,2,3,4]*{1930055|1910253|1630237|philipyuan007}@tongji.edu.cn*

Abstract. Nowadays, climate problems, such as urban ventilation, heat island effect are becoming increasingly serious. Performance-oriented buildings that respond positively to the environment are constructing a sustainable future of the living environment. This research introduces an autonomous Self-Formation Wind Tunnel (SFWT) platform based on 120 dynamic grid mechanical devices, and its building cluster morphology generation workflow in the conceptual design stage, for the rapid and mass formation experiments. The Self-formation wind tunnel plat-form, which has the advantages of both perceptive and real-time data, is able to use the techniques of machine learning to provide a new design paradigm, from environmental performance to physical morphology.

Keywords. Self-Formation Wind Tunnel; Building Cluster Morphology; Dynamic Models; Mechanical Grid Devices; Environment Performance Design.

1. Introduction

In the urbanization process, the modern high-density urban space provides us convenient and intensive living space. While at the same time, it also aggravates the deterioration of urban ventilation, heat island effect, air pollution, and so on. The formation of the numerous building clusters, which leads to local eddies as well as local strong winds, impacts malignantly on wind environment comfort of pedestrians as well as the location and strength of the air pollution (Ng, Yuan et al. 2011). Therefore, the optimization of environmental performance, the adjustment of the morphology and layout of the building cluster, play a really important role to improve the urban climate and atmospheric environment.

To adjust the platform to more complex terrain and massing schemes of complex building group morphologies, we develop a small-scale and self-formation wind tunnel (SFWT) based on the transmission principle of lifting machinery, which is movable, easy-disassembled, and three-unit designed, built by aluminum alloy profiles and acrylic boards. The platform is composed of the inlet unit (including stable section and contraction section), experimental unit (including smoke section, mechanical device) and the outlet unit (including

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 669-678. © 2021 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

diffusion section, fan section), also can be divided into the physical morphogenesis system, wind environment simulation system and data acquisition system.

With the rapid development of artificial intelligence technology and sensing technology in the post-Internet era, the customed physical wind tunnel has the dual advantages of perceptuality and real-time data. It can promptly generate a large number of physical and environmental data in a short period of time, cooperating with the big requirement of data sets in machine learning for the prediction from wind environment performance to architectural form, providing a new design paradigm combing physical experiment tools and machine learning algorithms, which is different from wind environment performance design method based on CFD (Yuan and Lin 2019).

2. Design Strategy of Dynamic Gridding Mechanical Devices

2.1. WIND TUNNEL ONTOLOGY DESIGN

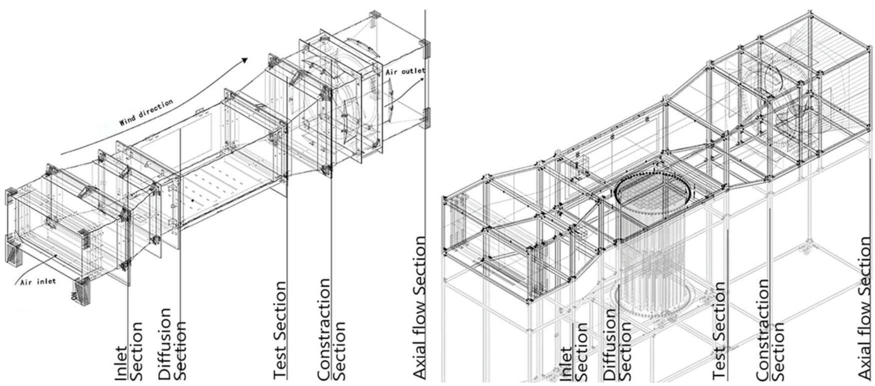


Figure 1. Wind tunnel ontology of previous work(Zheng, Yao et al. 2017) (left) and Self-formation wind tunnel proposed in this paper (right).

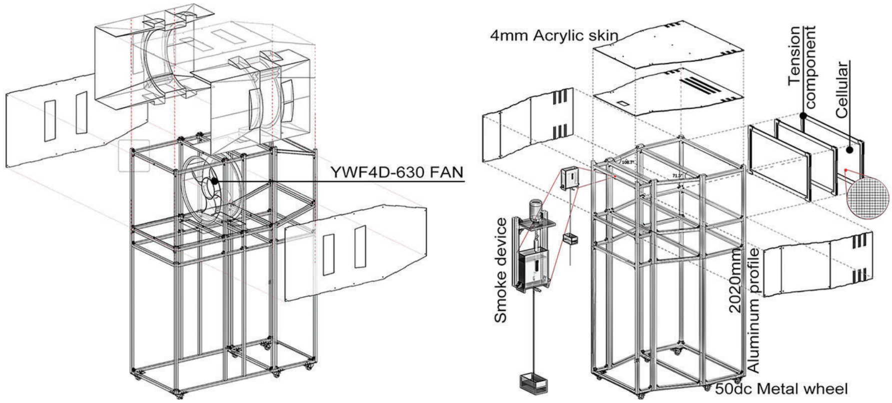


Figure 2. Construction diagram of fan section (left) and stability section (right).

The self-formation wind tunnel developed in this research is a low-cost mini customed wind tunnel as shown in Fig.1. It is totally improved on the basis of the team's previous researches (Zheng, Yao et al. 2017, Lin, Zheng et al. 2018), whose overall structure remains a five-segment structure, which is consisted of the fan section, con-traction section, test section, diffusion section, and stability section. The total length of SFWT is 3 meters while the test section is 1000mm long, 570mm wide, and 390mm high. It is constructed by 2mm thick transparent acrylic sheets and 2020 aluminum alloy profiles. The main differences between the two, mentioned above, are as follows: (1) The diffusion section integrates an improved smoking de-vice with an adjustable-rate; (2) The test section integrates the mechanical system under its bottom plate; (3) From the perspective of handling and disassembly, the wind tunnel is designed as a three-stage disassembly, composed by air inlet, experiment and air outlet. Each section is equipped with casters for movement; (4) A layer of profiles at the same horizontal level is added to the upper and lower parts of the wind tunnel so that the upper and lower parts can be separated, and the traditional use function can still be achieved without mechanical devices.

2.2. PRINCIPLE OF MECHANICAL TRANSMISSION

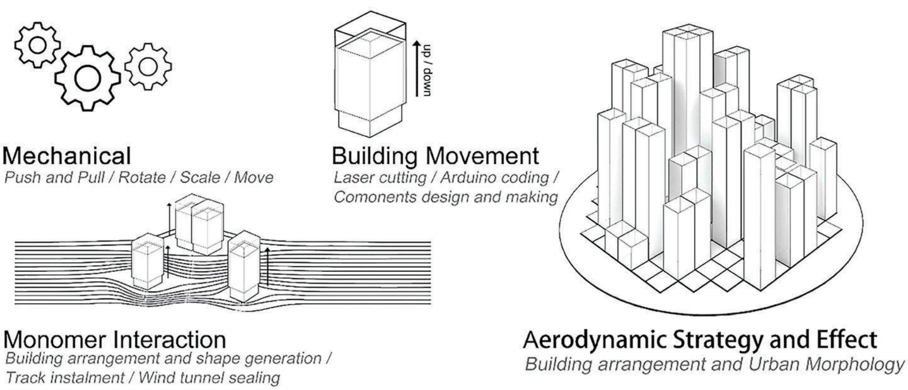


Figure 3. Principle of mechanical transmission.

The mechanical transmission of the lifting-up modular actuators provides the feasibility of diverse urban space formation. The Arduino electronic control system, which is based on the servo system, acts as the core mechanical transmission of this experiment. With the help of an electronic signal which is generated by a wind speed sensor, the device controls different morphologies. The detailed workflow is as follows: (1) The servo receives the signal source and drives the motor to rotate. (2) The gear set receives the motor signal and processes it to rotate the corresponding angle. (3) The rack is driven by gear, whose corresponding moving distance is determined both by the rotation angle and diameter of the gear. The experiments completed the morphological changes of the experimental model by gears or other parts (Rui-yan 2012).

2.3. MECHANICAL DEVICE DESIGN BASED ON DYNAMIC GRIDDING

2.3.1. Dynamic gridding unit

A primary need of the physical experimental platform is to ensure the accuracy of the wind environmental simulation as well as the accurate presentation of the building morphology in the wind tunnel. In order to achieve better universal experimental applicability, the dynamic model mechanical system is designed base on the gridded mass units. This paper is committed to studying how to implement the sensor placement and installation in the smallest block, and the selection of the servo steering gear to achieve the precise driving of each grid unit.

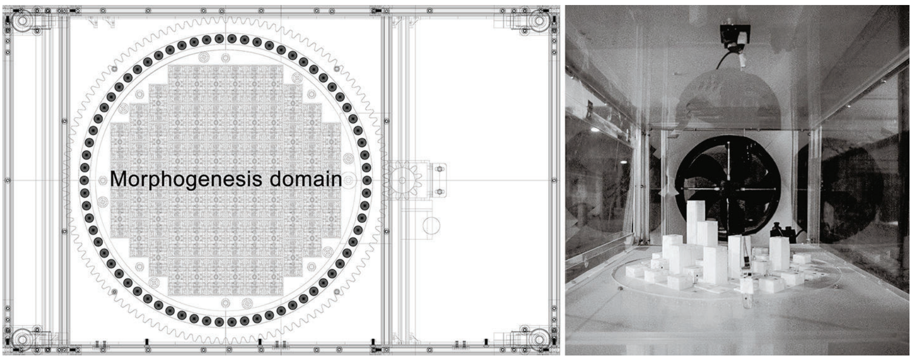


Figure 4. Morphogenesis domain.

Within the test section (1000mm length, 570mm width, 390mm height), this research developed mechanical lifting-up devices, which is composed of 120 dynam-ic grid units. To prevent interference with airflow from the inner wall (Hernández, López et al. 2013) and the morphogenesis domain is controlled in the space above 100mm from the wall. The windward area of the tested model is less than s ≤3.3×104 mm², to make true indicators of blockage within 15%. The lifting-up units group lo-cates on the chassis center of the test section, about 2/3 of the way from the inlet of the test section, forming the morphogenetic domain of the wind tunnel together with the chassis.

Since the simulation of the wind environment around building requires a standard test of a specific range of environmental masses around the measured building, and the experiment of urban morphology formation needs to consider the impact of roads, landscapes, and other open spaces, the 120 dynamic units, as a unit to simulate the smallest surrounding environment, could rise to a maximum of 250 mm at the same time in the windward direction. The average maximum height of all gridding units is 110mm, with the area of the windward surface with a maximum of 30000 mm². If using a maximum scale ratio of 1: 1000 to set the model size of the building group and setting the minimum floor height to 3m, the maximum plot ratio can be reversely calculated to obtain the experiment. In this case, the maximum plot ratio in the site was 36.67, which is far exceeding the maximum plot ratio of any high-density city center in reality. If then adding the influencing factors of the interior space and con-trolling the building density at 70%, the plot ratio comes to be 25.67. This data also meets the simulation demand for the maximum plot ratio of high-density urban centers. Therefore, for the application of the dynamic gridding mechanical model system in a mini wind tunnel, this paper developed a morphology test section with a diameter of 456mm composed of 120 grids, whose single side length is 34mm (certified after multiple tests). The center 64 units are the primary test area and the rest are the surrounding areas of the test subject. This method of determining the range of a dynamic grid system can be applied to physical wind tunnels of any different scales, and the size can be controlled by back-calculation based on its blocking degree.

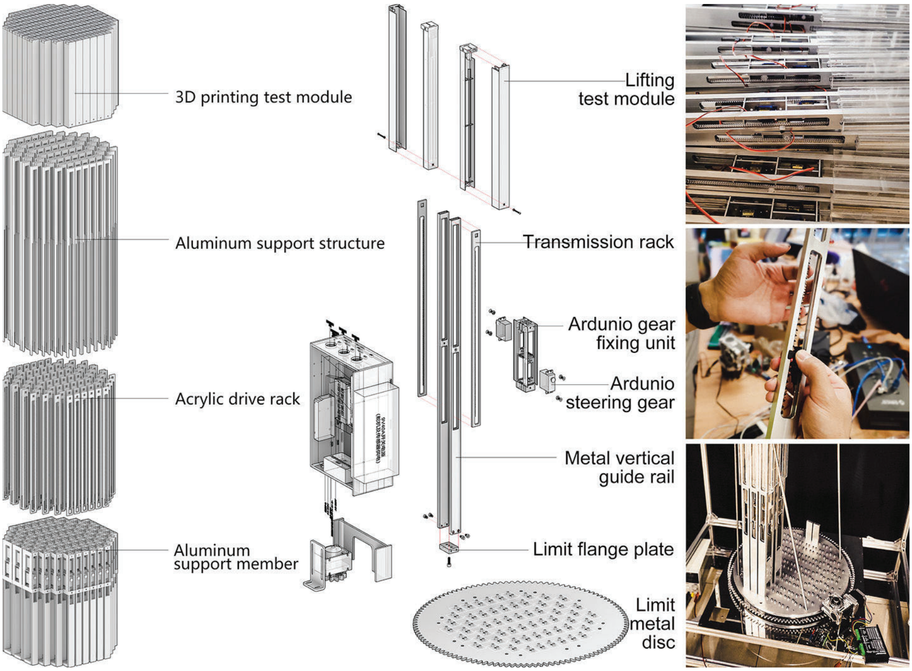


Figure 5. Construction diagram and pictures of dynamic model mechanical system.

Each unit in the dynamic model mechanical system can be divided into two main parts according to different functions: the 3D printed testing unit and the metal mechanical transmission unit. The ‘testing unit’ is mainly a part of the wind environment simulation experiment which is made of high stiffness PLA resin. This unit will change its lifting height, following the program instructions during the experiment. Every change in the morphology affects the airflow in the test section. The ‘mechanical transmission device’ is the driving device, which is located below the wind tunnel test section and does not interfere with the wind field environment in the wind tunnel. The mechanical transmission device is composed of vertical guide rails, internal drive racks, driving gears, and steering gear modules (including two steering gears arranged in opposite directions). Due to the size limitation of the dynamic griding, the size of a single servo has exceeded.

Therefore, merging the mechanical space of the adjacent units is necessary. The experiment arranges the servos in different layers to integrate the lower mechanical transmissions of the neighbor dynamic units. The assembly sequence also needs to be specially designed. The design and assembly of the experimental unit must ensure complete connection and airtightness to avoid affecting the environment in the wind tunnel.

2.3.2. Mechanical transmission device

The mechanical transmission system is the key technology of SFWT platform. In this research, we choose wind sensors, mechanical actuators and the Arduino open-source control software to build the mechanical transmission system with feedback capabilities and barrier-free perceptual acquisition.

The mechanical actuators such as servo steering gear offer the driving force for test models. Mechanical actuators such as servo steering gear offer the driving force for test models. Within the control by program instructions, the steering gear turns parameters 'n' are converted into the movement distance of rack, driving test units up and down '$h=2\pi r\times n$ (r is the radius of steering gear)'. The experiment uses 120 ZL-361S single-axis servos to control different units' height and a DM542 stepper motor driver to control the rotated angle of the morphogenetic domain. By many experiments, we find that all dynamic units can reach the maximum evolution height within 10s.

Researchers always use sensors as the data perception devices to collect the real-time environment data and then input them into the processing software for further calculation (Kensek 2014, Prohasky, Castro et al. 2014). In this study, The rectangular hole with a length of 20mm and a width of 2.5mm is obligated to each unit, through which the sensor can pass to extend the probe with the sensitive element out of the unit. After empirical calculations, 8 Rev.P wind speed sensors are evenly distributed in the morphogenetic domain to obtain more accurate measurement data. To avoid experimental errors caused by unstable airflow, sensors run measurements within 10s after the mechanical grid keeping a stable state.

The mechanical transmission of each dynamic unit provides the feasibility for the characteristic stimulation of the diverse building morphology and the different layouts of the building group. So when designing the tested model unit and mechanical transmission unit, it is necessary to establish a digital model to estimate the feasibility of the component's motion logic and write actuators data and wind sensor data into the real-time digital environmental performance database. Arduino is a flexible cyborg-physical combination platform (Badamasi 2014), helping designers establish a 'real-world environment-digital performance-physical geometry' data transformation architecture. According to the achievement of the CAADRIA2018 Workshop, it is confirmed that the different morphology of a single building can be generated based on Arduino and Firefly (Zheng 2018, Lin, Song et al. 2019). So in this paper, on the basis of our previous study result, we still use Arduino and Firefly to control the whole experiment.

3. Interactive design workflow based on physical wind tunnel experiment

Some pioneering custom-made wind tunnel projects are emerging in advanced university laboratories, such as Rensselaer Polytechnic Institute (Menicovich, Gallardo et al. 2012, Menicovich, Lander et al. 2014) and RMIT University (Prohasky and Watkins 2014, Williams, Moya et al. 2015) in the last several years, verifying their advantages of simple visualization, quick feedback, and effective data collection. This paper proposes an SFWT-based building cluster morphology generation method-ology. Through the long-term exploration of wind tunnel formation by the author's team, DDRC, this design method can be summarized as the process of "Strategy expression-Simulation test-performance evaluation-design optimization-final formation" (Lin, Yao et al. 2018, Yuan and Lin 2019). The specific steps are shown as follows. First, different design strategies and optimization directions are selected for different types of research subjects. In this research, building porosity, including building density, floor area ratio, windward area index, and building height deviation are all suitable for building group morphology expression. Second, in the digital information space and the physical wind tunnel space, modeling language and static construction or dynamic change based on the mechanical device are used respectively to present the model of the subject under test. Finally, the wind tunnel is opened for the acquisition of wind speed or wind pressure data, and the Arduino and Firefly platforms were returned to Grasshopper and Rhino platform to realize further data processing and analysis. It evaluates the environmental performance of the tested scheme, generates the next scheme, and then visualizes and tests the scheme in the wind tunnel.

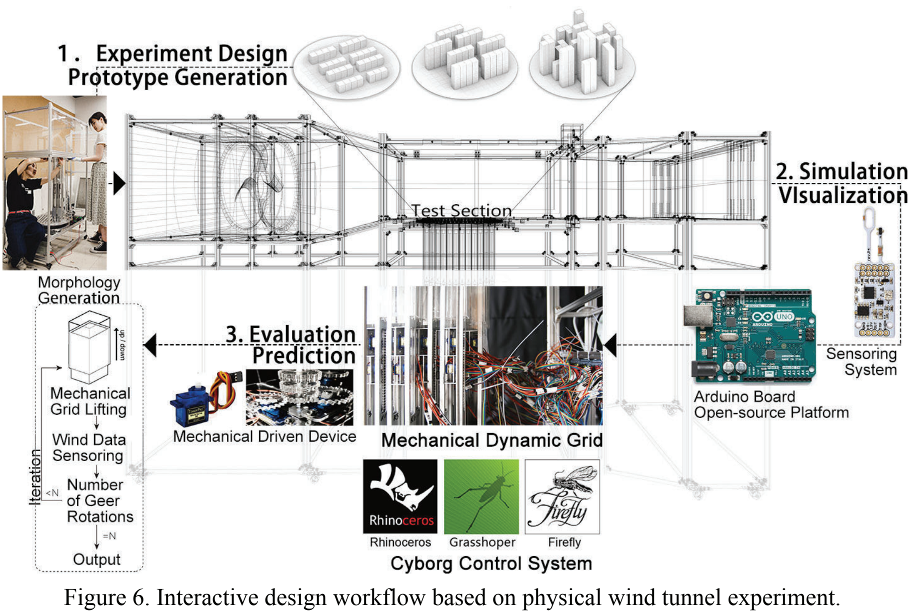


Figure 6. Interactive design workflow based on physical wind tunnel experiment.

The intervention of the dynamic mechanical devices essentially accelerates the process from the simulation test to design optimization. With the help of SFWT, designers can translate the digital geometric rules of building group morphology design optimization into the dynamic changes of the physical entities in real-time, making it possible to generate a large number of shapes and corresponding environmental data in a short time. This paper summarizes several popular building cluster formation design strategies for better wind environmental performance, including building density, floor area ratio, wind area index, and building height deviation, and uses different grid heights h to pixelated simulate buildings and open spaces (if $h=0$, the grid simulates the open space; if $h>0$, the grid simulates building). The workflow of building morphology generation experiment in SFWT is as follows: (1) Choose an apposite optimization engine (algorithms or software) around a specific design goal. Nowadays, because the input variables of environmental performance-based design have com-plex and non-linear interactions, designers usually choose the optimization engine which contains more than one iterative optimization algorithms, for a good solution with less time and effort. A large number of optimization methods have been developed, including genetic algorithms, machine learning algorithms, and artificial neural network algorithms, etc. (2) According to the selected design goal and optimization engines, the experimental programs are generated in Grasshopper. The morphological parameters are transformed by Firefly and Arduino into the driving parameters corresponding to the dynamic grid unit which means the steering angles of the steering gear. (3) Then start the SFWT experiment. Use the wind speed sensor to measure the speed in the wind tunnel; transmit and record the corresponding shape (the height data matrix of mechanical grids) and environmental data through the Arduino platform; and write to the evaluation system. The wind evaluation program automatically calculates environmental performance scores based on the wind environment evaluation indicators selected by the designer, such as the average wind speed values and wind speed discrete values of multiple sensor measurement points, thereby achieving wind environment data acquisition and evaluation translation. (4) Write the morphological parameters and wind environment parameters into the performance database in real-time. (5) Batch transfer the performance database parameters to the architectural functions of the optimization algorithm (in this study, we use a neural network algorithm model), to perform iterative training of the algorithm model. (6) Obtain an optimization algorithm (artificial neural network) with better prediction effect, into which input a large number of gradient building group index parameters and ideal wind environment data in the site environment to perform multiple predictions of building group morphological parameters; (6) Convert the predicted morphological parameters and the corresponding building group index parameters to possible morphological schemes, completing the prediction of morphology formation; (7) Convert specific morphological parameters into mechanical model parameters, present them in the wind tunnel and conduct smoke visualization experiments, and finally select the optimal scheme through the judgment of the designer to complete the “Human-machine collaborative generation” of building layout and volume height under the control of wind environment. The experimental photos of this process are as follows:

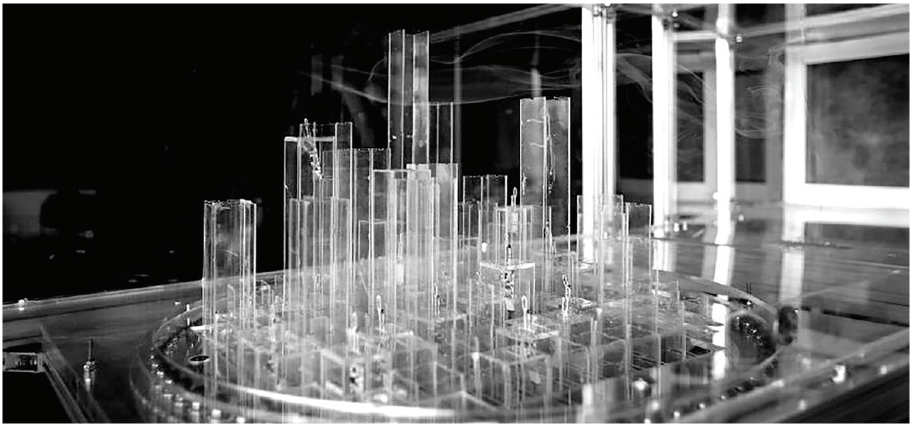


Figure 7. Picture of building cluster morphology generation experiment.

4. Summary

Based on the idea of a dynamic grid, this paper first develops a new self-formation wind tunnel with a set of morphogenesis machinery and then introduces an interactive building group morphology generation method which takes the urban wind environment performance as the entry point. On the simulation tool, we completed the digitization of the physical wind tunnel, and generate a feedback-type dynamic model of the sensors and actuators in order to use Arduino to set up a data feedback loop. On the design method, we aim to explore two aspects of wind performance-based design: quantitative data and qualitative streamlines. In this paper, the Grasshopper Firefly program is used to quantitatively associate the simulation data with the morphogenesis data of the building model. Under this open design frame, architects can adjust the morphological strategies, site environment, the positions of sensors, and data evaluation rules. With the introduction of some other sensors, for instance, wind pressure, wind temperature, humidity, and so on, the wind tunnel can upgrade to conduct a more comprehensive evaluation of the morphology, which enriches the significance of the physical environmental experiment and thus has high research significance and value.

By now, the wind tunnel simulation platform will no longer be only developed as a post-design testing and measurement tool, but enter the early design stage to generate the morphogenesis of the scheme design. Moreover, coupled with visualization tools, the SFWT, which performs real-time wind environment simulation, establishes a rapid feedback platform. Architects can clearly observe the aerodynamic effects of different building morphology in the three-dimensional space of the real scene. At the same time, the smoke flow lines were recorded as a series of diagrammatic auxiliary schemes for further research. Under this open design frame, architects can adjust the morphological strategies, site environment, the positions of sensors, and data evaluation rules. With the introduction of some other sensors, for instance, wind pressure, wind temperature, humidity, and so on, the wind tunnel can upgrade to conduct a more comprehensive evaluation of the morphology, which enriches the significance of the physical environmental experiment and thus has high research significance and value.

References

Badamasi, Y. A.: 2014, The working principle of an Arduino, *2014 11th international conference on electronics, computer and computation (ICECCO)*.

Hernández, M.A.G., López, A.I.M., Jarzabek, A.A., Perales, J.M.P., Wu, Y.L. and Sun, X.X.: 2013, Design methodology for a quick and low-cost wind tunnel, *Wind tunnel designs and their diverse engineering applications*, **1**, 1.

Kensek, K.M.: 2014, Integration of Environmental Sensors with BIM: case studies using Arduino, Dynamo, and the Revit API, *Informes de la Construcción*, **66**, 536.

Lin, Y.Q., Song, Y.N., Yao, J.W. and Yuan, F.: 2019, High-Rise Building Group Morphology Generation Approach Based on Wind Environmental Performance, *International Conference on Computer-Aided Architectural Design Futures Publisher: Springer*.

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, *AAG. 2018*, Gothenburg, 194-213.

McAlpine, J. D.: 2004, Computational fluid dynamics or wind tunnel modeling, *Envirometrics Inc.: Seattle*.

Menicovich, D., Gallardo, D., Bevilaqua, R. and Vollen, J.: 2012, Generation and Integration of an Aerodynamic Performance Data Base Within the Concept Design Phase of Tall Buildings, *ACADIA 12: Synthetic Digital Ecologies [Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture*, San Francisco, 87-96.

Menicovich, D., Lander, D., Vollen, J., Amitay, M., Letchford, C. and Dyson, A.: 2014, Improving aerodynamic performance of tall buildings using fluid based aerodynamic modification, *Journal of Wind Engineering and Industrial Aerodynamics*, **133**, 263-273.

Ng, E., Yuan, C., Chen, L., Ren, C. and Fung, J.C.: 2011, Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong, *Landscape and Urban planning*, **101(1)**, 59-74.

Prohasky, D., Castro, R.M., Watkins, S., Burry, J. and Burry, M.: 2014, Wind sensing with real-time visualisations for Designers-An approach to understanding wind phenomena for pedestrian comfort using low cost wind sensors, *Thompson, Emine Mine (ed.), Fusion - Proceedings of the 32nd eCAADe Conference - Volume 1, Department of Architecture and Built Environment, Faculty of Engineering and Environment*, **2014**, 165-171.

Prohasky, D. and Watkins, S.: 2014, Low cost hot-element anemometry verses the TFI Cobra, *19th Australasian Fluid Mechanics Conference*.

Rui-yan, C. A. I.: 2012, Design of Servo Control System Based on Arduino, *Computer Knowledge and Technology*, **15**.

Yuan, F. and Lin, Y.Q.: 2019, Research on High-Rise Building Group Morphology Generative Design Method Based on Physical Wind Tunnel and Neural Network Algorithm, *Journal of Human Settlements in West China*, **34**, 22-30.

Zheng, J.Y.: 2018, *A Design Method Research About Dynamic Architecture Model Morphology Based on Physical Wind Tunnel Experimental Platform*, Master’s Thesis, Tongji University.

Zheng, J.Y., Yao, J.W. and Yuan, F.: 2017, Architectural Generation Approach with Wind Tunnel and CFD Simulation: Environmental Performance-Driven Design Approach for Morphology Analysis in the Early Design Stage, *Proc. Association for Computer-Aided Architectural Design Research in Asia, CAADRIA-Short Papers, Suzhou*, 13-18.

LAND USE TYPE ALLOCATION INFORMED BY URBAN ENERGY PERFORMANCE: A USE CASE FOR A SEMANTIC-WEB APPROACH TO MASTER PLANNING

A USE CASE FOR A SEMANTIC-WEB APPROACH TO MASTER PLANNING

ZHONGMING SHI[1], PIETER HERTHOGS[2], SHIYING LI[3], ARKADIUSZ CHADZYNSKI[4], MEI QI LIM[5], AUREL VON RICHTHOFEN[6], STEPHEN CAIRNS[7] and MARKUS KRAFT[8]
[1,2,3,6,7]*ETH Zurich, Singapore-ETH Centre, Singapore, Singapore*
[1,2,6,7]*{shi|herthogs|vonrichthofen|cairns}@arch.ethz.ch*
[3]*shiying.li@sec.ethz.ch*
[4,5]*CARES, Cambridge Centre for Advanced Research and Education in Singapore, Singapore, Singapore*
[4,5]*{arkadiusz.chadzynski|mei.qi.lim}@cares.cam.ac.uk*
[8]*CARES, Cambridge Centre for Advanced Research and Education in Singapore, Singapore, Singapore; University of Cambridge, Cambridge, United Kingdom; Nanyang Technological University, Singapore, Singapore*
[8]*mk306@cam.ac.uk*

Abstract. Cities are growing fast and facing unprecedented challenges as urban populations grow and resources are becoming scarce. A city's master planning involves a series of decision-making processes and requires knowledge from various domains. Urban planners are seeking computational support. We present a use case of land use type or building function allocations informed by urban energy performance as a pilot demonstrator for a semantic-web approach to these challenges. The software used for energy performance assessment was the City Energy Analyst. Using a quarter in downtown Singapore as an example, the results indicated 70% to 80% residential supplemented by other land use types favours efficient use of district cooling systems and photovoltaic panels. Urban planners may use the results to narrow down the search space of land use type ratios for the selected mixed-use area in Singapore. The use case serves as a pilot demonstrator for a broader research scope, the project Cities Knowledge Graph. To support master planning, the project aims to build an extendable plat-form to integrate more datasets and evaluation software for various urban qualities and domains.

Keywords. Urban planning; knowledge graph; City Energy Analyst; simulation; energy-driven urban design; urban form.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 679-688.

1. Introduction

Urban areas and populations keep growing with no sign of slowing (United Nations, 2018). Urban planning is experiencing unprecedented challenges. For example, cities are responsible for approximately 75% of the primary energy use and 60% of the greenhouse emissions globally (UN-Habitat, 2012). Buildings are one of the main energy-use sectors of cities. Recent studies show that energy considerations should be integrated into multiple stages of an urban project, as early as the master-planning stage (Shi et al., 2020). Land use type allocation is one of the main tasks in a city's master planning, and it defines the buildings' functions or land use types in each block.

Land use type allocation, and master planning in general, involves a series of decision-making processes. Planning cities draws on transdisciplinary approaches of knowledge formation across various disciplines (von Richthofen, 2018). Growing proliferation of data and increasing computational power offer unprecedented possibilities for future planning tools (Batty, 2018). However, computational tools from different domains are usually developed and executed independently. As the aim of master planning is to develop a coherent synthesis between inputs and needs from different domains, there is a challenge to ensure the interoperability of domain-related tools and respective datasets. Semantic Web Technologies can be used to link data across domains and to tackle various aspects of urban planning (Gomes et al., 2012).

2. Background: the Cities Knowledge Graph Project

The present paper reports on work done as part of a multi-year research project that develops approaches to computationally support multi-domain interoperability and synthesis in city planning. The 'Cities Knowledge Graph (CKG)' project (Cities Knowledge Graph, 2021), which started in April 2020, applies semantic web technology to develop a pilot planning support system to help bridge gaps between individual knowledge domains (such as energy, mobility, or built form), supporting planners in synthesizing that knowledge into an integrated view of the future city. The CKG is an effort which brings together existing expertise on knowledge graph platforms (Eibeck et al., 2020) and city planning (Cairns and Tunas, 2019). The project's core aim is to demonstrate the potential of semantic web technology for city planning support, building on an understanding of prior work and research gaps in the domain of semantic city planning support (von Richthofen et al., 2021) in order to develop particular innovations. A key innovation is the ability to generate various alternative scenarios (called "parallel worlds") to represent cross-domain city planning scenarios or digital twins of cities (Eibeck et al., 2020). CKG is part of a larger endeavour of knowledge modelling called the World Avatar (Menon et al., 2019; Pan et al., 2016; Zhou et al., 2018).

The architecture of the CKG platform is a combination of a back-end system (knowledge graph platform) and a front-end interface to collect requests from urban planners. This work presents a pilot use case as the first exploration for the CKG platform. The layered architecture of this system works as follows. First, we build on a collection of 'common languages' (i.e. ontologies) that describe concepts and their relationships for different knowledge domains used in planning. In the use case, we demonstrate relating the concepts used in master-planning (i.e. land use) to those in urban building energy modelling (i.e. occupancy). Second, we use these ontologies to create a linked network (i.e. a semantic web) of knowledge domains, data related to these domains, and even software used by these domains. In the use case, we demonstrate linking the datasets acquired from the planning authority's open database and those for energy simulations. Third, we incorporate artificial intelligence, in the form of agents that work on the knowledge graph to better control information flows (to automate information retrieval or data conversion, operate software, or generate visualizations); answer multi-domain queries; and recognize new patterns and infer master-planning knowledge. In the use case, we pilot the processes of controlling the information flows by creating a series of possible planning scenarios, conducting assessment, reasoning for master-planning knowledge and generating output diagrams.

3. Method

In the use case, we aim to determine the ratios of these use types in-formed by urban energy performance. As an example, we use a quarter of downtown Singapore, where most of the street blocks are planned yet vacant. Figure 1 illustrates the area in the Singapore Master plan (Urban Redevelopment Authority, 2014). The gross plot ratio of each street block is defined, and the land use is colour-coded as white, which allows a combination of up to nine use types, including residential, office, shop, hotel, serviced apartments, recreation club, association, convention or exhibition centre, or entertainment. Different land use type mixes entail different performance or efficiency of the energy supply systems (Shi et al., 2017). In this example, we assume the district's cooling demand is serviced by a district cooling system (DCS), and the district's total electricity demand is supplied by electricity generated by building-integrated photovoltaic panels (PV) as an addition to the city electricity grid.

Figure 1. The selected area in downtown Singapore in the Singapore Master Plan.

Figure 2 illustrates our workflow. The methodology is structured according to four actions of master-planning. In the CKG, planning actions performed by the platform's multi-agent system are categorized as either Representation, Evaluation, Creation, or Knowledge Management actions (von Richthofen et al., 2021). The Knowledge Management action collects the required site data for the creation of planning scenarios (Section 3.2.1), executes data format conversions (Section 3.1.2), and conducts results analysis and reasoning in Section 4. The Creation action uses a parametric model to generate different scenarios of use type mixes based on the experimental design in Section 3.2. These design scenarios are assessed by Evaluation for their energy performance using the City Energy Analyst (CEA), an open-source toolbox for urban building energy modelling (The CEA team, 2020) (Section 3.3). The action of Representation is reflected throughout the three-step method and the results.

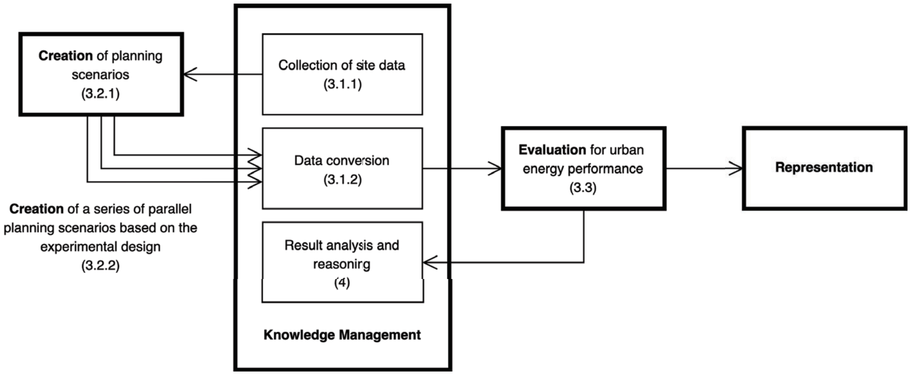


Figure 2. The workflow of the use case and the corresponding actions of master-planning.

3.1. KNOWLEDGE MANAGEMENT

3.1.1. Site data

We acquired the site data for the creation of various planning scenarios of land use type allocations from Open Street Map. Modifications were made based on the Singapore Master Plan, which is available at URA Space operated by Singapore's planning authority (Urban Redevelopment Authority, 2014). The site data includes street centerlines and borderlines of each street block in shapefiles, and the plot area ratio of each street block. Other input parameters were retrieved from the literature of existing studies of high-density areas of Singapore. Details can be found in Section 3.2.1.

3.1.2. Data conversion

The 3D city models produced in the Creation of planning scenarios are converted to the format required for City Energy Analyst. Figure 3 presents the UML (Universal Modeling Language) class diagram of these inputs' features and formats.

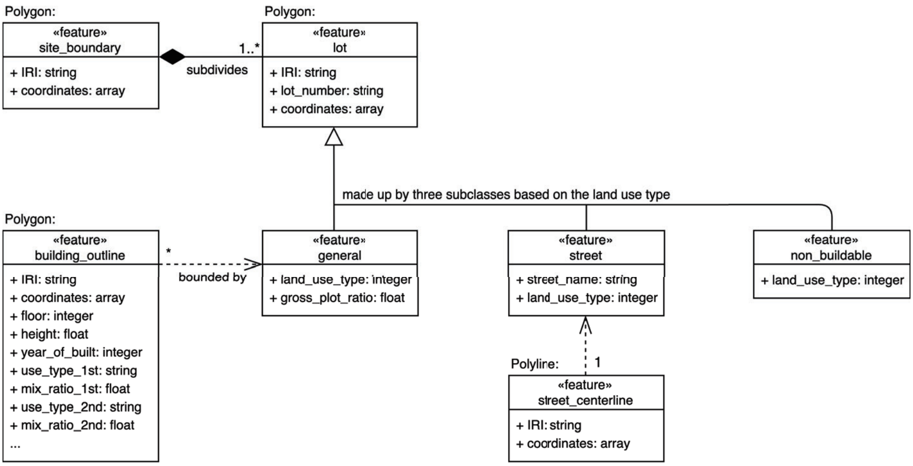


Figure 3. The UML class diagram of the master-planning ontologies used in this work. The selected area is subdivided into lots, which consist of three subclasses based on the land use type, including general plots, street plots, and non-buildable plots like water-bodies. Building outlines are bounded by general plots. Each item of the features is defined based on an open data platform of Singapore's planning authority named URA Space, comprising datasets across governmental sectors (Urban Redevelopment Authority, 2014). In addition, the use of IRI (Internationalized Resource Identifiers) helps identify and link the data point.

3.2. CREATION OF PLANNING SCENARIOS

3.2.1. Land use type allocations

The selected district contains 35 street blocks, 30 of which are planned using a gross plot ratio, which sets the maximum amount of allowable built area on a particular plot as a ratio to the plot's surface area). The five remaining vacant street blocks either are envisioned as open spaces or contain conservation buildings. Each block has one building, and the site coverage is set at 0.47. Each building's footprint follows a podium building pattern, which is offset by the block's borderline (Shi et al., 2020). Figure 4(a) shows 3D geometries conforming to the maximum planning settings above. Some of the nine land use types under the white-colour code have similar characteristics of energy use, in terms of occupancy and schedule. For simplification in this first-step demonstrator, we group similar ones. Thus, the number of use types is reduced to five, including residential, office, shop, exhibition, and entertainment.

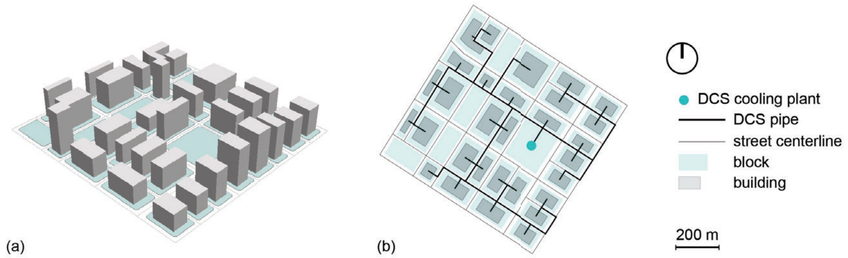


Figure 4. (a) the 3D scenario of master-planning made in Creation; (b) the piping network layout used in all samples.

3.2.2. Experimental design

To explore the impacts on urban energy performance of various ratios of the five defined use types, we try to evenly distribute the sampled da-ta point of the ratio of each use type and exhaust their combinations. We follow two steps. First, we group all thirty buildings of the district into ten groups of approximately the same gross floor area. The grouping only considers the gross floor area as a recent work indicates the impact of buildings' spatial locations on DCS's efficiency is relatively insignificant (Shi et al., 2021b). Second, we assign one of the five use types to these ten groups. Each group can only have one use type. Together, the ten groups can feature one, two, three, four, or all of the five use types. In this way, there are 1001 scenarios of various use type allocations. The ratio of each use type can be 0% to 100%, with a step of 10%.

3.3. EVALUATION FOR ENERGY PERFORMANCE

We use the City Energy Analyst (CEA) v3.13 (The CEA team, 2020) to simulate building energy demand (Section 3.3.1), PV electricity yields (Section 3.3.2), and district cooling system design and operations (Section 3.3.3). The metrics for assessing the energy performance are explained in Section 3.3.4.

3.3.1. Energy demand

The energy demand simulations are conducted for each scenario created in the previous section. The inputs comprise the building geometries, the occupancy profiles based on the land uses, and the energy supply-related data. These data, including the temperature set points, the ratios of air-conditioned area, the HVAC (Heating, ventilation, and air conditioning) technology selections, and building envelope properties, and the Singapore weather conditions, are available in the CEA database (The CEA team, 2020). CEA adopts occupancy schedules adjusted to Singapore conditions based on the ASHRAE standard schedules. The simulation outputs include hourly demand for space cooling, electricity for appliances, and domestic hot water in kWh. CEA converts these three types of energy demand into a single metric: total electricity demand from the city grid.

3.3.2. Photovoltaic panels

CEA simulates the photovoltaic (PV) electricity yields based on the results of a validated solar radiation simulation tool named DAYSIM (MIT Sustainable Design Lab, 2020). The shading effects of building geometries are accounted for. The results of the solar radiation simulations are also used in the energy demand simulations for solar heat gains. Based on a recent study in Singapore (Shi et al., 2021a), the annual solar radiation threshold for installing PV panels is set at 800 kWh/m2. The PV panel type used in the simulations is generic monocrystalline panels with a nominal efficiency of 0.16. The output is hourly PV electricity yields in kWh.

3.3.3. District cooling systems

We assume all the buildings within the district are serviced by a single-plant district cooling system (DCS). Figure 4(b) presents the DCS cooling plant integrated with the transit station, the piping network following the street layout, and buildings connected at the centroid of the building footprint in the CEA simulations. The pipe insulation is made of polyurethane, and its thermal conductivity is 0.023 W/mK. The supply temperature of the chilled water from the DCS cooling plant is ˜5.4 °C, and the plant COP (coefficient of performance) is ˜4.4. The choice of DCS technology remains the same in all iterations. The DCS cooling plant consists of vapour compression chillers and cooling towers. The outputs of the CEA simulations include the sizes of these DCS components, determined by the peak cooling demand and the thermal loss in the piping network. As the cooling demand fluctuates over time, the DCS does not function at its maximum at all times.

3.3.4. Assessment of urban energy performance

The metrics used for assessing the energy performance of the PV panels and the DCS are selected based on two recent studies (Shi et al., 2020, 2021). For PV panels, the metric used is solar energy penetration calculated as:

$$\text{Solar energy penetration} = PVel/ELgrid[-](1) \tag{1}$$

where PVel is the annual PV electricity yield in kWh; ELgrid is the annual total electricity demand from the city grid in kWh when no PV panels are installed. Higher solar energy penetration indicates higher integration of on-site solar energy into the electricity supply mix. For DCS, the metric is chiller capacity factor, which measures the utilization of the chillers throughout a year. It is calculated as:

$$\text{Chiller capacity factor} = Qc/Qs, nom[-](2) \tag{2}$$

where Qc is the annual cooling energy supplied by the DCS in MWh; Qs, nom is the annual cooling energy that the chillers in the DCS cooling plant can supply in MWh, provided they functioning at their nominal capacity. Higher chiller capacity factor indicates more efficient DCS.

4. Results

Figure 5(a) presents the results of our energy performance assessment for the 1001 planning scenarios of various land use type allocations, by their simulated chiller capacity factor and solar energy penetration. The scenarios in the top 20% of solar energy penetration show a broad range of performances on chiller capacity factor and vice versa. There are 22 planning scenarios that are in the top 20% for both energy performance metrics. Figure 5(b) presents the ratios of land use types for these 22 planning scenarios (vertical bars). The majority have 70%˜80% residential use. On one hand, high residential ratios necessarily imply high solar energy penetration, as residential use has a lower energy intensity than the other land uses (photovoltaic electricity yield is the same for all 1001 planning scenarios, as all scenarios feature the same built form). On the other hand, during the daytime, the negligible (solar) energy use of mostly absent residents is supplemented by the cooling demand of other land use types. Hence, despite solar energy penetration favouring residential use, up to 30% of other uses leads to more optimal land use type allocation scenarios, as these scenarios feature high chiller capacity factors, as they reduce the number of idle hours of the district cooling plant.

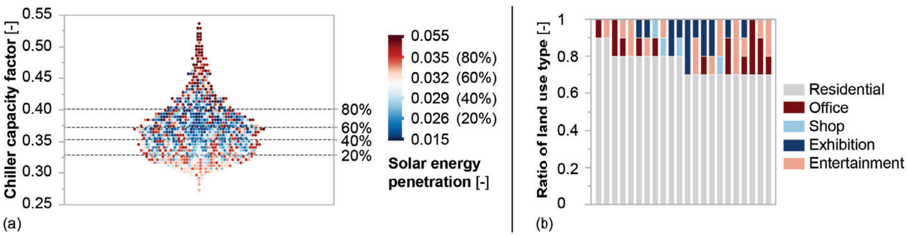


Figure 5. (a) The energy performance is assessed for the 1001 planning scenarios. The chiller capacity factor and solar energy penetration are displayed by the y-axis and the colour gradient. 5-quantiles are observed. (b) The ratio of land use type of the 22 planning scenarios (vertical bars) performing top 5% on both solar energy penetration and chiller capacity factor.

5. Discussion

The use case presented above will be part of a pilot demonstrator for the Cities Knowledge Graph (CKG) project. In this demonstrator, an urban planner uses an interface to raise the question: “In the selected mixed-use district, how do different ratios or combinations of land use type influence district energy performance?” After querying relevant datasets, conducting (CEA) evaluations, and reasoning, the CKG platform would return the needed knowledge of master-planning to the planner as represented in Figure 5 (b). Such energy-driven knowledge helps narrow down the design space for land use type allocation.

Keeping in mind the broader framework in which the presented use case will function, there are three main limitations and challenges of the present paper. Firstly, on the topic of simulation accuracy, the building geometries produced in the action of Creation are simplified as boxes, which affects the accuracy of electricity yield simulations, due to shading effects. Ideally, in future, the level of details of future 3D city models should be scalable, according to the respective master-planning questions. Similarly, for the accuracy of the energy demand simulation, specific occupancy data for each land use type should be used. Secondly, considering the practicality of the simulation, we should note the computational expense of the use case is high (CEA simulations require high computational power). At a project level, we should consider integrating alternative simulation software and experimental design methods, so we can adapt accuracy and computational expenditure depending on the planning task. Thirdly, the presented use case of course demonstrates but two aspects of an energy performance assessment. Simulations could take into account many more criteria that affect district-scale energy performance, as well as other domains (such as mobility, pollution, and outdoor thermal comfort) that introduce different or even contradicting parameters to determine land use type allocation.

Exploring how to support such complex planning interactions is a main aim of the CKG project, linking available cross-domain multi-scale urban datasets and respective evaluation software to support the decision-making processes of master-planning. The presented use case is the first step in this exploration.

6. Conclusions

In this paper, we have presented a pilot use case of land use type allocations informed by urban energy performance using a semantic-web approach. The metrics of solar energy penetration and chiller capacity factor are used for assessing the energy performance of photovoltaic panels and district cooling systems. Based on the experimental settings in this work, it is advised the residential use type should be kept 70%-80% supplemented by one or two or three use types of office, shop, exhibition, and entertainment. Urban planners may use the results to narrow down the search space and make decisions for the ratios of mixed-use projects. Furthermore, this work builds towards a pilot demonstrator of a broader research scope - the Cities Knowledge Graph (CKG). The pilot use case demonstrated CKG's threefold approach of relating concepts, linking datasets from various domains involved in master-planning as wells as automation of planning scenario generation, assessment, reasoning and visualization. CKG seeks to automate these processes and offer cross-domain master-planning support through a user interface to interact with urban planners. Also, CKG aims to integrate additional datasets and software of various urban planning related domains, beyond energy, using a semantic-web approach.

Acknowledgements

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

References

Urban Redevelopment Authority, U.R.A.: 2014, "URA SPACE" . Available from <https://www.ura.gov.sg/maps/?service=MP> (accessed 5 December 2017).

Batty, M.: 2018, *Inventing Future Cities*, MIT Press.

Cairns, S. and Tunas, D.: 2019, *Future Cities Laboratory: Indicia 02*, Lars Muller Publishers.

Eibeck, A., Chadzynski, A., Lim, M.Q., Aditya, K., Ong, L., Devanand, A., Karmakar, G., Mosbach, S., Lau, R., Karimi, I.A., Foo, E.Y.S. and Kraft, M.: 2020, A Parallel World Framework for scenario analysis in knowledge graphs, *Data-Centric Engineering*, **1**, e6.

Eibeck, A., Lim, M.Q. and Kraft, M.: 2019, J-Park Simulator: An ontology-based platform for cross-domain scenarios in process industry, *Computers & Chemical Engineering*, **131**, 106586.

Gomes, J., Urbano, P., Montenegro, N. and Duarte, J.: 2012, A computer-aided urban planning tool driven by semantic web ontologies', *7th Iberian Conference on Information Systems and Technologies (CISTI 2012)*.

Cities Knowledge Graph, C.K.G.: 2021, "no title given" . Available from <https://sec.ethz.ch/research/cities-knowledge-graph.html> (accessed 14 December 2021).

MIT Sustainable Design Lab, initials missing: 2020, "Daysim" . Available from <https://github.com/MITSustainableDesignLab/Daysim> (accessed 7 September 2020).

Menon, A., Krdzavac, N.B. and Kraft, M.: 2019, From database to knowledge graph — using data in chemistry, *Current Opinion in Chemical Engineering*, **26**, 33-37.

United Nations, initials missing: 2018, "World Urbanization Prospects, 2018 revision" . Available from <https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf> (accessed 4 November 2016).

Pan, M., Sikorski, J., Akroyd, J., Mosbach, S., Lau, R. and Kraft, M.: 2016, Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks, *Applied Energy*, **175**, 305-323.

von Richthofen, A.: 2018, *Urban Elements: Advanced Studies in Urban Design*, ETH Zurich.

von Richthofen, A., Herthogs, P., Lim, M.Q., Cairns, S. and Kraft, M.: 2021, Semantic City Planning Support: a literature review, *Unpublished manuscript*, **NA**, NA.

Shi, Z., Fonseca, J.A. and Schlueter, A.: 2017, A review of simulation-based urban form generation and optimization for ener-gy-driven urban design, *Building and Environment*, **121**, 119-129.

Shi, Z., Fonseca, J.A. and Schlueter, A.: 2021a, A parametric method using vernacular urban block typologies for investigating interactions between solar energy use and urban design, *Renewable Energy*, **165**, 823-841.

Shi, Z., Fonseca, J.A. and Schlueter, A.: 2021b, Floor area density and land uses for efficient district cooling systems in high-density cities, *Sustainable Cities and Society*, **65**, 102601.

Shi, Z., Hsieh, S., Fonseca, J.A. and Schlueter, A.: 2020, Street grids for efficient district cooling systems in high-density cities, *Sustainable Cities and Society*, **60**, 102224.

The CEA team, initials missing: 2021, "City Energy Analyst v3.13" . Available from <DOI:10.5281/zenodo.1487867> (accessed 10 November 2020).

UN-Habitat, initials missing: 2012, "Energy" . Available from <http://unhabitat.org/urban-themes/energy/> (accessed 8 November 2016).

Zhou, L., Zhang, C., Karimi, I.A. and Kraft, M.: 2018, An ontology framework towards decentralized information management for eco-industrial parks, *Computers & Chemical Engineering*, **118**, 49-63.

EXPLOITING GAME DEVELOPMENT ENVIRONMENTS FOR RESPONSIVE URBAN DESIGN BY NON-PROGRAMMERS

Melding real-time ABM pedestrian simulation and form modelling in Unity 3D

XIAORAN HUANG[1], GEOFF KIMM[2] and MARK BURRY[3]
[1]*North China University of Technology*
[1]*xiaoran.huang@ncut.edu.cn*
[2,3]*Swinburne University of Technology*
[2,3]*{gkimm|mburry}@swin.edu.au*

Abstract. Precinct-level pedestrian simulation often requires moderate to high-level modelling skills with a steep learning curve, and is usually non-flexible, time-consuming and exclusive of the broader public community. Confronting these problems, our research investigates a novel and agile workflow to test precinct pedestrian behaviours by melding agent-based simulation (ABM) and responsive real-time form modelling mechanisms within accessible visualisation of city and precinct environments in a game engine, Unity 3D. We designed an agent system prototype of configurable and interoperable nodes that may be placed in an urban modelling scenario. Realtime CSG, a fast polygon-based modelling plugin, is also introduced to our workflow where users can use the evidence observed when running a scenario to quickly adjust the street morphology and buildings in response. In this process, end users are kept in the design loop and may make critical adjustments, whereby a responsive, collective, informed design agenda for our built environments can inform more detailed outcomes of pedestrian behaviour and action and promote more efficient collaborations for both professionals and local communities.

Keywords. Agent-based pedestrian simulation; responsive modelling; computer-aided urban design; public participation.

1. Introduction

In urban design practice, there is a growing need for professional specialisations to be placed within a broader transdisciplinary concept of urban designing and, vice versa, urban design must be collaboratively conceptualised through the sum of the unique disciplinary perspectives (Burry and White 2020). Concomitantly, the digital technologies that have driven much recent professional speciation have also fostered the importance of simulation for better evaluation of built environment scenarios and creation of generative outcomes (Nguyen et al. 2014, Huang et al. 2017). In such simulations, games technology is used increasingly for its immersive user interaction, ready extensibility, visual descriptiveness, and

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 689-698.

flexible kit of parts (Indraprastha and Shinozaki 2009). The confluence of those three longstanding and strengthening trends in the urban design process supports investigation of exploiting game development environments for responsive urban design by non-programmers.

This paper presents a workflow for real-time urban simulation and responsive design within game engine development environments. The approach makes novel use of a game development environment to, rather than build and export a game for external or standalone use, embed the game and user experience itself directly within it by running in effect in "debug" mode. The process enables an integrated conjecture-test-refine workflow, accessible to non-experts from diverse backgrounds, of responsive, flexible urban simulation and design for advocating sustainable and liveable urban design schemes. The paper is structured as follows. Section 2 presents the rationale for the use of walkability and agent-based modelling (ABM), and the Unity 3D (Unity) game engine environment in its development and testing. Section 3 outlines the implementation of a prototype design computing tool ("the prototype") based on this workflow in Unity with emphasis on its design for accessibility by the non-programmer. Section 4 discusses the testing of the prototype in a one-day international workshop in which participants engaged in a series of design explorations using rapid, iterative visualisation with agent-based pedestrian modelling and related simulation techniques. Finally, a conclusion presents the key findings.

2. Exploiting Game Development Environments

2.1. UNITY 3D

Unity is used in this research for reasons of relative accessibility to the novice user, integrated manipulation of a game's 3D environment and running of that game directly within the development interface, and allowance for scripting custom logic in the C-SHARP programming language.

The flexibility and extensibility of the development environment of Unity have been exploited extensively by expert users in a broad gamut of built environment simulation and analysis research applications. In computer science, it has been used to generate training data for deep learning models to recognise components of urban scenes (Ros et al. 2016). In governance, it has been used in developing citizen-led interactive modelling of smart villages to identify and prioritise needs and novel solutions (Kimm and Bury 2020). In engineering, it has been used at building, precinct, and city scales to integrate external and embedded modelling tools for applications such as multi-modal traffic simulation (Olaverri-Monreal et al. 2018). In studies of pedestrian movement, Unity has been used for diverse purposes including VR-enabled modelling of pedestrian interaction with traffic, and the dynamics of social interactions in interior spaces (Orlosky et al. 2015, Pedica and Vilhjálmsson 2018).

While Unity is being increasingly used in research by adept users, a literature review indicates its potential as a non-expert or pedagogical built environment modelling tool is as yet understudied. Although Unity Technologies' 2020 release of the Bolt visual scripting add-on for Unity brings closer the accessibility seen in tools such as Grasshopper for the Rhinoceros3D application, it and Unity itself are not targeted specifically to design or built environment issues. Furthermore, the development environment of Unity is designed to be simple to learn but nonetheless is not readily usable by the neophyte user.

The objectives of this research therefore require the development of a user experience that utilises the components of, and sits within, the existing development environment to create a simple, intuitive, and design-focused interface. Creating the prototype within Unity's development environment, rather than developing it as a standalone app, exploits the existing user interface and reduces the resources required for its design and implementation.

2.2. WALKABILITY / ABM

Over the past decade, walkability has been widely considered a critical component of urban liveability and sustainability. As a result, facilitating pedestrian-friendly environments has become urgent for many urban design and planning agendas which require full engagement from different stakeholders (Aschwanden 2014).

To understand the walking experience with more profundity, many precinct-level pedestrian simulations have investigated the relationship between crowd patterns and urban typologies in recent studies (Asriana and Indraprastha 2016). However, these approaches are often less accessible for non-programmers due to the technical nature of ABM modelling and scripting. Therefore, walkability, and its simulation via ABM, was selected as the focus of a design computing tool for its ready, integrated support and accessibility in Unity and importance to effective urban responses to urgent environmental emergencies.

3. Prototype Development

A walkability ABM prototype was developed in the Unity development environment. Four key components were built on: the *hierarchy window*, the *scene view*, the *inspector window*, and the *game view* (Figure 1).

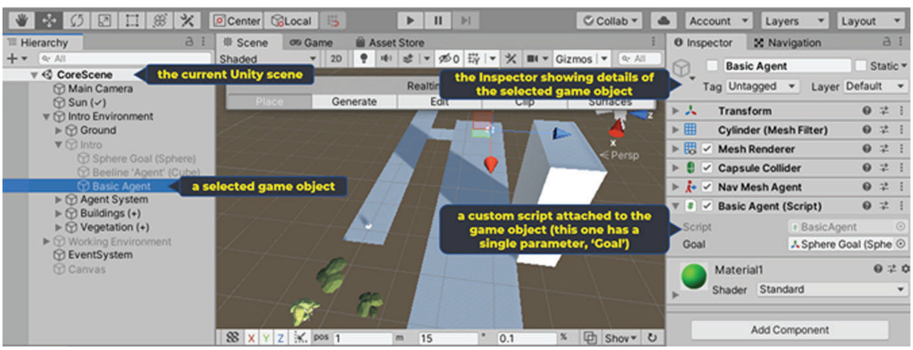


Figure 1. 1) Unity's hierarchy window, 2) the scene view with a game in progress showing spawn points (black cubes), agents, and sensors (orange columns), 3) the inspector window with details displayed of the Agent Spawner game object, and 4) the tab of the game view.

1. The hierarchy window presents a tree structure of all items in a Unity game or scene such as lights, geometry, or pedestrian agents. Each item is a *game object*. A game object may be empty, in which case it contains basic attributes including a name and a 3D position, and may have attached to it additional components and scripts. Scripts can add logic or actions to a game object; for example, a game object may be told to move in a certain direction when another game object is nearby. All game objects are a child of the scene itself or of another game object.
2. The scene view displays the game objects of the hierarchy window in 3D space. A user may directly select and reposition game objects in this view.
3. The inspector window displays the attributes of game objects selected in the hierarchy window or scene view. Those attributes, such as a parameter of a custom script, may be manually adjusted by the user within the inspector's UI.
4. The game view displays the game when it is run. The game is the sum of all game object presences and actions in the scene and the interactions of a user.

3.1. IMPLEMENTATION IN UNITY 3D

A framework for the proposed essential simulation workflow is encapsulated in the Unity scene within a single empty object named as the *Agent System* (Figure 1). Under this Agent System is an array of modules of game object and attached custom script pairs ("simulation modules") that each provides one aspect of the essential functionality and user interaction.

To facilitate non-expert participation, a design objective for the prototype was to simplify all user interaction. Unity is a professional tool: inherent in using it directly for participatory modelling is a tension between its sophistication and the potential inexperience of participants. We applied three principles to address this.

1. First, only a minimum necessary set of custom script functionality should be exposed in the inspector window so to not overwhelm the user.
2. Second, full interaction should be supported by as few UI elementary operations as possible. A user can fully interact with the simulation modules with only two operations: the creation or deletion of empty game objects within the scene, whose location within the scene's tree structure gives their meaning; and the adjustment of the behavioural control of custom scripts via the inspector window.
3. Third, what a participant should interact with should be explicitly clear. A schema of symbols was used to indicate what UI elementary operations may be taken on a simulation module (Figure 1). A plus symbol on a game object means child game objects may be added or removed. A tick on a game object means there's an adjustable custom script attached and on a custom script parameter means it's safe to adjust. A cross on any element warns it should not be touched.

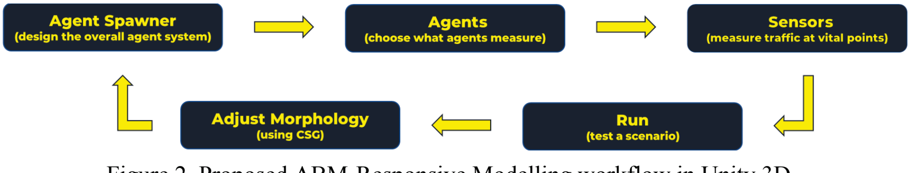


Figure 2. Proposed ABM-Responsive Modelling workflow in Unity 3D.

Three simulation modules are provided to the participant and control an agent's lifecycle and interaction with its environment: *Agent Spawner*, *Agents*, and *Sensors* (Figure 2). Together, the three modules, along with Realtime CSG, form the reification in Unity of the proposed essential workflow, as seen in the scene view of (Figure 1). Each workflow step is discussed below.

1. The Agent Spawner simulation module controls the spawning rate and maximum number of agents as well as essential characteristics of each newly spawned agent (Figure 1). New agent spawning nodes are assigned by a UI elementary operation: the 3D location of any game object placed under the Agent Spawner is automatically used to place agent spawn nodes when the scene is run. A spawn node game object is both a start and end point by default; a user may attach an optional *Agent Spawn Node* script to specify other behaviour.
2. The *Agent Controller* script of the Agents simulation module sets what illustrative visual guide an agent will display of its 'satisfaction' with the environment as it navigates between its birth and death spawn nodes. Four experience metrics are provided that are intended to be intuitive to understand and to cover the needs of common scenarios: *distance*, *speed*, *directness*, and *proximity*. An agent's satisfaction is indicated by its colour graduated between user-configurable 'good' and 'bad' colours. The distance metric considers an agent's maximum ideal journey distance; an agent exceeding this distance will become increasingly dissatisfied. The speed metric considers an agent's acceptable decrease in speed before its satisfaction starts degrading; an agent may be slowed if the street morphology contains chokepoints. The directness metric considers an agent's acceptable percentage increase in travel distance over the beeline distance; a street morphology that is circuitous or closed may rate poorly on this metric. The proximity metric considers an agent's personal space; an agent will be less satisfied the closer other agents are within this radius, and a street morphology that does not properly accommodate pedestrian volumes may also rate poorly.
3. Sensors added via the Sensors simulation module track pedestrian street use and are placed within the simulation in the same way as spawn nodes. A sensor in-game displays a dynamically updating 3D column whose height matches a count of passing agents. Two key parameters are exposed in the *Sensor Controller* script to facilitate users' particular hypothesis tests. *Range* determines the physical extent of the sensors' detection fields and allows fine-tuning of the granularity of a web of sensors in scene. *Window* sets the number of seconds for which to smooth data as a moving average: a user may hence see instantaneous feedback or results smoothed over changing simulation conditions. Sensors placed strategically within the scene may provide an overview of how a street morphology is functioning, and their dynamic response was developed as a precursor to the implementation of generative urban design functionality.
4. Initiation and scenario test: a participant may run the simulation after setting up their hypothesis. Once running, they may engage in on-the-fly editing of the simulation and dynamic moderation of their hypothesis testing. Switching to the scene view allows real-time repositioning of simulation elements such as spawn nodes. Similarly, the participant may change parameters of the custom scripts; within a single simulation session a scenario to test a particular street morphology may, for example, be 'stress tested' by greatly increasing the agent spawning rate.
5. Morphology adjustment: participants can exploit the evidence observed when

running a scenario to adjust city block and building envelope geometry. Constructive solid geometry (CSG) is used for this as it enables intuitive modelling and human-friendly interaction through separation of the creation of geometric primitives from the logic of how they combine into complex solids (Rossignac 1987). In CSG, geometric primitives are created relative to each other by the user who determines their interactions of boolean operations of union, intersection, and difference. This research uses Realtime CSG (realtimecsg.com), a third-party Unity tool, that integrates directly into the scene view (Figure 3).

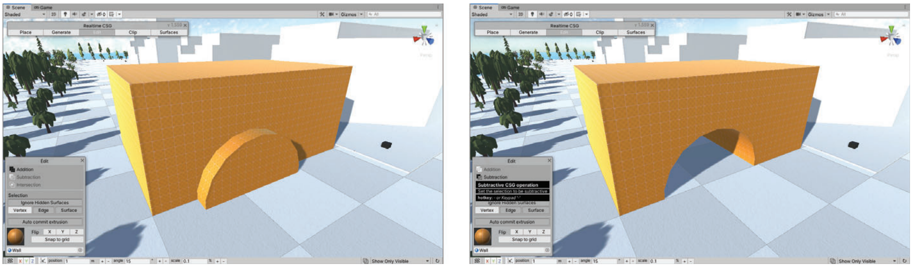


Figure 3. Built environment form adjustment using Realtime CSG in Unity.

4. Workshop Case Study

The proposed framework and ABM prototype were introduced and tested at an August 2020 one-day workshop held at an international conference. Participants were asked to engage with a series of design explorations using rapid, iterative modelling and simulation. The workshop objectives were twofold. The proximate aim was to investigate the capacity to design walkable communities to encourage collective responsibility for our planet and effective responses to environmental emergencies. The distal aim was to test the subject framework of this research through participants collaboratively developing their understanding of the use of responsive, custom modelling in the design of better-built environments.

4.1. WORKSHOP STRUCTURE

Due to COVID-19, the workshop was conducted fully online via Zoom. Fifteen participants were registered as active candidates and the group was diversified geographically and demographically (one-third female; participation numbers of 6 from Asia, and 3 each from Australasia, Europe, and elsewhere). No expertise with Unity was required. However, participants were asked to preinstall it, download an implementation project file, and review an instructional “cheat sheet”.

In accordance with the objective of accessibility of the computational framework, the workshop began with a morning two-hour skilling-up session as a complete introduction. Essential concepts of ABM and walkability were covered, along with a live “how-to” demonstration of the Unity environment and proposed framework. One virtual site of investigation, pre-packaged within the Unity implementation project, was demonstrated and offered as an exemplar based on the Barcelona superblocks urban scenario.

Preceding a midday break, active participants were divided into three groups based on their common interests in site selection or design proposition. Within those groups, all members were encouraged to explore different design directions and urban morphologies, and each member could have alternative or branching revised urban form propositions based on their personal investigation.

In the afternoon session, groups were assigned into breakout rooms (virtual sub-meetings within Zoom) to discuss and collaborate on their projects closely, while tutors jumped between different rooms providing hands-on assistance. Within their groups, candidates were asked to confirm the site and the type of urban morphology they would explore, and then probe possible design investigations through the proposed ABM-responsive modelling framework in an iterative design process. Urban morphology iterations were saved directly in the Unity projects themselves by simply duplicating their working environment root game object and deactivating the old copy. Hence, histories of essential geometries and agent system configurations were captured.

5. Results

5.1. CASE 1: FROM BARCELONA SUPERBLOCK TO ADELAIDE CBD

This group had relatively low experience with Unity but built essential skills quickly with tutor assistance. Some technical challenges delayed Unity project environments set up due to script incompatibilities arising from installation of different versions and a corrupted central project repository. Subsequently, they properly set up the simulation framework using the given Barcelona example project, and then tested alternative design possibilities by ‘injecting’ internal pedestrian paths using the framework introduced to them in the morning session.

The difficulties of the initial stage constrained the time available for their own design proposals; the group hence selected the CBD of Adelaide, Australia, as their site of investigation. Adelaide is renowned to designers for its unique grid pattern and hierarchical street layouts. Group members exploited this typological similarity to the Barcelona superblocks example and repurposed some of the critical agent settings from their Barcelona studies through a modification process. Realtime CSG integration also allowed them to expeditiously remodel urban massing and therefore novel design investigations were possible within the restrictive timeframe.

During iterations, they proposed and tested many pedestrian-oriented design strategies, including but not limited to: widening footpaths, proposing ground-floor pedestrian connections through podia, and suggesting 3D circulation with ramps and sloped landscapes (Figure 4). This case study demonstrated how flexible and accessible the proposed design framework could be for supporting fast iterative design within an intense schedule in pragmatic design practices.

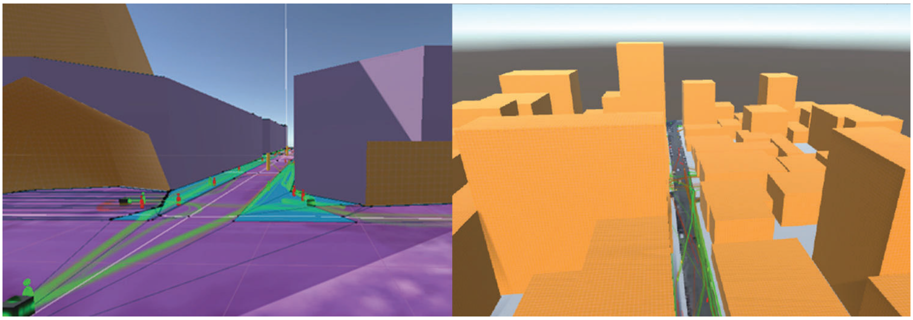


Figure 4. Left: Barcelona Superblocks test; Right: New proposed design scenario in Adelaide.

5.2. CASE 2: A RESIDENTIAL COMMUNITY NEAR THAMES RIVER, LONDON

This group was exceptionally experienced in computer-aided design and had a clear objective of seeking possible integrations between agent-based pedestrian modelling and their main research interests and expertise. Their workshop case study originated in one member's existing pedestrian density study of the Munich city. In it, a workflow of data collection, visualisation, and analysis was undertaken in which Rhino modelled city infrastructure and Python collected core data including Twitter geospatial usage. That workflow was applied in their workshop case study of London's East India Dock residential precinct. Subsequently, walkability costs of street spaces to differentiate more and less walkable spaces were defined according to the analysis results. Twitter geospatial data was used to determine the active population density in the selected site and adjust the Agent Spawner module for agent spawning rate and overall count.

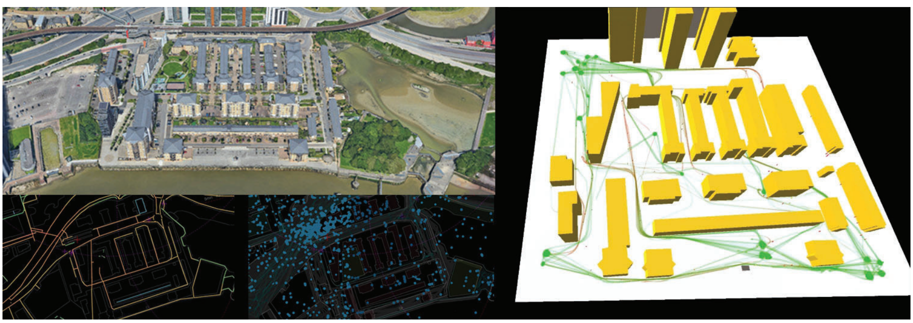


Figure 5. Left: The geographical information, population density, and Twitter signalling data were collected and analysed. Right: The running simulation scene in Unity 3D.

During simulations, the group explored precinct redesign to enhance local walkability. For instance, their prior big data collection revealed people prioritise a more walkable environment in the precinct's Virginia Quay Park area and this was verified with the agent experience metrics visualisation of the Agents simulation module. A chokepoint in the west of the precinct, and hence less walkable, was still traversed by many agents due to its proximity (Figure 5), and this is a piece of critical evidence that could support an alternative design blueprint. Similarly, other pedestrian-related issues, such as travelling time, were also identified through the iterative investigation process. Through this case study, the proposed design framework has proven a high extensibility and configurability when melding with other digital techniques and workflow and can be mutually verified with big data analysis and other research methods.

5.3. CASE 3: SHANGHAI NORTH BUND

This group engaged in a highly collaborative process and at the outset drafted a schedule with a distributed workload. Our proposed framework allowed them to split a complete procedure into individually executable tasks: site investigation and data collection, built environment modelling in Unity, ABM system set up, any script calibration, visualisation, and documentation. In design iterations, each member could contribute ideas by editing urban morphologies through Realtime CSG within minutes to be saved as a unique scene under the same project.

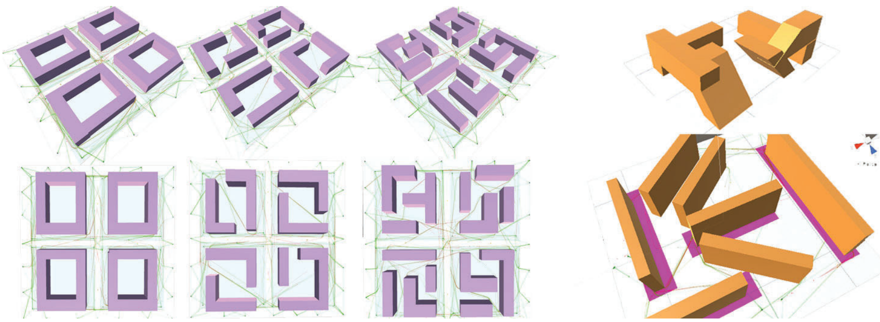


Figure 6. Left: Closed, through, and spread typical block morphologies in Shanghai North Bund district with the simulation results; Right: Morphologies emerged from the rapid-fire ideation process.

In their design investigation, *closed*, *through*, and *spread* typical residential block morphologies were selected from the Shanghai North Bund district to probe how urban form variations could influence pedestrian behaviours in a grid-based urban layout. In all simulations, the agent numbers and spawning positions were intentionally kept constant, and the average travel time and distance were reduced with the increment of the block permeability. This was not a novel approach per se, yet with the rapid modelling tool and configurable ABM system, they were able to recalibrate the urban massing by rotation, scaling, trimming or duplication and investigate the potential impact to pedestrians accordingly. More creative morphologies also emerged during the participative design process. Slopes, curvilinear compositions, and different visualisation options were enabled in a rapid-fire ideation process due to the simplified modelling and simulation procedure powered by the Unity platform (Figure 6).

6. Conclusion

In this research, we augment and incorporate concepts of digital simulation and pedestrian-centric design in the built environment by exploiting game development environments with agent-based modelling. A flexible and real-time ABM pedestrian simulation system is proposed and developed in Unity 3D, which has become readily available for the participation and contribution of non-programmers in the process, consequently increasing the design transparency. We also demonstrate how conventional urban form modelling and walking simulation can be integrated and reshaped by adopting our rapid ABM-responsive modelling workflow, addressing a range of spatial and temporal urban walkability concerns. The flexibility of our approach and its successful demonstration in the case studies suggest significant potential for exploiting game development environments in making highly configurable digital urban models accessible for public or non-expert participation and promoting responsive design and impact projection in global urban scenarios.

References

Aschwanden, G.: 2014, *Health and Place: an analysis of the built environment's impact on walking behavior and health*, Ph.D. Thesis, ETH Zurich.

Asriana, N. and Indraprastha, A.: 2016, Making sense of agent-based simulation: Developing design strategy for pedestrian-centric urban space, *Proc. of the 21st CAADRIA*.

Burry, J. and White, M.: 2020, From 'T'to 'pi'-shaped people: Better Urban Practice through Dual Depth in Architecture and Planning Education, *Architectural Design*, **90**(3), 114-121.

Huang, X., White, M. and Burry, M.: 2017, A pedestrian-centric design strategy: melding reactive scripting with multi-agent simulation, *in Proc. of SIMAUD2017*, 1-8.

Indraprastha, A. and Shinozaki, M.: 2009, The investigation on using Unity3D game engine in urban design study, *Journal of ICT Research and Applications*, **3**(1), 1-18.

Kimm, G. and Burry, M.: 2020, Encouraging Community Participation in Design Decision-making through Reactive Scripting, *Proc. of the 25th CAADRIA*, 51-60.

Nguyen, A.T., Reiter, S. and Rigo, P.: 2014, A review on simulation-based optimization methods applied to building performance analysis, *Applied Energy*, **113**, 1043-1058.

Olaverri-Monreal, C., Errea-Moreno, J., Diaz, A., Biurrun-Quel, C., Serrano-Arriezu, L. and Kuba, M.: 2018, Connection of the SUMO microscopic traffic simulator and the Unity 3D game engine to evaluate V2X communication-based systems, *Sensors*, **18**(12), 4399.

Orlosky, J., Weber, M., Gu, Y., Sonntag, D. and Sosnovsky, S.: 2015, An interactive pedestrian environment simulator for cognitive monitoring and evaluation, *Proceedings of the 20th International Conference on Intelligent User Interfaces Companion*, 57-60.

Pedica, C. and Vilhjalmsson, H.: 2018, Study of nine people in a hallway: Some simulation challenges, *Proc. of the 18th ICIVA*, 185-190.

Ros, G., Sellart, L., Materzynska, J., Vazquez, D. and Lopez, A.M.: 2016, The synthia dataset: A large collection of synthetic images for semantic segmentation of urban scenes, *Proceedings of the IEEE conference on computer vision and pattern recognition*, 3234-3243.

Rossignac, J.R.: 1987, Constraints in constructive solid geometry, *Proceedings of the 1986 workshop on Interactive 3D graphics*, 93-110.

DIGITAL INFRASTRUCTURE - A POTENTIAL METHOD FOR RURAL REVITALIZATION THROUGH DIGITIZATION OF RURAL INFORMATION

XIAONI GAO[1], XIANGMIN GUO[2] and TIANTIAN LO[3]
[1,2,3]*Harbin Institute of Technology,Shenzhen*
[1,3]*{hathaway886|skyduo}@gmail.com* [2]*xiangminguo@hit.edu.cn*

Abstract. Rural revitalization is becoming a trend to improve the country's economy. However, due to its remoteness and the infrastructure is not perfect, the village lacks the ability to attract young labor to some extent, reflecting the isolation of rural information. Thus, constructing rural information on digital infrastructure and breaking the barriers between urban and rural areas is based on a "digital village" and even "intelligent village." This paper will discuss the potential of digitizing rural information, using digital information as a bridge between urban and rural areas, and connecting top-down and bottom-up stakeholders through a network or platform to promote rural cultural cognition and attract investment. The new form of rural development is a digital village that integrates rural information data's virtual interaction. The successful construction and promotion of digital villages will promote the revitalization of rural areas and data-driven development in the future information age.

Keywords. Digital infrastructure; rural information; digital data; virtual interaction; digitization.

1. Introduction

Due to the rapid development of times, information has become a basic strategic resource for nations. On a global scale, using information to promote economic development and improve urban and rural construction is becoming a trend (Adamowicz et al., 2020). The countries are promoting the application of information digitization vigorously (Zhang et al., 2018). With communication technologies, cities and villages can utilize resources more efficiently (Braun et al., 2018). Thereby, they can not only save costs and energy but also improve services and life quality. The transition to digitization and intelligence is necessary for urban living environments (Zavratnik et al., 2018). Otherwise, it is also essential for underdeveloped rural areas to develop the economy (Ding, 2020).

Digital village refers to the application of network, informatization, and digitization in rural economic and social development. It also means rural economic development and transformation with the improvement of farmers' modern information skills (Cao, 2019). In the information age, digital technologies such as the Internet, big data, the Internet of Things, cloud computing,

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 699-708.

artificial intelligence, and 5G are changing with each passing day. As a result, digital technologies have a lot of influence on national politics, economy, society, culture, and life. It has formed a strong digital governance network. Combining this powerful digital network with rural villages is named digital villages (Akbar et al., 2020). Digital villages can benefit residents and businesses with the above technologies and strengthen the combination of traditional development approaches such as new networks and services. In other words, it is necessary to adopt a bottom-up integrated information digitization method to build digital villages.

Rural residents can use modern digital technology with the help of digital villages to improve the local economy. But the infrastructure is still carried out by the sustainable development goal. This effective treatment has provided the opportunity for the future of energy security, and the integration of rural economic development. However, it is essential to regard the digital village as an autonomous and independent entity and digitize it in the spatial dimension.

The essence of rural digitization is to activate various rural development elements with the use of information flow. In the process of rural digitization development, the construction of rural information, that is, “the digital infrastructure,” should be considered first. Spatial data is a basic data resource for digital villages and a carrier for other information to exchange, share, and combine applications. It is an effective way to create rural digitization by integrating various data such as village history, current situation, planning, etc., and building a spatiotemporal big data platform. Rural digitization can share applications, provides space-based data integration. Simultaneously, a unified spatial data platform is needed in various fields of rural informatization construction. This paper integrates the requirements of spatial data information from countries of different types and proposes the construction of a spatial-temporal platform. The platform will use digital infrastructure to integrate geographic information, digital economic information, and rural visual information. The construction of digital infrastructure could achieve the idea of “construct in one place, apply in multiple places.”

2. Background

From the aspect of informatization, the digital village is the advanced stage of rural informatization construction. Its core is to use the Internet of things, cloud computing, big data, artificial intelligence, spatial information integration, and other information technologies to serve rural planning, construction, management, and service through digital integration. As a result, it can achieve the goal of “serving the people in the whole process, efficient and orderly urban governance,” and promote the high-quality development of economic society.

In China, although the concept of digitalization has been integrated into many urban environments, the application in rural areas is still in its infancy. To implement the rural revitalization strategy, the government put forward the “implementation of the digital rural strategy” (Zhu, 2019). The use of networks, information, and digital technology will play a role in rural economic and social development (Li, 2020). Simultaneously, the construction of digital rural areas can effectively connect the development of urban and rural areas. The construction can promote the all-round industrial transformation at all levels in rural areas and the whole chain's digital transformation. It can also promote the comprehensive upgrading of agriculture and the all-round progress of rural areas. However, in recent years, although China has strengthened the construction of digital rural information, the digital foundation of China's rural areas is relatively weak (Chen&Wang, 2020). As a result, it is difficult for infrastructure to quickly keep up with the demand and development of digital rural construction. The digital gap has become the bottleneck restricting the construction of digital villages.

Most of the existing researches are just a policy for digital rural areas. With the emergence and application of a series of new technologies, digital rural areas' construction has been promoted. However, the lack of basic data makes these modern information technologies unable to be applied widely (Holten, 2006). Therefore, building the digital infrastructure of rural information can break the gap between urban and rural areas. Using data as a bridge between urban and rural areas can better understand rural areas' various properties and economic potential. The result can make resources more effectively allocated. The use of different methods to digitize rural information can promote the development of rural areas more effectively. For rural content of digital information and the objective trend of rural digital development, this paper will discuss from 3 points of view: the methods of data acquisition, the processing and induction of data, and the analysis of data. This paper will analyze the main strategic issues that should be solved in digital rural construction and promotion. Thereafter, this paper will discuss how they can offer many opportunities and even become smart villages.

3. Digitization of rural information

Digital rural strategy is an important way to realize the modernization of agricultural and rural areas, which endows traditional agricultural and rural areas with new life. In the situation of continuous urbanization and informatization, many issues appear, like how to solve the problem of the last kilometer of the digital countryside and smart agriculture, how to help rural areas get rid of poverty accurately, and how to open up a new situation of an urban-rural integrated economy. The construction of digital infrastructure has opened a new stage for rural construction. This paper mainly studied and discussed the contents of digital infrastructure includes geographic information, digital economy information, and rural visualization information.

3.1. GEOGRAPHIC INFORMATION

In recent years, with the progress of remote sensing detection platforms and the constant update of data transmission and processing technology, remote sensing technology, as a convenient and accurate means of information acquisition, has played an important role in various geographic information monitoring such as land cover, water resources, atmosphere, and ecological environment. From the perspective of information acquisition, remote sensing technology can provide the necessary data to support digital rural construction. According to the platform classification, remote sensing technology has three categories: ground remote sensing, aerial remote sensing, and aerospace remote sensing.

3.1.1. Ground remote sensing

Ground remote sensing is installing sensors on ground platforms (such as vehicle-mounted, shipborne, portable, fixed or mobile elevated platforms, etc.). The remote sensing technology system, ground object spectrometers, or sensors installed on these platforms can carry out various ground object spectrum measurements. The surface remote sensing technology can obtain the long-term surface monitoring data and low-altitude remote sensing data of the detection area, providing a new detection and analysis method for detecting the quality index of rural cultivated land (Zhang et al., 2020).

3.1.2. Aerial remote sensing

Aerial remote sensing, also known as airborne remote sensing, is a multi-functional and comprehensive detection technology developed from aerial photographic reconnaissance. It is a remote sensing technology that sets sensors on aircraft (such as balloons, model airplanes, aircraft, and other aircraft and remote sensing platforms, etc.) in the air. The use of aerial remote sensing technology to monitor and research rural land has further promoted the detection work. It has moved agricultural production and research from traditional concepts and methods to a new stage of precision agriculture, quantitative and textured agriculture, and research from the experience level to the theoretical level (Zou&Shi, 2017).

3.1.3. Aerospace remote sensing

Aerospace remote sensing is the remote sensing technology that sets the sensor on the spacecraft (such as artificial satellite, space shuttle, spacecraft, space laboratory, etc.) (Wang, 2019) (Figure 1). The space satellite remote sensing technology can effectively estimate the village's biomass and vegetation coverage (Kale et al., 2002). Then it can reveal the real-time and the importance of rural ecological destruction in a wide range of fields (Xia et al., 2020). Besides, aerospace remote sensing technology also has great advantages in carrying out agricultural remote sensing monitoring and early warning. It also obtains accurate and long-term information data promptly.

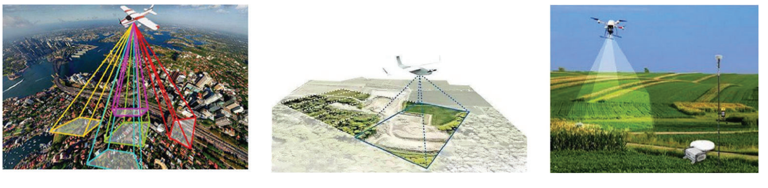


Figure 1. Remote Sensing Technology (Wang,2019).

As a continuously innovating data collection method, remote sensing technology is an important part of the digital infrastructure's data information. Remote sensing technology can monitor rural land use in real-time, help the digital transformation of rural industries, support digital rural spatial planning, and detect rural ecological, environmental energy. It can also provide real-time, accurate, and rich geographic information for rural digitalization, which plays an important guiding role in constructing and developing digital rural areas. Therefore, with the gradual application of remote sensing technology, digital rural construction will develop from the three aspects of improving the comprehensive benefits of land, comprehensive utilization of agricultural resources, and safeguarding the ecological landscape environment. It is bound to promote the construction and implementation of the rural revitalization strategy.

3.2. THE DIGITAL ECONOMY

The digital economy is injecting strong new drivers into rural revitalization. The operation process is also the integration of new technologies such as artificial intelligence and blockchain in production, exchange, distribution, and consumption.

The Rural digital economy is based on the rural modern information network, with the new generation of information technology as the driving force. It integrates digital technology, human resources, information, knowledge, and management as a production factor to push forward primary, secondary and tertiary industries in the countryside (Huang,2019). The Rural digital economy replaces and transforms the traditional elements, optimizes the allocation of resources, and speeds up the convergence to improve rural industry digitization. It constantly activates new rural industries characterized by digital formats to realize the economic form of agricultural, rural economic development in high quality (Chen, 2020). It is important to clarify the connotation of the rural digital economy and put forward the characteristics, performance, and problems in the process of rural digital transformation.

The influence of the digital economy on agriculture-related industries is reflected in the reorganization of the industrial organization system, the upgrading of the industrial chain, and the improvement of the agricultural energy level and efficiency (Feng et al., 2016). The digital economy takes digital technology innovation as the core driving force, and digital technology has natural permeability, fusion, and empowerment. As a kind of integrated economy, although the main body belongs to the real economy, it must rely on integrating digital technology and traditional hinges. With the help of digital technology, it can enable traditional industries to improve production efficiency and promote high-quality development by embedding new productivity factors (Figure 2).

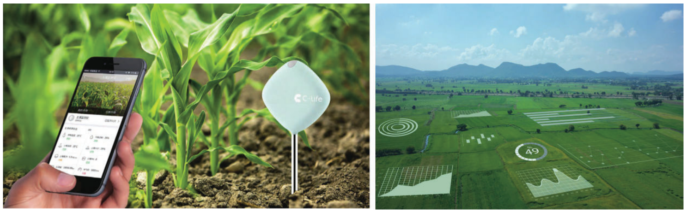


Figure 2. The Application of Remote Sensing Technology in Agriculture (Huang, 2019),(Chen, 2020).

3.3. RURAL VISUALIZATION

The construction of digital villages should be classified according to different rural environmental factors and local conditions. Relying on "Internet +," characteristic protected villages dig deep into the unique resources of local culture, carry out high-quality rural tourism projects, and build internet-featured tourism villages. As a standard to measure the quality of tourist attractions, tourism experience affects the development of tourism. With the growth of the tourism market, tourism experience has become a focus topic (Liu&Li, 2017). To further improve people's travel experience, the promotion of tourism information services and the "Internet + tourism" strategy in the tourism industry will become important construction content and key projects. The new interactive mode of augmented reality has great potential in the tourism world's information service and content construction.

3.3.1. 3D modeling virtual technology

With 3D modeling virtual technology's continuous progress, 3D modeling virtual technology has been applied in various fields. The combination of virtual reality and rural culture can better show the interaction and immersion of reality. The so-called virtual tourism refers to 3D modeling virtual technology based on the real tourist landscape, digital media technology, and creative publicity design, cleverly combining text, sound, and video. (Yi, 2020). to make tourists have a deep impression. The three-dimensional virtual environment can make the users understand tourism information without leaving home. It can meet special groups' tourism needs, save costs, and provide users with a convenient, comfortable, and immersive travel experience (Figure 3). For example, in the context of the Covid-19, people can also feel the rural environment without leaving home.

3D modeling virtual technology can attract potential visitors to explore tourist destinations by providing a rich rural virtual environment while also providing destination marketing and target market communication opportunities. Potential tourists' cognitive experience can better promote their tourism interaction through virtual reality technology.

Figure 3. 3D modeling virtual technology (Yi,2020).

3.3.2. AR interaction technology

Augmented reality (AR) is a new technology that combines computer technology with communication technology and multimedia technology to overlay virtual information onto reality. It can make users interact with virtual content through multi-modal interaction technologies such as motion capture and gesture recognition. AR interaction model overturns the traditional interpersonal interaction model and provides a new way for people to recognize and experience the things around them (Figure 4).

The formation of tourism experience is determined by good cognitive conditions and high-quality cognitive results. Augmented reality interaction mode has changed people's cognitive style and cognitive efficiency by influencing the information processing process. VR interaction technology can expand and strengthen the scope and degree of interaction between people and the countryside, break the boundary of space and time, improve the sense of immersion and improve people's cognitive quality of the rural environment and culture.

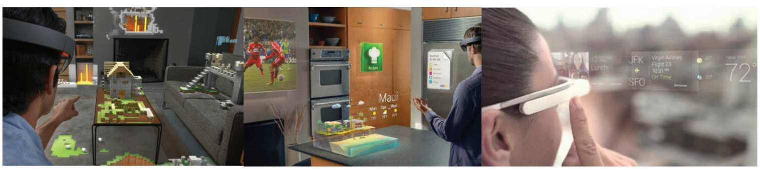


Figure 4. AR interaction technology equipment and operating scenarios(Ding,2016).

Digital rural construction is a complex and huge system engineering. It needs to incorporate digital information based on traditional rural construction. Digital construction is not only a realistic or paper objects into digital products but also an integrated platform construction based on lots of information technology such as 3S, intelligent sensor network (Figure 5). With the development of science and technology, many cities have realized some constructions of smart cities. With the combination of technology and data, the various urban operations data are visualized on the platform. As a result, big data can be visualized and analyzed for all aspects of urban construction. The technology improves the level of urban management. In the digital village, the visualization system's construction can also effectively improve comprehensive management levels.

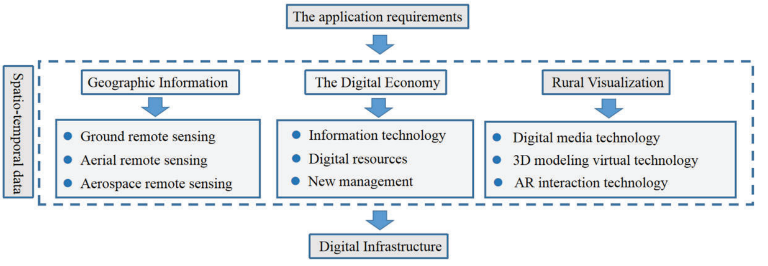


Figure 5. Digital information framework.

4. Problems in the Digitization of Rural Information

At present, the collection, classification, processing, and analysis of rural data information are still in the stage of basic theoretical research and experimental analysis. Due to the constraints and complexity of acquiring information, the theoretical system and technical system of rapid inheritance of rural information still need to be further constructed and improved.

- The construction of rural information infrastructure is still not perfect.

The promotion and construction of digital technology cannot be separated from the support of the Internet. However, the information infrastructure in rural areas, especially remote areas, is still relatively weak. The optical fiber network, 4G network, and other information infrastructure have not been fully covered, and the communication network signal in remote areas is relatively weak. Therefore, accelerating the construction of infrastructure is the key to the construction of digital villages. Improving rural Internet facilities and accelerating the development of broadband Internet, mobile Internet, digital TV, and the next-generation Internet in rural areas will promote rural areas' digital transformation.

- Obstacles to the acquisition, transmission, and use of rural data.

In the current rural development, information on rural production, environmental protection, rural governance, public services, and other aspects of the data are increasing. However, due to the limitations of rural hardware conditions and the differences in personnel quality, there are non-standard and incomplete situations in data collection. In data transmission, there are such situations as bar segmentation, lag, or string alteration. In data use, due to the lack of a corresponding information exchange platform, all kinds of information transmission and sharing in the practice of rural construction are not timely. It causes the error and the problems of information sharing. The data collection platform built on the digital infrastructure unitizes the various fields of rural information digital construction to the space platform so that the "digital infrastructure" can achieve "construct in one place, apply in multiple places."

- Awareness of rural digital development and shortage of talents.

Although the development and research of agricultural and rural electronic digitization gradually become formal, rural residents generally lack a profound understanding of digital technology and the economy. Their awareness of constructing digital rural areas is not strong. Also, the large economic development gap between villages and cities makes villages lack attraction to digital technical personnel, the current rural information data processing personnel, information service personnel, and so on. Therefore, it is necessary to break through the current shortage of rural talents, build a talent engine for rural revitalization, and actively introduce foreign talents while cultivating local talents to enhance talents' bonus effect and help the construction of digital villages.

- Insufficient technical support for rural data application.

Digital technology is embedded in rural development inseparable from the technical support of big data, the Internet of Things, and cloud platforms. In particular, it is necessary to use the whole-process big data technology such as data collection, data management, data sharing, data analysis, data application, and data security to dig out the valuable information hidden in the massive data and apply it to the practice of rural development. In fact, in addition to better infrastructure in some smart cities and large Internet enterprises, rural areas are relatively backward in developing and applying digital technology. The development and utilization of rural data should be integrated into the national informatization development strategy from the national level. It is essential to accelerate the digital transformation of the industrial chain and promote digital technology's penetration into the whole industrial chain.

5. Conclusion

Based on strengthening overall planning and improving policies and measures, it is particularly critical to encourage the weak links of rural information infrastructure to promote rural areas' digital construction. It is also necessary to build a digital infrastructure in rural areas. Compared with smart cities, digital villages provide data reference for the differentiated development of township governments and healthy competition and provide information highways connecting villages and cities. The development of digital rural construction, on the one hand, is conducive to further tap the huge potential of informatization in the rural revitalization and drive the modernization of rural areas with digital guidance. On the other hand, information flow can help drive technology flow, capital flow, talent flow, and material flow to rural areas. It can optimize the allocation of the labor force, land, capital, technology, data, and other resource elements between urban and rural areas, inject new impetus, and provide new paths for rural development.

ACKNOWLEDGEMENTS

The authors would like to acknowledge that this paper was financially supported by The Later-stage funded project of the National Social Science Foundation(No. 19FXWB026),The Science Research Project of Guangdong Province(No. 2017A020220011) and National Natural Science Foundation of China (No. 51908158).

References

Adamowicz, M. and Zwolińska-Ligaj, M.: 2020, The "Smart Village" as a Way to Achieve Sustainable Development in Rural Areas of Poland, *Sustainability*, **12**(16), 6503.

Akbar, A., Flacke, J. and Martinez, J.: 2020, Knowing My Village from the Sky: A Collaborative Spatial Learning Framework to Integrate Spatial Knowledge of Stakeholders in Achieving Sustainable Development Goals, *ISPRS International Journal of Geo-Information*, **9**(9), 515.

Cao, Z.Q.: 2019, Build a talent engine to help rural revitalization, *People*, **29**(23), 70-71.

Chang, J.R.: 2020, The construction of digital rural virtual agricultural technology service platform in the 5G era, *Southern Agricultural Machinery*, **51**(17), 6-7+18.

Chen, Q.Y.: 2020, Digital "connection": solving the pain points of rural revitalization, *Xiao Kang*, **17**(28), 42-44.

Chen, T. and Wang, P.: 2020, Information Gap and Practice Symptoms of Digital Village Construction, *E-government*, **17**(12), 2-12.

Ding, L.: 2016, *Research on Application of Interactive Interface Design in Construction Engineering Informationization*, Master's Thesis, Shanghai Jiaotong University.

Ding, S.: 2020, Digital cultural governance empowers rural cultural revitalization, *Journal of Hubei University of Arts and Science*, **41**(4), 33-38.

Feng, L., Alberto, N. and Sinead, R.: 2016, How smart cities transform operations models: a new research agenda for operations management in the digital economy, *Production Planning & Control*, **27**(6), 514-528.

Holten, D.: 2006, Hierarchical edge bundles: Visualization of adjacency relations in hierarchical data, *IEEE Transactions on visualization and computer graphics*, **12**(5), 741-748.

Huang, H.L.: 2019, The Development and Thinking of Digital Village in Zhejiang, *Information construction*, **23**(08), 55-56.

Kale, M.P., Singh, S. and Roy, P.S.: 2002, Biomass and productivity estimation using aerospace data and Geographic Information System, *Tropical Ecology*, **43**(1), 123-136.

Li, L.W.: 2020, Digital Supervision in Comprehensive Rural Improvement: Taking Village D's Experience as an Example, *E-government*, **17**(12), 13-23.

Liu, Y. and Li, Y.: 2017, Revitalize the world's countryside, *Nature News*, **548**(7667), 275.

Wang, M.: 2019, *Research on UAV-borne catadioptric real-time panoramic remote sensing imaging and image processing technology*, Master's Thesis, National Defense University.

Xia, T., Shi, Y. and Wu, W.B.: 2020, The role of remote sensing technology in the construction of digital villages, *Satellite application*, **11**(09), 8-13.

Yi, J.: 2020, The latest technology in 3D city modeling, *China Surveying and Mapping*, **29**(05), 76-79.

Zavratnik, V., Kos, A. and Stojmenova, D.E.: 2018, Smart villages: Comprehensive review of initiatives and practices, *Sustainability*, **10**(7), 2559.

Zhang, C.L., Han, X.W. and Li, J.T.: 2018, A comparative study of smart city construction between China and Singapore in the context of big data, *The Modern intelligence*, **38**(10), 126-131.

Zhang, F.Y., Hu, Y.M., Chen, L.C. and Wang, G.Y.: 2020, Research on the Dual Acquisition System of Cultivated Land Quality Low Altitude Remote Sensing and Ground Sensing, *Journal of South China Agricultural University*, **41**(03), 117-125.

Zhu, H.Y.: 2019, Digitalization empowers rural revitalization, *Smart China*, **6**(04), 85-87.

Zou, Z. and Shi, Z.: 2017, Random access memories: A new paradigm for target detection in high resolution aerial remote sensing images, *IEEE Transactions on Image Processing*, **27**(3), 1100-1111.

THE POTENTIAL OF IOT-BASED SMART ENVIRONMENT IN REACTION TO COVID-19 PANDEMIC

QIN CHUAN CHEN[1], VAISHNAVI LAKSHMI NARASIMHAN[2]
and HYUNSOO LEE[3]
[1,2,3]*Yonsei University, Seoul, South Korea*
[1,2,3]*{chenqinchuan|vaishu|hyunsl}@yonsei.ac.kr*

Abstract. COVID-19 was first reported in late December 2019 and quickly become a global health crisis. In the COVID-19 pandemic context, the dense and open characteristics make the public spaces a potential virus transmission hotspot. Therefore, it is extremely critical to adopt a more advanced and effective method in public environments to slow down its spread until a vaccine is widely used. A smart environment in the form of IoT, also known as the architecture of IoT, consists of three layers: perception layer, network layer, and application layer. A smart environment allows data and activities that happen in this environment to be collected, processed, and shared in real-time through various sensors. It can be introduced for early detection, tracking, and monitoring of potential confirmed cases. The smart environment is considered one of the most promising approaches to face and tackle the current scenario. However, research focusing on the potential of IoT smart environment in reaction to COVID-19 is still meager. Therefore, this paper identifies the smart environment's potential based on the concept of IoT architecture's three layers and further discusses how IoT can be introduced in public spaces to help battle the pandemic.

Keywords. Internet of Things; Smart environment; COVID-19.

1. Introduction

The coronavirus (COVID-19) pandemic redefined the global health crisis of our time and has become the most significant challenge that the world has ever confronted with. The COVID-19 was first reported in Wuhan, China, and subsequently, since its emergence in Asia late last year, the virus has spread all over the world. The outbreak of COVID-19 in China was believed to have a link with Huanan Seafood Wholesale Market in Wuhan (Wu et al., 2020). Since then, countries around the world such as Italy, the United states, India, Spain and Germany have reported cases of COVID-19 outbreaks happened in public spaces (Liu et al., 2020). Indeed, public spaces are generally dense, open, and lack surveillance. It is likely to cause a wide spread of diseases if an infected person enters the public space.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 709-718.

Figure 1. Ground marking for social distancing.

A large number of researchers and virologists have been working hard to explore new solutions to contain the pandemic in all possible ways. There are measures launched to prevent the transmission of the COVID-19 virus in public spaces, such as maintaining social distancing and limiting visitors' numbers (Lewnard and Lo, 2020). At the same time, visitors must wear masks when entering a public facility and avoid contacting people who have a fever or respiratory symptoms (Kang et al., 2020). Furthermore, in some countries, to stop the spread of viruses, additional measures are being implemented to regulate people's behavior in public spaces. In India and Indonesia, all visitors are requested to keep the social distancing by following the markings on the ground when queuing (Figure 1). However, the implementation of these measures mainly depends on people's self-awareness. Degaonkar (2020) noted that these measures could not effectively protect both visitors and vendors due to a lack of proper guidelines and rules. Therefore, more advanced strategies are in demand to further limit the spread of the virus. In this context, IoT technologies have received significant attention worldwide. The rapid development of the advanced Internet of Things (IoT) technology has brought remarkable changes to the way we live, work, and travel. The IoT-based smart office has exceptional benefits in producing a comfortable smart office work environment (Nasajpour et al., 2020). It is also found that the most rising trend in the number of IoT projects currently is as expected in smart cities, connected health, and smart supply chain segments, with an annual rise over 30% in the EU and USA (Nižetić et al., 2020).

It is also revealed that a smart environment in the form of IoT allows data to be collected and shared in real-time to have the potential to reduce the risk of virus transmission (Kumar et al., 2020). The IoT-based smart environment consists of three layers: perception layer, network layer, and application layer. With the help of various sensors, a smart environment can provide services such as identifying suspected COVID-19 cases, sending an emergent warning to visitors, and automatically managing public space facilities. The IoT-based smart environment brings a new perspective for further progress in reaction to COVID-19 in public spaces. However, the potential is yet to be explored. Therefore, this shows an evident indication that more intense research activity should be conducted in this challenging field towards new and essential benefits for society.

Taking this as a lead, this paper studies IoT's role in public spaces in reaction to COVID-19. This paper's scope is to discuss the IoT's capabilities based on the three-layer concept of IoT architecture, aiming to provide a safe, secured smart environment for the occupant. This paper is divided into two sections. The first section introduces the key IoT technologies that can be utilized in public spaces during the pandemic. These technologies can be adopted in other environmental settings to subside COVID-19 transmission. The following section, taking these key IoT technologies introduced in the previous section, further briefs the smart environment's possibilities in response to the current scenario based on the concept of three layers of IoT architecture. This process can be approached towards any complex public environmental setting to detain the COVID-19 spread.

2. Key Technologies of IoT in Reaction to COVID-19

2.1. GPS

GPS is a satellite-based positioning system that helps to track and provide users' coordinates. Contact tracking tools use location-based GPS to locate and trace individuals who contact an infected person. GPS features would continuously track suspected cases' real-time movements within a geographical area and update back to the COVID-19 database platform (Weizman, Tan and Fuss, 2020). Countries and regions worldwide like South Korea, the United States, Europe, and Taiwan are using the data updated by GPS to identify the travel paths of confirmed cases and report it to their citizens through national networks (Costanzo and Flores, 2020).

2.2. QR CODE

A Quick Response Code (QR code) is a machine-readable image containing data as dots or lines arranged in matrix form. A QR code is often used to encode URL that links to a web page or application carrying various detailed information about a service or a user (Focardi, Luccio and Wahsheh, 2019). During the pandemic, the QR code is used to help slow down the virus's transmission is soaring. China has been promoting personal health QR codes to record the users' health data, such as travel history and drug purchase records. Citizens must present a green code before entering any public facilities (Wu, 2020). A QR code-based tracking system has also been developed in Korea, where visitors need to scan personal QR codes containing personal information such as full names, phone numbers, and the date of visit when they wish to enter any public spaces (Kim, 2020). Adopting QR code scanning allows the authority to track COVID-19 suspects when entering any public space.

2.3. IOT SENSING TOOLS

Table 1. IoT sensing technologies.

Author	IoT	Aim	Description
Polard (2020)	Facial recognition sensor	Detection	Face mask detection
Gazis et al. (2018)	Activity recognition sensor and RFID	Monitoring	Density monitoring
Nadokattu (2020)	Social distancing smart device	Tracking	Social distancing tracking
Islam et al. (2020)	Wearable Band	Monitoring	Respiration rate monitoring
M.S et al. (2020)	Wearable Band	Monitoring	COVID-19 related body analysis
M et al. (2020)	Sensor	Monitoring	Cough and body temperature monitoring
Costanzo and Flores (2020)	Sensor	Monitoring	Body temperature monitoring

In addition to GPS and QR Code, researchers and engineers are putting efforts into developing advanced IoT sensing tools to help people better fight the virus (Table 1). A sensor plays a vital role in IoT for tracking the objects and users' status in terms of movements, temperature, location, etc. Integrating a certain number of sensor nodes with different functions forms a sensor network. With the development of technology, the traditional sensors perform various tasks in different scenarios such as health and environmental monitoring (Yu et al., 2012). These technologies play an essential role in reducing the risk of COVID-19 spread.

3. Three-layer of IoT Architecture

This study is carried out based on the three-layer of IoT architecture, which is considered one of the fundamental guidelines for developing a smart architectural setting. A three-layer IoT architecture is commonly composed of the perception layer, network layer, and the application layer (Zhong et al., 2017). Most of the research on the smart environment based on the three-layer of IoT architecture focuses on developing a more user-friendly and high productive space for users through IoT technologies. For example, Yu et al. (2012) proposed a smart hospital concept based on the three-layer of IoT architecture setting to overcome the problems existing in hospitals, such as inflexible networking mode and manual input of medical information. In this case, the perception layer of the smart hospital was proposed to identify hospital information such as staff (doctors and nurses) identity and medical information (patient personal information and medical equipment information etc.) The collected information can be shared and checked by doctors and nurses through the network layer when needed. The application layer was applied for hospital management, such as financial management and drug management. The smart hospital can positively affect the present treatment mode and diagnosis in the hospital, improve doctors' work efficiency, and enhance the supervision over patients.

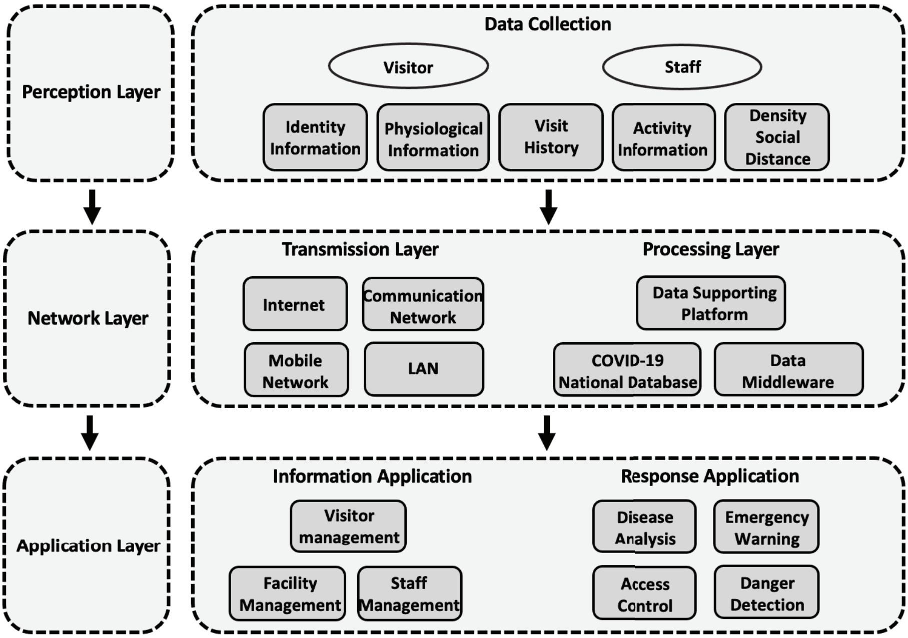


Figure 2. The architecture of IoT in reaction to COVID-19.

Unlike the previous studies, in this paper, our goal is to reveal the potential of incorporating IoT technologies in an environmental setting for controlling COVID-19. In this section, we carry out a discussion of the IoT smart environment based on IoT architecture layers (Figure 2). This approach is a promising measure to tackle the pandemic.

3.1. THE PERCEPTION LAYER OF THE SMART ENVIRONMENT

The perception layer is also known as a sensing layer. This layer includes different sensing equipment that enables the interconnection between the physical and digital worlds by gathering real-time data from users (Burhan et al., 2018). According to Rinott et al. (2020), fever is one of the most common COVID-19 symptoms, and monitoring visitors with high body temperature could help identify suspected COVID-19 cases. The thermal fever detection camera's goal is to quickly scan visitors to check abnormal body temperatures and guide them to the medical care services if a sign of trouble was detected. This camera uses infrared technology to capture the heat generated from the human skin (Joy, 2019). Moreover, this system is not foolproof. Previous literature has pointed out that measuring skin temperature often underestimates the actual body temperature. Esophageal temperature and rectal temperature are considered the most accessible and reliable sites for evaluating body core temperature, which is considered the most accurate human body temperature (Mercer and Ring, 2009). Therefore, the thermal camera can only be introduced as an initial screening for processing visitors as they enter any space.

Wearables sensors are electronic sensing devices to record the users' physiological data and allow users to interact with the environment (Weizman et al., 2020). Wearable technology plays a significant role in the detection of COVID-19 symptoms. COVID-19 affects people's physical condition in different ways. As discussed earlier, thermal cameras are used to monitor symptoms regarding each person's temperatures who wishes to enter a space. However, there are cases reported that a person who carries the COVID-19 virus may not exhibit any symptoms like a change in body temperature. Relying only on thermal cameras may be inaccurate and can increase the possibility of the virus spread. Therefore, the continuous real-time data monitoring generated by wearable sensing technology could help us overcome these risks of spreading the virus in public places (Islam et al., 2020). In addition to high body temperature, COVID-19 confirmed cases also show a lower respiratory tract infection resulting in respiratory difficulty with a respiration rate $\geq$ 30 breaths/min, which can lead to acute respiratory distress syndrome (Gibson, 2020). Researchers have proposed wearable devices to measure the respiration range (MS et al., 2020). Wearable devices can be recommended to all the permanent staff of a public space, such as management staff, to monitor and sense the symptoms of COVID-19 as a preliminary measure.

Facial and activity recognition has gained attention globally due to its applications in different industries such as intelligent environment, health, and surveillance (Hussain et al., 2019). Existing research has defined activity, and facial recognition helps detect a user's activities based on information obtained from different sensors (Wang et al., 2011). By applying more advanced vision-based technologies, sensors can be used to capture different human activities. A Chinese company developed a facial recognition sensor technology to identify visitors when wearing a mask (Pollard, 2020). Moreover, (Gazis et al., 2018) presented a method to count and track visitors inside a building through activity recognition sensors. This system allows the building operators to count and visualize all visitors in an area and track people's numbers and density in a building. In the context of COVID-19, public space operators could use this system to limit visitors to minimize the virus's spread.

3.2. THE NETWORK LAYER OF THE SMART ENVIRONMENT

The network layer is responsible for real-time processing, delivery, and sharing of the information obtained by the perception layer through various wired or wireless based network services. The network layer is like a bridge, linking the perception and application layer (Burhan et al., 2018). The smart environment's network layer can be divided into two sub-layers: the transmission layer and the processing layer.

The transmission layer is the backbone of the public space network. It plays an important role in transferring real-time information collected by the perception layer through various internet services. The processing layer is a platform to implement the integration of various data. It processes all the suspicious information gathered by the perception layer and identifies the signs of danger. This layer should be used to access the national COVID-19 database to exchange the most updated data.

3.3. THE APPLICATION LAYER OF THE SMART ENVIRONMENT

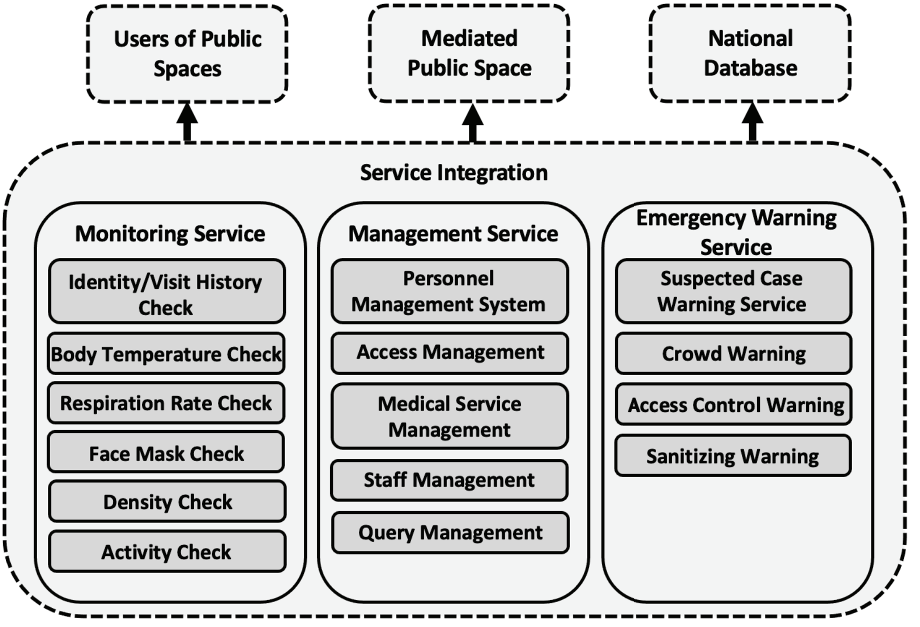


Figure 3. Services of smart environment in reaction to COVID-19.

The smart environment's application layer uses the data processed and analyzed by the previous layers to provide various services (Figure 3) and swiftly react to COVID-19 suspicious signs. The application layer has two parts: the response application and the informatization application.

3.3.1. Response Application

Response application is a senior application responsible for disease analysis and risk management. It allows further decisions (emergency warning, access control, etc.) to be made reacting to any sign of danger.

- Monitoring Service

A significant advantage of the IoT smart environment is the ability to automatically monitor and collect visitors' physiological conditions such as body temperature and respiration rate through biometric sensors. At the same time, user activities can be tracked at any time through the implementation of various IoT sensors to identify any signs of danger. The data can be further digitalized and integrated into an internal database. This internal database can be shared and accessed through backbone internet services and accessed by the other IoT-based mediated public spaces. Together, these databases could form a bigger central network system (Figure 4) for public-health agencies to access and monitor the COVID-19 pandemic.

- Warning Service

Another advantage of the IoT smart environment is the timely warning service. It is addressed that developing an early warning system is extremely crucial during the COVID-19 pandemic (Kogan et al., 2020). The IoT smart environment has been empowered with the ability to monitor the conditions and activities of users. The warning service's purpose is to alert the users if any signs of trouble were detected. Further, through mobile network systems, the warning service provided the visitors an ability to get the information of the space (the crowded area, the current number of visitors, etc.) in a timely manner, which allows the user to feel utmost safe.

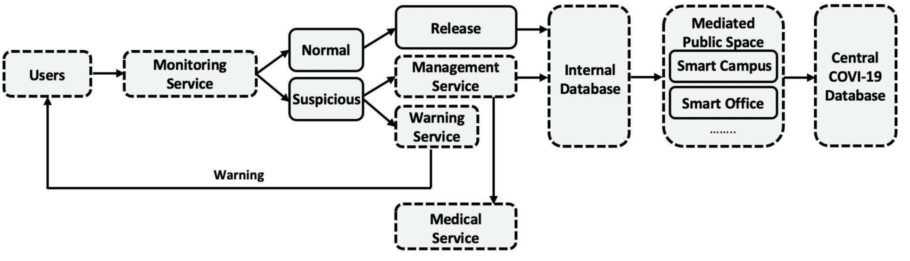


Figure 4. Database network of IoT smart environments.

3.3.2. Informatization Application

The informatization application includes the informatization of visitor management (numbers of the visitors, physiological information, etc.), staff management, and facility management (gate, alarm, etc.).

- Management Service

Management service is an integrated platform for making polymerization for distributed IoT applications in the environment responsible for controlling the space and making overall decisions. It allows the environment to react to emergent situations quickly. Its primary function is as follow: management of visitor identities (including visitor name, travel history, and phone number), control of access to limit the density of the visitors, staff operation management (identification of staffs, sanitizing history, etc.), management of emergency medical services for suspicious cases.

4. Conclusion

Although IoT-related academic studies for COVID-19 in the medical sector are currently on high focus, research linked with public spaces is less explored. The Global Challenge of the COVID-19 pandemic has raised concerns about safety in public spaces. This paper contributed to this current challenging scenario by identifying the IoT-based key technologies related to COVID-19. Further, we discussed the potential of how a smart environment based on the three-layer of IoT architecture can enhance the environment in terms of user safety in the context of the COVID-19 pandemic. The three-layer based theoretical framework assures access for the occupant to a safe setting in any public environment. However, the challenges in implementing IoT cannot be ignored in public ambiance as it needs authorized supports and execution from each country's government edge. This scheme can be further extended on a more determined strategy in combination. Further, each public space is a complex setting, so more comprehensive research is needed regarding individual public space based on its physical characteristics.

References

Burhan, M., Rehman, R.A., Khan, B. and Kim, B.S.: 2018, IoT elements, layered architectures and security issues: A comprehensive survey, *Sensors (Switzerland)*, **18**(9), 2796.

Costanzo, S. and Flores, A.: 2020, A Non-Contact Integrated Body-Ambient Temperature Sensors Platform to Contrast COVID-19, *Electronics*, **9**(10), 1658.

Degaonkar, S.: 2020, "Shoppers throng vegetable stalls, no social distancing" . Available from <https://punemirror.indiatimes.com/pune/civic/shoppers-throng-vegetable-stalls-no-social-distancing/articleshow/74867729.cms>.

Focardi, R., Luccio, F.L. and Wahsheh, H.A.: 2019, Usable security for QR code, *Journal of Information Security and Applications*, **48**, 102369.

Gazis, A., Stamatis, K. and Katsiri, E.: 2018, A Method for Counting , Tracking and Monitoring of Visitors with RFID sensors, *Panhellenic Electrical and Computer Engineering Students Conference (ECESCON)*, **10**, 199-204.

Gibson, P.G., Qin, L. and Puah, S.H.: 2020, COVID□19 acute respiratory distress syndrome (ARDS): clinical features and differences from typical pre COVID-19 ARDS, *Med J Aust.*, **213**(2), 54-56.

Hussain, Z., Sheng, M. and Zhang, W.E.: 2019, Different approaches for human activity recognition- A survey, *arXiv*, 1-28.

Islam, M.M., Mahmud, S., Muhammad, L.J., Islam, M.R., Nooruddin, S. and Ayon, S.I.: 2020, Wearable Technology to Assist the Patients Infected with Novel Coronavirus (COVID-19), *SN Computer Science*, **1**(6), 1-9.

Joy, K.: 2020, "How Does Fever Detection Technology Work in Healthcare?" . Available from <https://healthtechmagazine.net/article/2020/07/how-does-fever-detection-technology-work-healthcare-perfcon>.

Kang, J.H., Jang, Y.Y., Kim, J.H., Han, S.H., Lee, K.R., Kim, M.K. and Eom, J.S.: 2020, South Korea's responses to stop the COVID-19 pandemic, *American Journal of Infection Control*, **48**(9), 1080-1086.

Kim, A.: 2020, "S. Korea walks a fine line between coronavirus tracing, privacy breach" . Available from <http://www.koreaherald.com/view.php?ud=20200609000957>.

Kogan, N.E., Clemente, L., Liautaud, P., Kaashoek, J., Link, N.B., Nguyen, A.T., Lu, F.S., Huybers, P., Resch, B., Havas, C., Petutschnig, A., Davis, J., Chinazzi, M., Mustafa, B., Hanage, W.P., Vespignani, A. and Santillana, M.: 2020, An Early Warning Approach to Monitor COVID-19 Activity with Multiple Digital Traces in Near Real-Time, *arXiv*.

Kumar, K., Kumar, N. and Shah, R.J.: 2020, Role of IoT to avoid spreading of COVID-19, *International Journal of Intelligent Networks*, 31-35.

Lewnard, J.A. and Lo, N.C.: 2020, Scientific and ethical basis for social-distancing interventions against COVID-19, *The Lancet Infectious Diseases*, **20**(6), 631-633.

Liu, Z., Magal, P. and Webb, G.: 2020, Predicting the number of reported and unreported cases for the COVID-19 epidemics in China, South Korea, Italy, France, Germany and United Kingdom, *J Theor Biol.*.

M.S, J., L, L., R Nair, R., P, V., R, G. and Jothikumar, R.: 2020, Monitoring and sensing COVID-19 symptoms as a precaution using electronic wearable devices, *International Journal of Pervasive Computing and Communications*, **16**(4), 341-350.

Mercer, J.B. and Ring, E.F.J.: 2009, Fever screening and infrared thermal imaging: Concerns and guidelines, *Thermology International*, **19**(3), 67-69.

Nasajpour, M., Pouriyeh, S., Parizi, R.M., Dorodchi, M., Valero, M. and Arabnia, H.R.: 2020, Internet of Things for Current COVID-19 and Future Pandemics: An Exploratory Study, *Journal of Healthcare Informatics Research*, 1-40.

Pollard, M.: 2020, "Even Mask-Wearers Can Be ID'd, China Facial Recognition Firm Says" . Available from <https://www.usnews.com/news/world/articles/2020-03-09/china-firm-develops-system-to-recognize-faces-behind-coronavirus-masks>.

Rinott, E., Kozer, E., Shapira, Y.J., Bar-Haim, A. and Youngster, I.: 2020, Ibuprofen use and clinical outcomes in COVID-19 patients, *Clin Microbiol Infect.*, **26**(9), 1259.e5–1259.e7.

Wang, J., Cao, Y.T., Xie, J.Y. and Chen, S.F.: 2011, Energy efficient backoff hierarchical clustering algorithms for multi-hop wireless sensor networks, *Journal of Computer Science and Technology*, **26**(2), 283-291.

Weizman, Y., Tan, A.M. and Fuss, F.K.: 2020, Use of wearable technology to enhance response to the Coronavirus (COVID-19) pandemic, *Public Health*, **185**, 221-222.

Wu, Y.C., Chen, C.S. and Chan, Y.J.: 2020, The outbreak of COVID-19: An overview, *Journal of the Chinese Medical Association*, **83**(3), 217-220.

Wu, J.Y., Xie, X.W., Yang, L., Xu, X.Y., Cai, Y.Y., Wang, T.G. and Xie, X.X.: 2020, Mobile health technology combats COVID-19 in China, *J Infect.*, **82**(1), 159-198.

Yu, L., Lu, Y. and Zhu, X.J.: 2012, Smart hospital based on internet of things, *Journal of Networks*, **7**(10), 1654-1661.

Zhong, C.L., Zhu, Z. and Huang, R.G.: 2017, Study on the IOT Architecture and Access Technology, *Proceedings - 2017 16th International Symposium on Distributed Computing and Applications to Business, Engineering and Science, DCABES 2017*, 113-116.

URBAN DESIGN OPTIMIZATION: GENERATIVE APPROACHES TOWARDS URBAN FABRICS WITH IMPROVED TRANSIT ACCESSIBILITY AND WALKABILITY

Generative approaches towards urban fabrics with improved transit accessibility and walkability

FERNANDO LIMA[1], NATHAN BROWN[2] and JOSÉ DUARTE[3]
[1]*Pennsylvania State University | Federal University of Juiz de Fora*
[1]*fernando.lima@arquitetura.ufjf.br*
[2,3]*Pennsylvania State University*
[2,3]*{ncb5048|jxp400}@psu.edu*

Abstract. This paper investigates computational optimization techniques at the urban design scale, aiming to improve the performance of urban fabric layouts according to predefined evaluation metrics. To this end, this work addresses the use of optimization tools in urban design by comparing various optimization algorithms for generating urban fabrics with improved walkability and by analyzing the outcomes of different urban design rules. These rules formulate orthogonal and non-orthogonal grids from the perspective of transit accessibility (TA), thereby minimizing automobile usage and improving the walkability of neighborhoods. Transit accessibility is also evaluated alongside estimated infrastructure cost to verify the suitability of applying optimization in urban design. Our results suggest that the RBFOpt algorithm performs best for generating urban fabrics according to our quantitative design objectives; more flexible and complex grids in terms of shape and dimensions tend to deliver greater TA than rectangular and uniform-oriented grids; different block patterns can lead to solutions more directed at TA or to infrastructure cost, outlining a trade-off; and multicriteria optimization helped in identifying designs that balanced transit accessibility and infrastructure cost.

Keywords. Urban design; Optimization; Transit accessibility; Walkability.

1. INTRODUCTION

Design approaches that include generative and parametric features increase designers' ability to explore wider sets of potential solutions. In this context, computational optimization is increasingly being adopted to solve complex design problems, from energy consumption to structural performance (Wortmann and Nannicini, 2017; Wortmann, 2019; Brown, Jusiega and Mueller, 2020). However,

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 719-728.

computational optimization techniques at the urban design scale have been limited compared to architecture due to increased complexity and computation requirements (Navarro-Mateu, Makki and Cocho-Bermejo, 2018; Makki et al., 2019; Yang, Samaranayake and Dogan, 2020). However, opportunities are numerous, especially if we consider urban design's influence on the economy and quality of life in a city. The work described in this paper hypothesizes that computational optimization can be useful in urban design when associated with generative design systems and evaluation metrics. It consists of sets of experiments that involve the formulation, evaluation, and optimization of urban fabric configurations according to predefined evaluation metrics. The overall objectives are i) to evaluate the benefit of employing optimization tools to improve urban performance; ii) to compare the effectiveness of various optimization algorithms for tackling problems that are recurrent in urban design, and; iii) to explore and assess different generative approaches towards the formulation of orthogonal and non-orthogonal grids from the perspective of transit accessibility. Transit accessibility is an urban development principle based on locating amenities and housing within walking distance from transit hubs, thereby minimizing automobile usage and improving walkability in neighborhoods. Therefore, transit accessibility was used in conjunction with infrastructure cost as estimated by road area as quantitative design objectives to verify the suitability of applying optimization in urban design, with the expectation that such an application may be expanded to encompass other design qualities in the future.

In this context, the experiments combine algorithms for blocks and streets generation; CityMetrics tools (Lima, 2017) for fabrics performance evaluation, and various Grasshopper optimization plugins for guiding generation towards solutions with optimized performance, namely Galapagos, Silvereye, Radical, Opossum, and Goat for single-criteria, and Wallacei for multicriteria optimization. Problem formulation for the experiments comes from the following questions: i) can optimization be useful in finding better arrangements for urban fabrics (blocks dimensions, shape, and rotation) that yields greater transit accessibility for a neighborhood? ii) which optimization algorithm performs better, considering this specific context of generating orthogonal and non-orthogonal grids, seeking to improve transit accessibility and walkability? iii) can multicriteria optimization help within this context?

This paper is structured into four sections that present, respectively, the materials and methods of the research; the performed case studies that address the use of optimization in urban fabrics generation; the case studies results; and a discussion on the results and final remarks.

2. MATERIALS AND METHODS

2.1. RESEARCH FRAMEWORK

The overall research framework consists of combining algorithms for blocks and streets generation; Physical Proximity Calculator for evaluating the generated fabrics performance; and various Grasshopper optimization plugins for guiding generation towards solutions with optimized performance. Thus, in summary, we implemented a generative approach for optimizing urban fabric configurations through evaluation metrics set as fitness functions in optimization.

2.2. TRANSIT ACCESSIBILITY

Promoting short distances to access public transportation means better connecting the city, encouraging walking, cycling, and using the public transport system. Distance has substantial implications for a public transport system's viability and effectiveness - in essence, distance allows one to measure a transit station's proximity or accessibility in aggregate. However, efforts to make cities more connected have often been predicated on allowing people to move around the city more quickly, opening an ever-increasing number of ways to move cars rather than bringing urban services closer to people. In this regard, Calthorpe (1993) points out that transportation systems need to be structured to facilitate access to a wide variety of destinations, such as work, services, and recreation, among others. In this context, transit accessibility is a transit-oriented development principle based on locating amenities and housing around transit hubs (Figure 1) and minimizing automobile usage, thereby contributing to more walkable and sustainable neighborhoods (Dittmar and Ohland, 2004; Farr, 2013; Suzuki, Cervero and Iuchi, 2013).

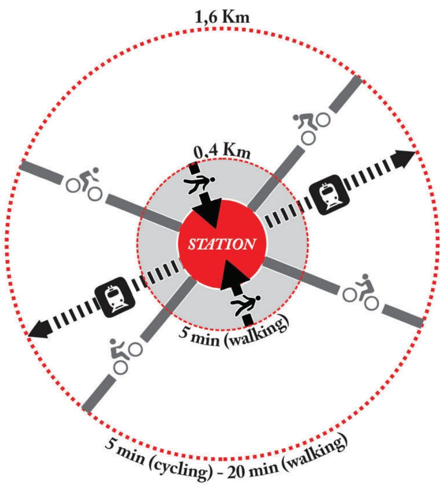


Figure 1. Diagram summarizing the Transit Accessibility idea: all neighborhood activities within walking distance of a central station. Source: Adapted from Lima (2017).

2.3. PHYSICAL PROXIMITY INDEX (PPI)

Transit accessibility can be evaluated in early design by calculating Physical Proximity Index (PPI). PPI is an index extracted from Physical Proximity Calculator (PPC), a CityMetrics tool (Lima 2017) that expresses, on a 0 to 1 scale, the smaller distance between a target (e.g., a transit station) and other locations in a neighborhood (origins). To this end, PPC identifies, considering the streets network, the path(s) with smaller distance(s) between one or more particular target(s) and all selected locations in an area. For instance, if a given location is within 400 m (5 min walk) from a station, it returns a PPI of 1. This index decreases as the distance approaches 1.6 km (20 min walk) and becomes 0 when the distance becomes greater than 1.6 km. In these research experiments, which aim to assess proximity for all blocks within a neighborhood, we set PPC to calculate the distances between each block's corners and then extract the average between them. Thus, the algorithm expresses a particular block's physical proximity by performing its corners' average physical proximity indexes. When considered across an entire neighborhood, these calculations provide information about the whole design. Figure 2 depicts the PPI calculation logic.

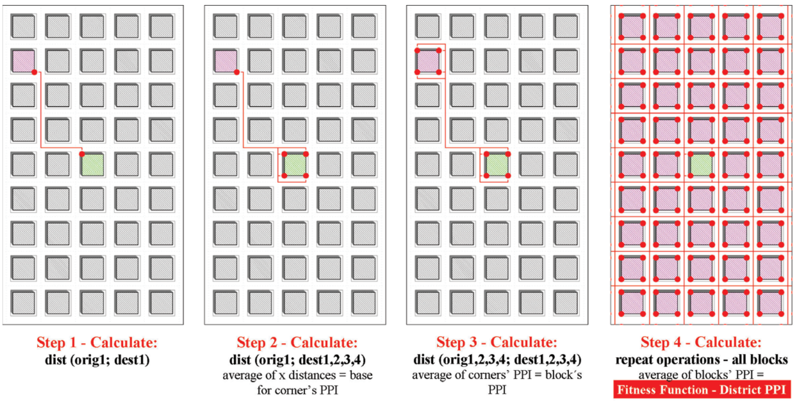


Figure 2. Steps for calculating the Physical Proximity Index.

2.4. COMPUTATIONAL OPTIMIZATION IN URBAN DESIGN

The use of computational optimization to address complex design problems has increased significantly, although its use in urban design is limited when compared to architecture due to the increased complexity and computation requirements. To investigate the performance of different optimization techniques in an urban design context, we have addressed several tools encoding different algorithms for generating optimized urban fabrics from the transit accessibility perspective. In summary, we addressed six Grasshopper optimization tools (Galapagos, Silvereye, Radical, Opossum, Goat, and Wallacei) and their different possibilities to implement the ten following algorithms: i) Galapagos - Genetic Algorithms (Rutten, 2011); ii) Galapagos - Simulated Annealing; iii) Silvereye - ParticleSwarm (Cichoka et al., 2017); iv) Radical - GN Direct (Brown, Jusiega and Mueller, 2020); v) Radical - GN Origin Direct; vi) Opossum - RBFOpt (Wortmann, 2017); vii) Opossum - CMAES; viii) Goat - CRS2 (Flöry, 2015); ix) Goat - COBYLA, and; x) Wallacei - NSGA-2 (Makki, Weinstock and Showkatbajhsh, 2020). These algorithms were tested in three different case studies considering solution quality and computation time.

3. CASE STUDIES

To explore optimization possibilities in urban fabric generation, we implemented two case studies of varying complexity. For each case study, we tested several different optimization tools for a total of 168 hours of CPU processing (9 tests x 8 hours in case 1 approach 1 + 9 tests x 8 hours in case 1 approach 2 + 3 tests x 8 hours in case 2). The first case consisted of generating uniform and non-uniform blocks using single-criteria optimization for finding urban fabric arrangements with higher physical proximity indexes. The second case, in turn, consisted of addressing different approaches for modifying the best solution found in case 1, using multicriteria optimization to deal with the transit accessibility and Infrastructure cost trade-off (maximizing Physical Proximity Index vs. minimizing the streets' total length). Figure 3 illustrates the logic of the case studies described below.

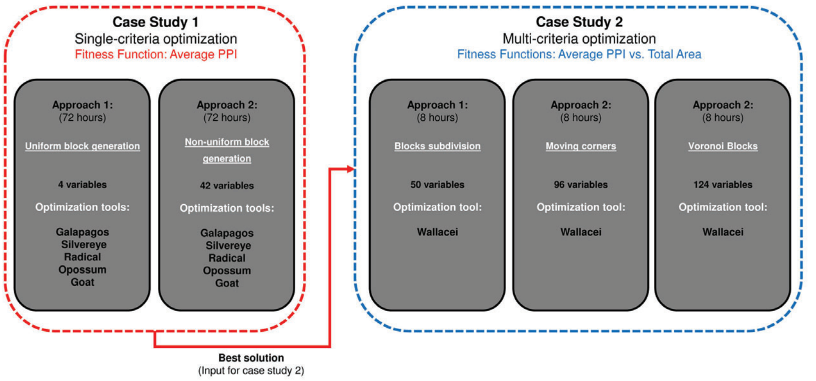


Figure 3. The case studies' logic: single and multicriteria optimization with multiple generative approaches for fabric generation.

4. Case study 1

Case study 1 consisted of two basic parametric approaches (Figure 4a): uniform block generation and non-uniform block generation. In the first approach, a generative algorithm was implemented to create a rectangular grid of blocks and streets for a given area. In this experiment, all blocks had equal dimensions, and four variables were optimized: blocks length (60 to 200m), blocks width (60 to 200m), streets width (12 to 20m), and grid rotation angle (-90 to 90 degrees). The average Physical Proximity Index between all blocks and the station block (the central one) was set as a fitness function. One test, lasting up to 8 hours, was performed with each optimization tool (Figure 4b).

The second approach followed the same basic structure, with one crucial difference: blocks could have different dimensions while keeping grid alignments (Figure 4c). In this scenario, the number of parametric variables reached forty-two, increasing the problem's complexity and allowing us to compare the optimization tools' effectiveness.

In both approaches, the optimization tools mentioned before were set to find fabric layouts that provided the higher physical proximity index between the neighborhood's central block and all others. The goal was to identify which approach would provide better solutions and which optimization algorithm would perform better, considering solution quality and computation time.

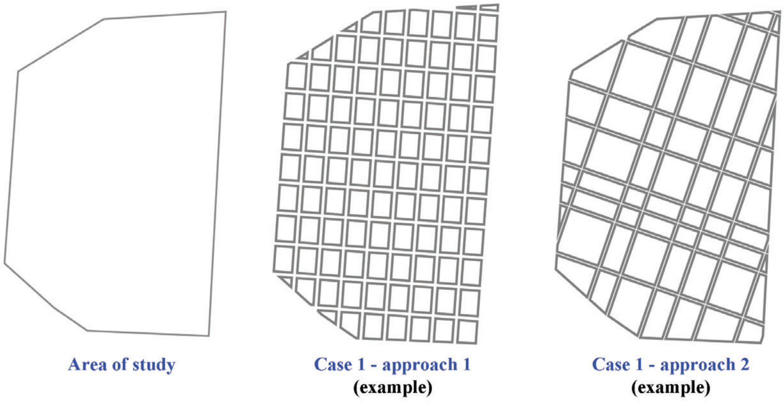


Figure 4. Case 1's approaches for generating the fabrics' settings.

5. Case study 2

In case study 2, optimizations were performed according to the same logic as in case study 1, but with freedom beyond that of a rectilinear uniform grid. In this sense, the second case study consisted of further refining the best solution found in case 1 through three different deforming approaches for subsequent optimization: blocks subdivision, moving corners, and Voronoi blocks (Figure 5).

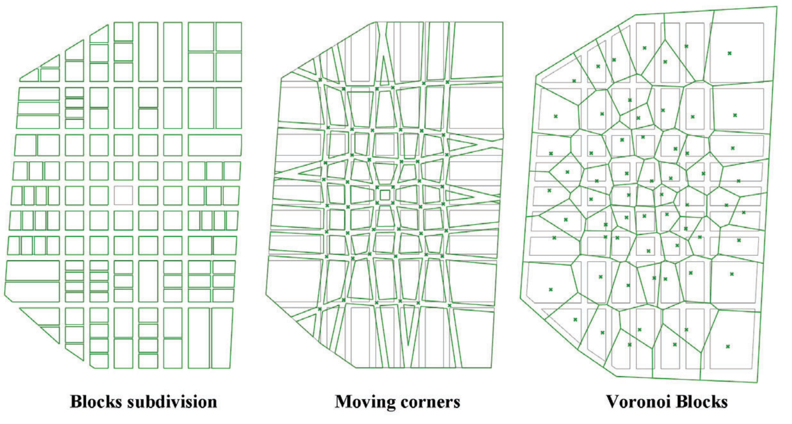


Figure 5. Case 2's approaches for generating the fabrics' settings.

Blocks subdivision consisted of subdividing the blocks by creating new in-between street and block configurations, aiming to verify the outcomes of softening the original grid alignment. In turn, the moving corners approach consisted of evaluating the effects of moving the blocks‘ corners while keeping the streets' widths, generating non-orthogonal grids. The Voronoi blocks approach consisted of extracting the original blocks'centroids to generate a Voronoi diagram with them. Thus, the idea was to explore moving these central points and evaluating different Voronoi shaped fabrics, defined according to the movement of original blocks centroids.

Moreover, the first case study confirmed our perception of an existing trade-off between transit accessibility and infrastructure cost. We observed that as the Physical Proximity index to the central block increased, the streets' total area also increased. Thus, in this second case, we addressed implementing a multicriteria optimization framework (Wallacei) to deal with trade-offs between Transit accessibility (Physical Proximity Index) and competing metrics such as infrastructure cost (total area of streets).

6. RESULTS

Case study 1 optimizations led, in the best case, to a PPI average increase of 0.07 (approach 2, Opossum RBFOpt test) compared to initial model conditions. If we consider that each 0.01 PPI value means 12 m of walking and that an inhabitant of a neighborhood goes back and forth once a day to the station, a 0.07 optimized value means 168 m less of daily walking per person, equivalent to 2.1 minutes (considering just home-station-home commuting) of daily walk. This value may also mean shorter distances to other neighborhood amenities, and therefore, greater overall walkability.

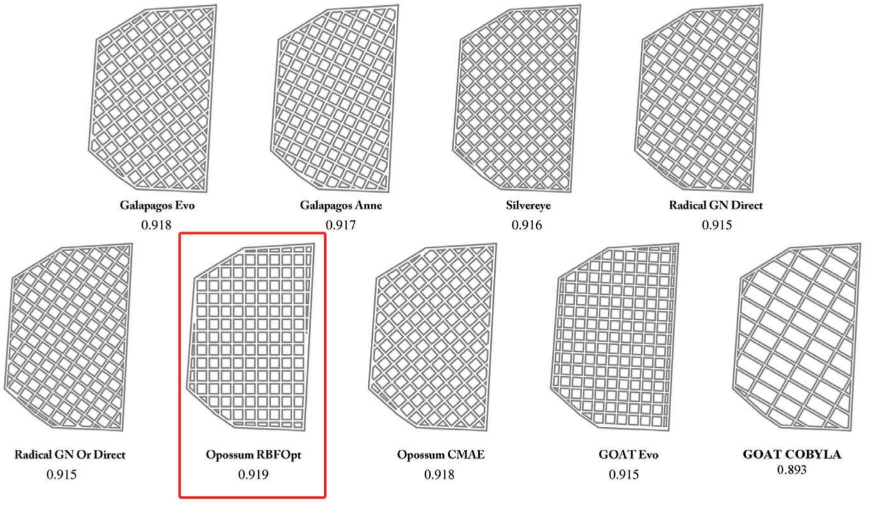


Figure 6. Results of case 1 approach 1. The better solution found is highlighted.

Case study 1 led to several key findings (Figures 6, 7, and 8). First, the RBFOpt algorithm provided the best solution vs. time relation when considering only single-criteria tools, suggesting that it performs better than others in problems of this nature. COBYLA (Goat) solutions were significantly worst in both approaches, which can be explained by the algorithm's successive linear approximation approach, which does not work well given the problem formulation. Such a result is a caution against using certain algorithm types like a black box solver without considering the problem type. Finally, approach 2 solutions generally performed better in terms of PPI than approach 1 solutions, suggesting that increasing geometric flexibility beyond a rectilinear grid provided room for physical proximity improvement.

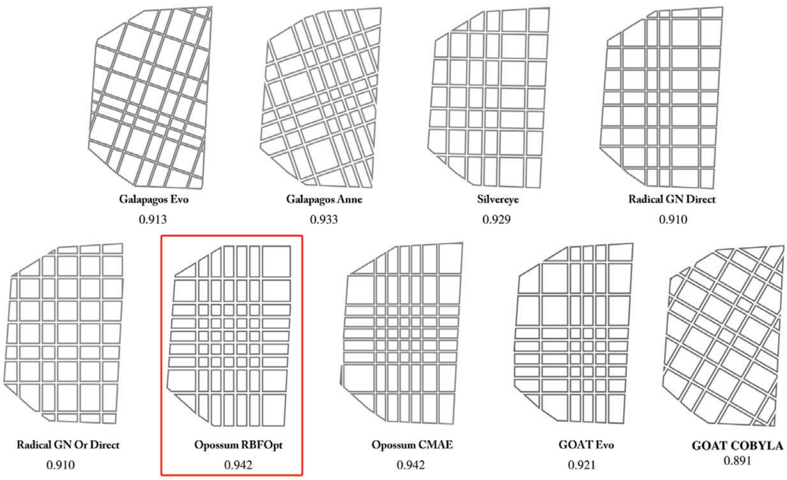


Figure 7. Results of case 1 approach 2. The better solution found is highlighted.

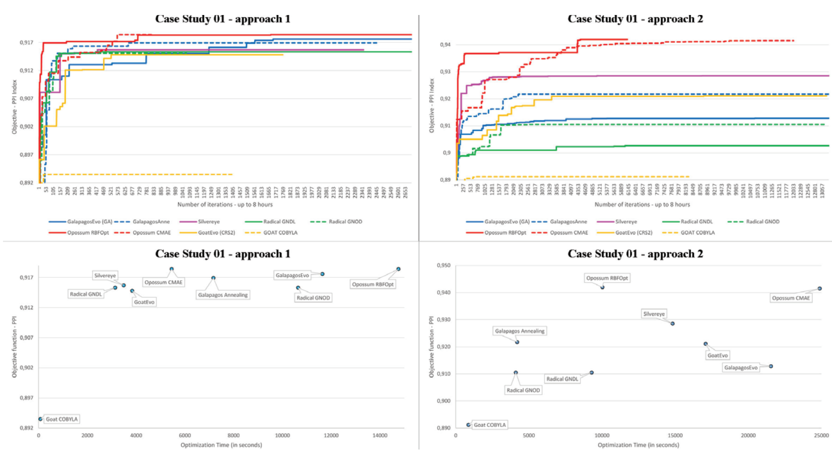


Figure 8. Best solutions through time graphs for both case 1's approaches.

Case 2, in turn, provided us with the following findings (Figure 9). All three case 2 approaches provided better solutions than the original input in terms of PPI (case 1 best solution). As such, the optimization helped to identify that more flexible and complex grids in terms of shape and dimensions tend to deliver greater TA than rectangular and uniform-oriented grids. In addition, the adoption of different block patterns can lead to solutions more directed at TA or infrastructure cost, confirming the trade-off. Overall, the use of different generative approaches allowed for exploring a wide range of solutions, while multicriteria optimization helped in identifying designs that balance transit accessibility and infrastructure cost. The Voronoi approach solutions tend to yield fabrics with less streets' area (lower infrastructure cost), and moving corners solutions returned highest Physical Proximity Indexes.

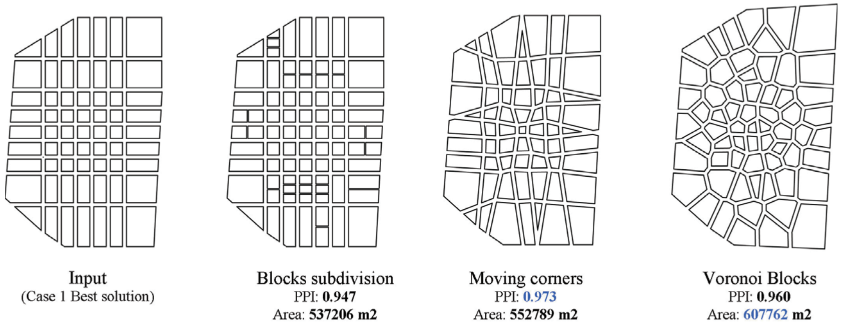


Figure 9. Case 2 results. Different approaches tend to yield different fitness functions.

7. DISCUSSION AND FINAL REMARKS

Optimization provided meaningfully better solutions than the input design in both case studies, allowing us to explore a wide range of solutions according to performance metrics. Besides, this work also investigated different CO tools' performance, bringing up some advantages and drawbacks. Although these results are not enough to definitively assert which tools are most suitable for urban fabrics design, they suggest that the RBFOpt algorithm might perform better in problems structured in this way, while COBYLA might perform worse.

At the same time, we recognize these experiments have some limitations due to urban design's complexity, multiple viewpoints, and stakeholders since this research simplifies urban design aspects into several significant quantitative objectives. Optimization here is thus explored as a tool for discovering potentially improved solutions or even directions for further modification, rather than as a deterministic approach for selecting a single, perfect design at this stage of the process.

In future works, we intend to add more complexity to the model by considering other parameters, like the location of public amenities and housing, and by adding grammatical rules for topological variation, which would significantly increase the universe of possible solutions. On the other hand, this experiment provided a solid basis for future work with its extensive assessment of nine different optimization approaches. Further developments will require careful analysis and interpretation of the results since slightly different fitness values may significantly impact people's lives, given the larger design scale.

ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES), Finance Code 001 and by the Stuckeman Center for Design Computing (SCDC), Penn State University, USA.

References

Brown, N.C., Jusiega, V. and Mueller, C.T.: 2020, Implementing data-driven parametric building design with a flexible toolbox, *Automation in Construction*, **118**, 103252.

Calthorpe, P.: 1993, *The next American metropolis: Ecology, community and the American dream*, Princeton Architectural Press, New York.

Cichoka, J., Migaslslka, A., Browne, W. and Rodriguez, E.: 2017, Silvereye– the implementation of Particle Swarm Optimization algorithm in a design optimization tool, *Future Trajectories*.

H. Dittmar and G. Ohland (eds.): 2004, *The new transit town: Best practices in Transit-Oriented Development*, Island Press, Washington, DC.

Farr, D.: 2008, *Sustainable Urbanism: Urban Design With Nature*, John Willey and sons, Hoboken, NJ.

Flöry, S.: 2015, "Goat" . Available from <www.rechenraum.com/goat/download.html> (accessed 10 February 2019).

Lima, F.: 2017, *Metricas Urbanas: Sistema (para)métrico para análise e otimização de configurações urbanas*, Ph.D. Thesis, Universidade Federal do Rio de Janeiro.

Makki, M., Showkatbakhsh, M., Tabony, A. and Weinstock, M.: 2019, Evolutionary algorithms for generating urban morphology: Variations and multiple objectives, *International Journal of Architectural Computing*, **17**(1), 5-35.

Makki, M., Weinstock, M. and Showkatbajhsh, M.: 2020, "Wallacei" . Available from <www. wallacei.com> (accessed 16th June 2020).

Navarro-Mateu, D., Makki, M. and Cocho-Bermejo, A.: 2018, Urban-Tissue Optimization through Evolutionary Computation, *Mathematics*, **6**(10), 189.

Rutten, D.: 2011, "Grasshopper" . Available from <www.grasshopper3d.com> (accessed 10 February 2019).

Suzuki, H., Cervero, R. and Iuchi, K.: 2013, *Transforming Cities with Transit: Transit and Land-Use Integration for Sustainable Urban Development*, World Bank, Washington, DC.

Wortmann, T.: 2017, Opossum: Introducing and evaluating a model-based optimization tool for grasshopper, *Protocols, Flows and Glitches*, Hong Kong, 283-292.

Wortmann, T.: 2019, Genetic evolution vs. function approximation: Benchmarking algorithms for architectural design optimization, *Journal of Computational Design and Engineering*, **6**(3), 414-428.

Wortmann, T. and Nannicini, G. 2017, Introduction to Architectural Design Optimization, *in* A. Karakitsiou, A. Migdalas, S.T. Rassia and P.M. Pardalos (eds.), *City Networks: Collaboration and Planning for Health and Sustainability*, Springer International Publishing, Cham, 259-278.

Yang, Y., Samaranayake, S. and Dogan, T.: 2020, An Adaptive Workflow to Generate Street Network and Amenity Allocation for Walkable Neighborhood Design, *Proceedings of SimAUD 2020*, online.

DESIGNING CROWD SAFETY

Agent-Based Pedestrian Simulations in the Early, Collaborative Design Stages

NICK FÖRSTER[1], IVAN BRATOEV[2], JAKOB FELLNER[3],
GERHARD SCHUBERT[4] and FRANK PETZOLD[5]
[1,2,3,4,5]*Technical University of Munich*
[1,2,3,4,5]*{nick.foerster|ivan.bratoev|jakob.fellner|schubert|petzold}@tum.de*

Abstract. Contemporary agent-based pedestrian simulations offer great potential to evaluate architectural and urban design proposals in terms of medical risks, crowd safety, and visitor comfort. Nevertheless, due to their relative computational heaviness and complicated input-parameters, pedestrian simulations are not employed during the design process commonly. Simulation results significantly impact planning decisions, especially when they are already available in the early design phases. This paper analyzes the requirements of pedestrian simulations for early planning stages, such as seamless integration into iterative and collaborative design processes, interactivity, and appropriate visualization of results. For this purpose, we combine two existing projects: a high-accuracy pedestrian simulation and the CDP//Collaborative Design Platform. To adapt the simulation method to the requirements of early planning stages, we investigate interactions that blend intuitively with the design process and enable multiple users to interact simultaneously. We simplify simulations' input parameters to match the level of detail of the early design phases. The simulation model is adapted to facilitate continuous and spontaneous interactions. Furthermore, we develop visualization techniques to support initial design negotiations and present strategies for compensating computation time and giving constant feedback to a dynamic design process.

Keywords. Pedestrian Simulation; Agent-Based Simulation; Early Design Stages; Collaborative Design; Human Computer Interaction.

1. The Potential of Pedestrian Simulations in the Early Design Stages

During the medical crisis of 2020, the relevance of pedestrian flows for the management of public spaces and buildings have become evident. The need to adapt various existing areas and buildings to uncertain and dynamically changing conditions has drawn additional interest to computer simulations that predict crowd dynamics and congestion (accu:rate, 2020a). In a short time, public spaces, event spaces, and working environments have to be changed to fit new safety

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 729-738.

regulations. Moreover, in other planning contexts, the prognosis of pedestrian movement is essential to guarantee comfort (Asriana et al. 2016), security (Kretz 2007), and health (Aschwanden 2012).

Simulations reveal the most meaningful impact on the design in the early planning stages (Roetzel, 2014). Embedding knowledge from simulations in the planning process could enable designers to foster pedestrian comfort in conformity with other economic, ecological, and aesthetic goals. Furthermore, simulations anticipate problems, which can be solved with less effort in the early design stages than in later phases of planning and construction (Serginson et al. 2013). However, the early design stages imply a high level of uncertainty, which is reinforced by the involvement of various actors, like laypeople, planners, and professionals, and the relevance of heterogeneous design parameters (Wurzer et al. 2012). Complex planning problems have no single 'good' solution but can only be resolved by informed negotiation (Rittel and Webber 1973). Designers collaboratively iterate countless alternatives to evolve an acceptable solution. Since these negotiations are highly contingent, dynamic, and complex, the supply of relevant information can be crucial for a productive debate (Kunze et al. 2012).

Advanced behavioral agent-based pedestrian simulations are seldom used in the early design stages (Asriana and Indraprastha 2016). Commonly they work as stand-alone desktop applications with user input and output unfit to meet the described dynamic conditions. While only a relatively small amount of research concerning agent-based simulations in early planning phases exists (e.g., Aschwanden 2012, Asriana and Indraprastha 2016), this topic is well explored in the context of energy and climate simulations. The research covers the availability of input parameters (Roetzel 2014), integration of tools into design interactions (Attia et al. 2012), and the presentation of relevant results (Petersen and Sendsen 2010). For this reason, these tools can serve as a reference for the development of interactions and visualization techniques regarding pedestrian simulations.

2. Project Setup

In this research project, we embed highly accurate agent-based pedestrian simulations in the early design stages. To achieve this goal, we link the existing simulation tool *crowd:it* (accurate 2020a) with the project CDP/Collaborative Design Platform which was developed during the last 10 years at the Technical University of Munich (Schubert 2020).

2.1. CROWD:IT SIMULATION METHOD

The assessed simulation tool *crowd:it* was developed as a spinoff in the research context. On the one hand, this method builds upon the theoretical work of Angelika Kneidl on pedestrian locomotion and navigation (Kneidl 2013). On the other hand, it is based on the *Optimal Steps Model* model by Michael Seitz and Prof. Gerda Köster (Seitz 2016) (accu:rate 2020b). In combination, these approaches enable indiscrete, microscopic movement, including behavioral and biomechanical aspects (Seitz and Köster 2012) as well as advanced wayfinding (Kneidl al. 2012). Thus, they give insight into local crowd dynamics such as cueing or stop-and-go-waves (Kneidl 2013). On the downside, this high resolution of results is computation-intensive and requires a relatively high literacy for preparing and evaluating the simulation. At this point *crowd:it* is mainly employed as a pc application for high-fidelity prognoses of pedestrian behavior in late planning phases.

2.2. CDP / COLLABORATIVE DESIGN PLATFORM

Conventional simulation interfaces (mouse, keyboard, screen) do not match the prerequisites of cooperative design situations (Kunze et al. 2012). Therefore, the project builds upon a seamlessly connected hard- and software solution (Schubert 2014). We suggest a hybrid physical-digital interface to incorporate the simulation in a haptic design model (see figure 1). This interface consists of a horizontal touch-sensitive screen serving also as a table. Planning contexts are imported from OpenStreetMap (Petzold et al. 2015). Physical objects (e.g., styrofoam blocks) can be placed on the table and serve as haptic input. A 3D-scanner recognizes these elements and places them in the virtual planning context. Users interact with the table by cutting, deforming, and moving these physical objects as well as via simple touch gestures (Schubert 2014).

Figure 1. CDP//Collaborative Design Platform - a hybrid digital-physical interface.

3. Prototype development

Early design stages involve the iteration of various design alternatives. Multiple qualitative and quantitative criteria are juxtaposed in open-ended discussions.

Users interact frequently and simultaneously with the design to understand the impact of adaptations on relevant planning parameters. Therefore, design tools have to provide meaningful and immediate feedback. Our prototype aims to support this erratic and dynamic process without disrupting the design flow. Contrasting to conventional PC simulations, we recognize the following criteria:

- **Integration:** The tool must integrate seamlessly into the planning process. It ought to facilitate intuitive geometric modifications. Furthermore, simulation results have to be relatable to the current design. By this, simulation output becomes relevant in the discussion.
- **Interactivity:** The prototype must foster a simultaneous and non-hierarchical interaction and presentation of results. Interfaces must be accessible for all collaborators to support an open and productive discussion. Furthermore, tools must facilitate continuous interaction instead of interrupting the design process with passive calculation phases.
- **Intuivity:** User interactions and the presented results must be comprehensible for non-experts. User-input ought to be effortless and no obstacle in the design flow. The shown information and visualization methods must be chosen carefully to match the conditions of early design discussions.
- **Synchronicity:** To inform dynamic interactions, the simulation has to react directly to user input. A significantly delayed presentation of results disrupts the discussion. Thus, initial feedback must be provided responsively.

3.1. USER INTERACTION

To achieve these goals, we adapt simulation inputs to the described table setup. Collaborators gather around the table and have equal access to the input model. Instead of importing the contextual geometry from a .dxf file, the context is loaded from OpenStreetMap and can be modified during the negotiation process. The interaction with the simulation must be easily understandable, effortless, and synchronous with the design process. To achieve this goal, we elaborate on simplified, intuitive, and continuous interactions.

3.1.1. Reduction to Benchmark-Scenarios

The parameters for sophisticated simulation settings are unavailable in the early design stages or are highly insecure. Thus, replacing the intricate contextual setup of a simulation with predefined ‘benchmark-scenarios’ is a strategy derived from energy evaluation tools in the early design phases (Roetzel 2014, Attia et al. 2012). Hence, we assure that the input does not exceed the level of detail of the early planning stages. Instead of delivering absolute numbers (like evacuation time), the simulation should evaluate crowd-dynamics qualitatively regarding key scenarios. Therefore, the extensive settings are reduced to three cases: *Entrance, Exit, and Stay.* Through these scenarios, the simulation addresses different aspects like efficiency, pedestrian comfort, and safe evacuation. Simulation settings like the setup of agents’ checkpoints and targets are defined by presets depending on the scenarios. Thus, we bypass a time-intensive setup.

3.1.2. Intuitive Interaction with Simulation Objects

Physical objects on the table serve as a haptic interface. They represent simulation objects such as agent-sources, obstacles, and targets. By modifying these elements, users interact with the design and the simulation simultaneously. Each element's color defines its meaning in the design context (see figure 4): Red objects represent entrances and exits. Yellow blocks stand for minor attractions like food stands, blue ones for major attractions such as a festival stage. Simple obstacles are embodied by grey blocks or can be drawn as polylines on the table using hand gestures. An element's size defines its relative importance - the number of spawning or attracted agents. The simulation interprets these objects depending on the selected scenario. During an (emergency) *Exit,* all agents spawn in attractions, from which they move towards the entrance objects. During a *Stay* scenario, entrances serve as both the agents' sources and their final targets, whilst attractions signify intermediary checkpoints.

3.1.3. Continuous Interaction

Classical pedestrian simulations do not facilitate user interactions during the simulation process. Even on a highly performant PC, this simulation process endures from several minutes to hours for large-scale simulations. However, in a dynamic design discussion, the calculations are likely to be interrupted by frequent and unanticipated interactions. An adaptation in the scenario's geometry requires a restart of the simulation: agents are removed and reset to their origin. Therefore, we propose two measures to compensate for this break in the user interaction: continuous simulation and seamless blending.

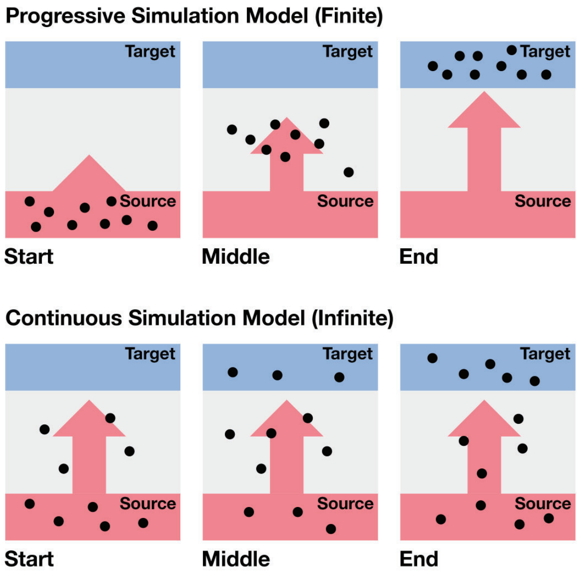


Figure 2. Progressive vs. continuous model.

Continuous Simulation: Classical agent-based simulations spawn a limited amount of agents and terminate when the last agent has reached its ultimate destination (see figure 2). Therefore, the simulation time and the total amount of agents are finite. Thus, users have to wait until agents spread over the simulated area to estimate crowd dynamics far from the agents' sources. Until the impact of a design adaptation becomes visible, agents have to reach this part of the simulation area. To reduce this delay, we propose a continuous simulation model. Agents are spawning and exiting the simulated area infinitely. After a restart, agents are partly generated on the way to their targets. By this, we achieve an instantaneous and constant distribution of agents.

Seamless Blending: The disappearing and respawning of all agents at the start of a simulation represents a problematic break. Therefore, we suggest 'blending' the new simulation seamlessly into the old one by preserving the agents' positions and current targets if possible. Only significant modifications (e.g., removing an entrance) require updating the concerned agents' status. By this, agents generally persist after interactions and even keep moving in the same direction. The initial calculation time of started simulations can be compensated by blending them visually with the terminated one. This method may compromise simulation results initially since the new simulation parameters would not have led to this exact constellation of agents. However, due to the continuous simulation model, this inaccuracy is leveled out while the simulation is proceeding further.

3.2. VISUALIZATION

For a meaningful integration of simulations in planning discussions, results must be intuitively relatable to the design. Being displayed on the table, the simulation augments the design model with an additional information layer. Thereby, the information is well visible for all attendees. To inform tentative design actions, we elaborate on the ad hoc display of adequate simulation results.

3.2.1. Heat Cloud

Differentiated heatmaps and statistical graphs represent simulation results accurately but are hard to interpret for laypersons and are often inappropriate to the level of detail of the early design stages (Attia et al. 2012). Instead of precise numbers (like absolute evacuation time), early and contingent design iterations benefit from 'ballpark figures' to evaluate initial alternatives (Roetzel 2014). Relevant information with respect to our key scenarios *Entrance, Exit, and Stay* is displayed: Problematic densifications have to be highlighted to indicate bottlenecks and overcrowded facilities. Pedestrian comfort and personal distance are also relevant in non-emergency scenarios. Furthermore, the realistic simulation of local crowd dynamics is an advantage of accurate agent-based simulation tools. This simulation output should be presented since it can provide valuable hints about congestion development.

Typical representations for pedestrian simulations are the animation of agents, agents' paths, and heatmaps (see figure 3). The animation of agents directly renders the agents' movements in the simulated environment. This method illustrates dynamic crowd movements clearly. However, it does not display pedestrian densities comprehensibly. Agents‘ paths reveal patterns of crowd movement. Nevertheless, this method does not show if densified paths signify congestions or a consecutive passage. Heatmaps offer great potential for evaluating designs since they highlight problematic areas and differentiate congestion levels. Several types of information can be depicted in heatmaps, such as occupancy, significant congestion, or ’frustration‘ (Kretz 2007). The proposed display methods cover relevant aspects of pedestrian simulations. Nevertheless, switching and meticulously comparing these representations in discussions is effortful and confusing. Therefore, we aim to combine these techniques’ advantages in a single visualization method - an indiscrete *Heat Cloud*.

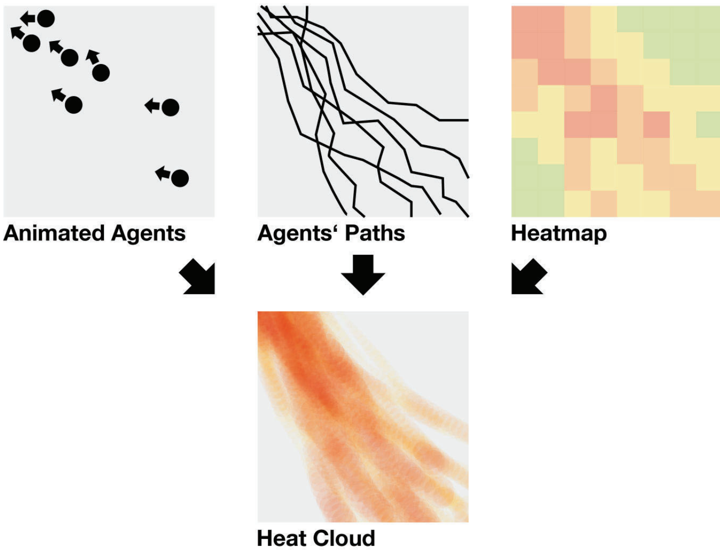


Figure 3. Synthesis of different visualization methods.

As an indicator, we revisit the principle *Level of Service*, derived originally from traffic planning (Oeding 1963, Fruin 1970). This concept distinguishes five *Levels of Service* defined by the available area per agent in relation to their speed - from a free flow of pedestrians to densification to problematic congestion (Bitzer 2010). This principle correlates pedestrian density, comfort, and velocity in ’fundamental diagrams’ (Holl 2016). The agents’ *Level of Service* is evaluated in each simulation step by calculating the average distance to its closest three agents. If the resulting value signifies a problematic density, the agent’s location is added to the *Heat Cloud*. Thus, this map stores one point for every congestion event. The points’ size and hue represent the specific *Level of Service*. By this, it is possible to differentiate between casual and grave congestions. Tracking agents’ congestion levels during several simulation steps also reveals their movement patterns, and the dynamics of congested spots become distinguishable (see figure

4). Since the *Heat Cloud* points are linked to specific agents and localized in the simulation space, it is possible to detect all points affected by a design interaction. By removing and updating parts of the cloud selectively, most of it can stay intact after user interactions.

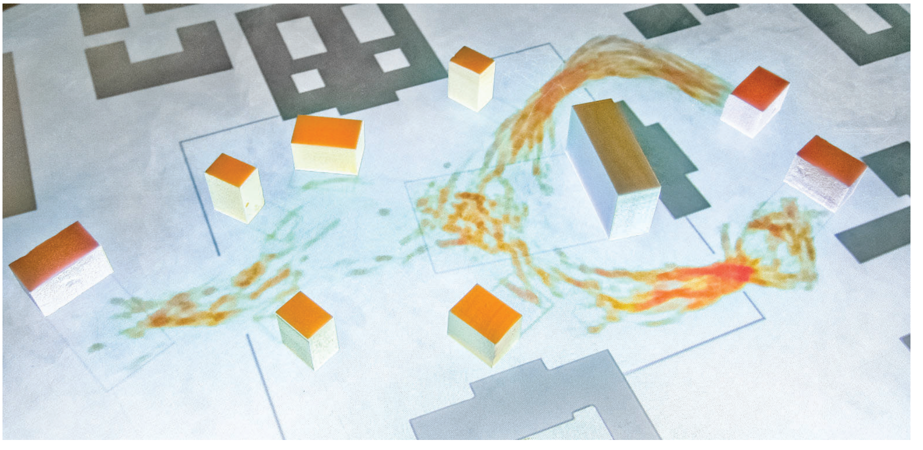


Figure 4. Blocks of different colors and sizes as input, and Heat Cloud visualization.

3.2.2. Responsive, Preliminary Results

Design interactions in the early design stages can be experimental and erratic. Instantaneous feedback is essential to inform design modifications. Thus, results can serve as hints, which support iterative problem solving (Petersen and Svendsen 2010). Since large scale agent-based simulations are computation-intensive, final results are not available instantly. Intermediary simulation output (the agents' movement steps) can be displayed immediately. The *Heat Cloud* grows while the calculation proceeds. Nevertheless, this is not sufficient to give dynamic feedback to design discussions. Therefore, we introduce two types of provisory results (see figure 5). The agents' targets are available at the beginning of the simulation. Afterward, a static navigation field is calculated before the first step of the agents' movement. Based on this data, rough navigation graphs are generated for an initial prognosis of the agents' movement. From these hypothetical trajectories, preliminary points in the *Heat Cloud* are added. The first approximation based on the agents' targets is replaced as soon as navigation fields are available. Afterward, this preview is updated with the final results as soon as they become available. Thus, the simulation immediately responds to interactions with a first preview and approximates final results subsequently.

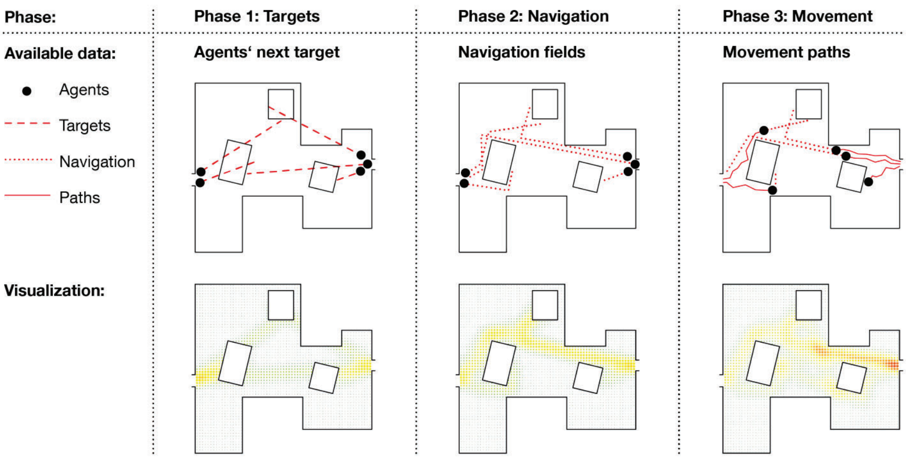


Figure 5. Responsive visualization employing preliminary results.

4. Conclusion

We have presented an approach to introduce advanced pedestrian simulations in the early design stages. By this, designers can optimize pedestrian flows mutually with other relevant planning parameters. Compared to contracting an external enterprise for a comfort and safety analysis, this integrated method is extremely time-efficient. Since the creation and exchange of data-models, the simulation, the preparation of results, and the subsequent evaluation take up to several days, our method represents a significant optimization.

To achieve this integrated solution, we have shown how to embed pedestrian simulation in a collaborative, interactive environment. Also, we have elaborated on user input suitable to the conditions of the early design stages. A haptic, non-hierarchical user interface enables dynamic and simultaneous interactions. The simplification of input-parameters adjusts the simulation to the level of detail of early-stage negotiations. Furthermore, the simulation is adapted to allow the continuous adaptation of the input model. Thus, we embed the user-input seamlessly in the negotiation process. We have presented visualization methods that effectively support the design process by highlighting problematic congestions and displaying crowd dynamics. We achieve responsive feedback by amortizing computation time with the usage of preliminary results. The impact of design adaptations is instantly presented and influences the discussion reciprocally.

Acknowledgements: This project was funded by the research initiative “Zukunft Bau” of the German Federal Office for Building and Regional Planning.

References

accu:rate, I.F.C.S.: 2020a, “Safe operation for visitors and employees?” . Available from <https://www.accu-rate.de/en/social-distancing-en/> (accessed 1st November 2020).
accu:rate, I.F.C.S.: 2020b, “A digital world needs digital tools” . Available from <https://www

.accu-rate.de/en/software-crowd-it-en/> (accessed 13th October 2020).
Aschwanden, G.: 2012, Agent-Based Social Pedestrian Simulation for the Validation of Urban Planning Recommendations, *Proceedings of SIGRADI 2012*, Fortaleza, 332-336.
Asriana, N. and Indraprastha, A.: 2016, Making Sese of Agent-Based Simulation: Developing design strategy for pedestrian-centric urban space, *Proceedings of eCaade 2016*, Hong Cong, 342-352.
Attia, S., Gratia, E., De Herde, A. and Hensen, J.L.M.: 2012, Simulation-based decision support tool for early stages of zero-energy building design, *Energy and Buildings*, **49**, 2-15.
Bitzer, T.F.: 2010, *Mikroskopische Modellierung und Simulation des Fußgängerverkehrs*, Ph.D. Thesis, University of Stuttgart.
Fruin, J.J.: 1970, *Designing for Pedestrians: A Level of Service Concept*, Ph.D. Thesis, University of Brooklyn.
Holl, S.: 2016, *Methoden für die Bemessung der Leistungsfähigkeit multidirektional genutzter Fußverkehrsanlagen*, Forschungszentrum Jülich GmbH, Jülich.
Kneidl, A.: 2013, *Methoden zur Abbildung menschlichen Navigationsverhaltens bei der Modellierung von Fußgängerströmen*, Ph.D. Thesis, Technical University of Munich.
Kneidl, A., Borrmann, A. and Hartmann, D.: 2012, Using a Multi-Scale Model for Simulating Pedestrian Behavior, *PED 2012 - Pedestrian and Evacuation Dynamics*, Zurich.
Kretz, T.: 2007, *Pedestran Traffic: Simulation and Experiments*, Ph.D. Thesis, University of Duisburg-Essen.
Kunze, A., Burkhard, R., Gebhardt, S. and Tuncer, B. 2012, Visualization and Decision Support Tools in Urban Planning, *in* S.M. Arisona, G. Aschwanden, J. Halatsch and P. Wonka (eds.), *Digital Urban Modeling and Simulation*, Springer, Berlin Heidelberg, 279-298.
Oeding, D.: 1963, *Verkehrsbelastung und Dimensionierung von Gehwegen und anderen Anlagen des Fußgängerverkehrs*, German Ministry for Traffic, Bonn.
Petersen, S. and Svendsen, S.: 2010, Method and simulation program informed decisions in the early stages of building design, *Energy and Buildings*, **42**, 1113-1119.
Petzold, F., Schubert, G., Mühlhaus, M. and Seifert, N.: 2015, GIS vs. BIM – semantische Modelle in frühen Planungs- und Entwurfsphasen, *Geoinformations-systeme 2015*, Munich, 35-46.
Rittel, H.W.J. and Webber, M.M.: 173, Dilemmas in a General Theory of Planning, *Policy Sciences*, **4**, 155-169.
Roetzel, A.: 2014, Occupant behaviour simulation for cellular offices in early design stages: Architectural and modelling considerations, *Buidling Simulation*, **8**, 211-224.
Schubert, G.J.: 2014, *Interaktionsformen für das digitale Entwerfen*, Ph.D. Thesis, Technical University of Munich.
Seitz, S.M.: 2016, *Simulating pedestrian dynamics: Towards natural locomotion and psychological decision making*, Ph.D. Thesis, Technical University of Munich.
Seitz, M.J. and Köster, G.: 2012, Natural discretization of pedestrian movement in continuous space, *Physical Review*, **86**, 046108-1 - 046108-8.
Serginson, M., Mokhtar, G. and Kelly, G.: 2013, A Theoretical Comparison of Traditional and Integrated Project Delivery Design Processes on International BIM Competitions, *International Journal of 3-D Information Modeling*, **2**, 52-64.
Wurzer, G., Popov, N. and Lorenz, W.E.: 2013, Meeting Simulation Needs of Early-Stage Design Through Agent-Based Simulation, *Proceedings of eCaade 2013*, 613-620.

A LAYERED APPROACH FOR THE DATA-DRIVEN DESIGN OF SMART CITIES

VICTOR CALIXTO[1], ROBSON CANUTO[2],
MARCELA NORONHA[3], AIDA AFROOZ[4], NING GU[5] and
GABRIELA CELANI[6]
[1,4,5]*University of South Australia*
[1]*victor.calixto@mymail.unisa.edu.au*
[4]*{aida.eslamiafrooz}@unisa.edu.au*
[2,3,6]*University of Campinas*
[2]*robsoncanuto.arq@gmail.com* [3]*m024502@dac.unicamp.br*
[6]*celani@unicamp.br*

Abstract. Current approaches to smart cities have focused on implementing technologies to harvest and analyse data through sensors and artificial intelligence to improve urban performance from the top-down. However, cities are complex systems of interconnected layers that change at different speeds. More persistent layers, like networks and occupation, must have smartness embedded in them through smarter design processes. In recent years, there has been an increase in digital tools for urban design, applying computational design methods and data analytics strategies, enabling collaborative and evidence-based approaches that support sustainable urban design. A critical evaluation of their potential to inform design is necessary to aid practitioners to choose and adopt these novel strategies and tools in practice. This paper presents a critical review of selected data-driven design cloud platforms, focusing on data-driven urban design approaches that can enable the use of ICTs to steer cities into a smarter future from the bottom-up.

Keywords. Smart Cities; Data-Driven Urban Design; Computational Design.

1. Introduction

Smart cities have been defined as innovative approaches to increase the efficiency of cities. There was a general assumption that developments in Information and Communication Technologies (ICTs) would enable cities to become more equitable and sustainable (M. Batty et al. 2012). This is what Grassl and Groß's (2019, p. 25) call the "holistic smart city" discourse. Nonetheless, current practical approaches to smart cities are better identified in their definition of *"connected smart cities"*, that focus on implementing technologies to harvest and analyse data through sensors and artificial intelligence to improve urban performance, in hopes that urban development will follow.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 739-748.

Hitherto, these improvements do not correlate with higher equitability and sustainability in a city, unless these questions were already being addressed before it began adopting smart technologies (Zheng et al. 2020). Thus, "holistic smart cities" are unlikely to be achieved through technological development alone, as cities behave as complex adaptive systems (Michael Batty, Bettencourt, and Kirley 2019). Over relying on private companies to propose closed technological solutions for various urban problems from the top-down, without accounting for how people's behaviour and the agency is being affected by the existing built environment and by all the devices, apps and platforms available to them, e.g. smartphones, social media or routing tools, can lead to unforeseen bottom-up social, economic and environmental consequences (Zvolska et al. 2019). There are layers of interconnected infrastructure in a city that change and are assimilated at different speeds (van Schaick and Klaasen 2011). ICTs for smart cities are but one of these layers, developing ever-evolving devices and software to harvest and analyse data in the attempt to fix urban problems from the top-down (Bettencourt 2014).

There are other infrastructural layers, e.g. the substratum with its natural resources, and the built environment, which, despite changing at slower paces, also have their own potential to embed smartness through data-informed urban design, to enable the "holistic smart city" concept to come to fruition (Grassl and Groß, 2019; Kvan 2020). This time-dependent, design-driven approach to smart cities has been understudied in existing frameworks (Yigitcanlar et al. 2018). Nonetheless, in recent years, there has been an increase in digital tools for urban design, applying computational design methods and data analytics strategies, enabling collaborative and evidence-based approaches that support sustainable urban design in early stages of the design process.

This paper aims to contribute to bridging the gap between urban design and smart city ICTs, critically reviewing urban design data-driven tools based on key evaluation criteria of interface development, data-driven flow, early stages of the design process as well as its impact on a layered understanding of the city and its alignment with an integrated and holistic view of the sustainable smart city approach. A conceptual framework for approaching smart cities as layered, time-dependent entities was developed, focusing on a data-driven urban design approach is essential to enable the use of ICTs in a non-disruptive manner, to steer cities into a smarter future from the bottom-up.

2. Context

Cities as Complex Adaptive Systems (CAS) has become a recurrent topic in the fields of urban planning and design, characterised by emergent, non-linear, behaviours that cannot be explained as the sum of their parts and should be approached as complex systems, grounded in complexity theory (Holland 2014). For Marshall (2009), urban planning for cities as CAS should apply small scale design interventions to trigger self-organisation, allowing them to evolve as ecosystems, from their internal interactions. This creates a state of indeterminacy, in which planning and design outcomes are unpredictable (Verebes 2013). Hence, urban planning and design should rely on the formulation of possible future scenarios through the observation of existing phenomena and extrapolation of existing data. Thus, generative methods can be used to create prospective scenarios to inform design decisions and improve urban development (Dovey and Pafka 2016).

The concept of smart cities in its inception was strongly related to technology-driven sustainable development. However, current practice demonstrates a great difficulty in bringing those intentions to fruition. By overfocusing on technology at the expense of the multidimensional aspects related to smart cities, e.g. community, policy, ecology and design, holistic smart cities remain out of reach (Yigitcanlar et al. 2016; Zheng et al. 2020).

We used the framework proposed by Yigitcanlar et al. (2018) as a starting point to develop a layered time-dependent framework for holistic smart cities that takes into account the concept of complex adaptive systems, in order to embed smartness into different urban systems from the bottom-up, so that technology can contribute to urban sustainability.

The framework development is based on the method proposed by Walloth (2016) to approach cities as Emergent Nested Systems (ENS). ENS are complex enclosing systems that change at a slower pace than the systems they enclose. Changes within the enclosed subsystems trigger emergence and self-organisation in the enclosing system. Therefore, predicting what individual interferences in the subsystems can trigger in the whole is a challenging task. Understanding the paces and rules with which subsystems change and how they affect emergence in the enclosing system can be a way to plan localised interventions for influencing the whole (Walloth 2016).

In the context of smart cities, by taking a layered approach to an urban system, natural systems can be understood as an enclosing system for networks, that in turn are enclosing systems for occupation. ICTs are systems enclosed by all of them, and change at the fastest pace. While they affect the enclosing systems, they do so at a slow pace. Much slower than the time they take to change themselves.

The Dutch Layers Approach (van Schaick and Klaasen, 2011) divides the physical components of an urban system into Occupation, Networks, and Substratum, according to the time they take to incur significant change. Occupation changes significantly over a generation, networks every two generations, and substratum takes over 100 years to change. For this framework to be better adapted to smart cities, other layers, understood herein as nested systems, should be added, such as those discussed by Yigitcanlar et al. (2018), i.e. community, policy and technology. Most of these layers behave as nested systems, with one system influencing the other at different temporal steps. Nonetheless, while information and communication technologies (ICT's) are influenced by them, the interaction takes a longer time to go in the other direction. In the 20th century cars completely changed urban networks and occupation patterns, but the same has still not been observed for ICT's. These technologies must become embedded in urban networks and occupation to achieve *holistic smartness* by influencing community behaviours and policy. To achieve this, design processes and urban space production must change through data-driven, empirically-based, predictive and optimisation methods.

3. Methodology

To comprehend how ICT infrastructure is impacting current urban design practice, interacting within the three urban system layers defined by van Schaick and Klaasen (2011) as well as to understand the barriers that practitioners are facing to adopt these strategies into their design process, this paper reviewed four urban design cloud-based services that aim to deliver a data-driven platform for designers, collaborators, investors, and other stakeholders that seeks an evidence-based exploratory environment. A successful platform should provide a user-friendly environment, support the collaboration between clients and designers, and integrate available public and private data into the design process to shape design decisions. While those strategies represent novel design-decision tools, they need to be critically evaluated on their potential to impact and inform design.

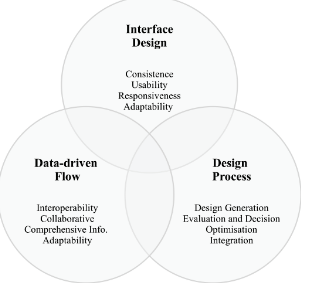


Figure 1. Diagram of relations between the three evaluation criteria.

The methodology was developed based on key evaluation criteria for interface development, data-driven flow and design process as shown in figure 1. For each key evaluation criteria, four sub-criteria were defined and, for each sub-criteria, four questions were established. These questions were formulated in order to obtain binary answers: yes or no. Each positive answer corresponds to a value of 2 or 2.5 points, without the need for computing any partial points. This means that only values 2 or 2.5 are assigned, see table 01. Subsequently, the scoring system was plotted in radar charts to assess the ability of the tool to support the design of smart territories.

According to Shneiderman et al. (2016), there are eight golden rules to measure the performance of an interface development: Consistency, Usability, Feedback, Cohesion (Design dialogues to yield closure), Error Prevention, Action Reversal, User Control, and Reduction of Short Term Memory. In this study to make the analysis more concise, we clustered the concepts in groups as follows; Consistency, Usability (Usability and User Control), Responsiveness (Feedback), Adaptability (Cohesion, Reduction of Short Term Memory, Error Prevention, and Action Reversal). The questions essentially sought to assess, respectively, whether the design of the interface seeks consistency, whether it seeks universal usability and keeps users under control, whether it offers informative feedback, and whether it designs dialogues to close errors and allow easy reversal of actions.

The data-driven flow criteria aim to assess the interoperability and collaborative potential of the design tool, as well as its availability of comprehensive and general information. The stakeholders involved in this process are clients, investors, community, and designers. The interoperability verifies whether the design tool has a common data format, whether it allows exchange information, whether it is based on an open standard and whether it is compatible with others. The collaborative process measures specifically the ability of the design tool to support a collaborative workflow among stakeholders, and the capacity of users to work on the project in real-time, with feedback and crowdsourced inputs. Comprehensive information measures the information availability for community, clients, investors and designers. Ultimately, the general information sub-criterion seeks to evaluate whether the design tool addresses social, behavioural, environmental, perception and economic information.

The design process assessment considered the triad: design, evaluation and optimisation. It is understood that these three criteria are essential parts of the digital design process. However, possible integration with other digital tools has also been included as a criterion especially because it would make the design process more flexible. Regarding sub-criteria, the design generation was established to first assess the availability of geospatial data (such as satellite image, topographical maps, street network, urban block perimeters and plot subdivision) as an initial database for the design conception, and second to verify the generative capacity, parametric control, and flexibility of the tool to allow creative thinking. The design evaluation sub-criterion measured the ability of the tool to offer social and visual perception, environmental and economic performance analyses, as well as to make possible the design exploration of multiple alternatives to aid the decision-making process. The design optimisation checked whether the tool provides any type of optimisation, multi-objective optimisation or even one near-optimal solution according to predefined fitness criteria. Finally, the integration evaluated the capacity of the tool to exchange information with other Computer-Aided Design (CAD) tools, such as the ease to import, export projects, as well as the integration with other analysis tools.

3.1. SELECTION CRITERIA

The selection of design tools was based on three fundamental aspects, as follows: being a cloud-based tool; focusing on urban design for smart territories, allowing street network, plots, and building volumes to be modelled, and offering free trial versions. Based on these three criteria, six cloud-based tools were identified: *Scout*, *Delve*, *SpaceMaker*, *Giraffe*, *Archistar.ai*, and *Digital Blue Foam*. These tools were identified through social media such as LinkedIn, Twitter, and Facebook in which most of them have recently been launched.

It is also important to note that all developers were requested by email to offer a trial version of the design tool so that the authors could test and evaluate their features according to the pre-established criteria. The vast majority replied to the request, except for *Archistar.ai*. In addition, the developers of *Delve* responded that, currently, it is only offering a commercial version of the tool, and they expect to make trial versions available for academia in 2021. The other four cloud-based services named *SpaceMaker*, *Giraffe*, *Digital Blue Foam*, and *Scout* offered trial versions enabling this research.

Table 1. Evaluation Criteria (Interface, Data-Driven Flow, and Design Process).

INTERFACE DESIGN EVALUATION		**DATA DRIVEN-FLOW**		**DESIGN PROCESS EVALUATION**	
EVALUATION CRITERIA	**SCORE**	**EVALUATION CRITERIA**	**SCORE**	**EVALUATION CRITERIA**	**SCORE**
CONSISTENCY (Consistency)		**INTEROPERABILITY**		**DESIGN GENERATION** (Design Process: geospatial data, parametric control, generative capacity, flexibility and creative thinking)	
1- Is the terminology identical in prompts?	2.0	1 - Does the design tool have a common data format?	2.5	1- Does the design tool provide geospatial data?	2.0
2- Is the terminology identical in menus?	2.0	2 - Does the design tool exchange information?	2.5	2- Does the design tool enable parametric control of urban elements (street network, plots and buildings)?	2.0
3- Is the terminology identical in help screens?	2.0	3 - Is the design tool based on open standard?	2.5	3- Does the design tool allow generating design alternatives?	2.0
4- Are the colours, fonts and capitalisation consistent?	2.0	4 - Is the design tool compatible with others?	2.5	4- Does the design tool provide flexibility enough to generate and modify objects?	2.0
5- Are the exceptions comprehensible?	2.0	**COLLABORATIVE PROCESS**		5- Does the design tool promote creative thinking?	2.0
USABILITY (Usability and User Control)		1 - Does the design tool support collaborative workflow among stakeholders?	2.5	**DESIGN PERFORMANCE EVALUATION AND DECISION MAKING** (Design Process: social, visual perception, environmental, economic analysis and design exploration of multiples alternatives)	
1 - Is the interface designed to facilitate novice users?	2.0	2 - Does the design tool allow two or more users to work on the same project real-time?	2.5	1 - Does the design tool offer social analysis?	2.0
2 - Is the interface designed to attend the expectation of expert users?	2.0	3 - Does the design tool allow community feedback?	2.5	2 - Does the design tool enable visual perception analysis?	2.0
3 - Is the interface designed to assist users with disabilities?	2.0	4 - Does the design tool allow crowdsourced inputs?	2.5	3 - Does the design tool allow environmental analysis?	2.0
4 - Are there explanations on how to use them?	2.0	**COMPREHENSIVE INFORMATION**		4 - Does the design tool provide economic evaluation?	2.0
5 - Are there hotkeys for expert users?	2.0	1 – Is there comprehensive information for the community?	2.5	5 - Does the design tool offer design exploration of multiple alternatives?	2.0
RESPONSIVENESS (Feedback)		2 - Is there comprehensive information for clients?	2.5	**DESIGN OPTIMISATION** (Design Process: reasoning or solving problem)	
1 - Is there feedback for every user action?	2.5	3 - Is there comprehensive information for investors?	2.5	1 - Does the design tool offer any type of optimisation?	2.5
2 - Is there feedback in minor actions?	2.5	4 - Is there comprehensive information for designers?	2.5	2 - Does the design tool allow multi objective optimisation?	2.5
3 - Is there feedback in major actions?	2.5	**GENERAL INFORMATION**		3- Does the design tool provide more than one near-optimal solution?	2.5
4 - Is there visual feedback?	2.5	1 - Does the design tool address social information?	2.0	4- Does the design tool transparent regarding the method or mixed methods used in the optimisation, such as algorithms, and criteria.	2.5
ADAPTABILITY (Cohesion, Reduction of Short Term Memory, Error Prevention, and Action Reversal)		2 - Does the design tool deal with behaviour information?	2.0	**INTEGRATION** (Design Process: import, export and integration with other CAAD and analysis tools)	
1 - Does the interface offer an "undo" option?	2.0	3 - Does the tool gather environmental information?	2.0	1 - Is it possible to import projects?	2.0
2 - Does the interface record actions?	2.0	4 - Does the design tool address perception information?	2.0	2 - Is it possible to export projects?	2.0
3 - Does the interface allow you to input invalid types?	2.0	5 - Does the design tool address economic information	2.0	3 - Is there integration with other CAAD or Parametric Design tools?	2.0
4 - Does the interface provide ways of getting back to previous stages?	2.0			4 - Is there integration with other spatial analysis tools?	2.0
5 - Does the interface save the content?	2.0			5 - Is there integration with environmental analysis or CFD tools?	2.0

4. Results

4.1. SOUT

Scout **interface design** is defined by parameter sliders, analysis toggle buttons, and a 3D viewport visualisation of the intervention. The range of the parameters is predefined by the creator of the algorithm as well as the analysis toggle button. The terminology in the prompts are identical, and the colours, fonts and capitalisation are *consistent*. Because of the simplicity of the interface, there are no exceptions, menus or help screens. Regarding its *usability*, the interface is easy for novice users, however, it does not offer advanced customisation options or hotkeys for expert user neither does it offer support to assist any disabilities. The *responsiveness* of *Scout* is only related to its minor action feedback. The interface *adaptability* regards its ability to record actions, accept only valid inputs and save content.

Analysing the **data-driven flow** criteria, regarding its *interoperability*, *Scout* has a common file format to save the geometry (three.js) that could be read by other platforms or software, allowing the exchange of data. Also, the file type Three.js is based on an open standard. The *collaboration* is related only to its workflow among different stakeholders, lacking real-time collaboration for a specific project, community feedback or crowdsourced inputs. Regarding *Scout comprehensibility* of the information among the different stakeholders, it is clear and comprehensible among all stakeholders (community, clients, investors and designers). In the demo version, *Scout* manages social, environmental, perception and economic information.

Scout's **design process**, regarding its *design generation*, *Scout* supports parametric control of urban elements and allows design alternative generation. In terms of *performance evaluation and decision-making*, *Scout* supports analysis tools of social, perception, environmental, and performance and offers design exploration of multiple alternatives. *Scout* does not have embedded *optimisation* algorithms. Regarding its *integration* projects can be imported and it is integrated with Rhino3D-Grasshopper allowing other analytical tools to be used through the predefined algorithms. However, there are no ready-to-go functionalities to export projects.

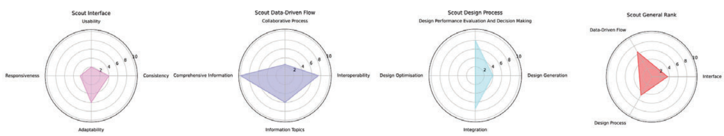


Figure 2. Scout Analysis.

4.2. DIGITAL BLUE FOAM

The *Digital Blue Foam* **interface design** is based on small icons, distributed around a circled toolbar, rather than on menus. The *terminology* is identical in the prompts and help screens. The visualisation of urban elements is schematic but *consistent*, clear and coloured. Regarding its *usability*, the generation of buildings is faster and automated, however, it is not possible to ensure that designers have systematic parametric control of building generation. *Digital Blue Foam* does not have advanced customisation options and hotkeys. Neither does it assist users with disabilities. The *responsiveness* relies on its visual feedback. Respective to its *adaptability*, it has an 'undo' option, it records actions, it is reversible for previous stages and saves the design content.

The first concept of **data-driven flow** criteria is *interoperability*. *Digital Blue Foam* is based on a common file format (three.js), allowing the exchange of data and is an open standard. Regarding its *collaboration*, workflow among different stakeholders is the only achieved sub-criteria. Nonetheless, all the criteria for *comprehension* of the information among the different stakeholders were reached.

Digital Blue Foam manages environmental and economic information in the demo version.

As for **design process** on *design generation*, *Digital Blue Foam* allows multiple design alternatives generation, supporting modification of objects and promoting creative thinking. Moreover, it allows to easily set up a mix of building functions (residential, commercial, office, leisure and education) through the Program Mixer toolbar. On *design optimisation and decision-making* it includes environmental, i.e. solar radiation and a wind rose and, and economic analyses, i.e. gross floor area (GFA). *Digital Blue Foam* does not have any *optimisation* algorithms. The *integration* in this tool meets all the set of sub-criteria. It is possible to import and export projects as well as exporting the design to other CAD tools through the SLT extension supporting posterior analysis.

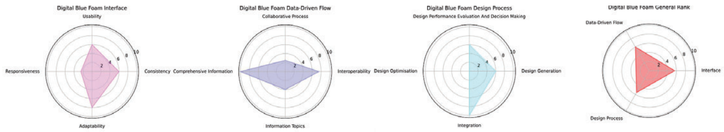


Figure 3. Digital Blue Foam Analysis.

4.3. GIRAFFE

Giraffe **interface design** is based on Mapbox which enables site search, exploration of surrounding areas and accessing geospatial data, e.g. existing street network, blocks, plots and buildings volumes. The interface *consistency* meets all criteria. Regarding its *usability*, it offers thorough explanations and is manageable for novice users. However, it lacks advanced customisation features or hotkeys. Regarding its *responsiveness*, *Giraffe* offers feedback for major actions and visual feedback. On *adaptability*. *Giraffe* records actions, does not allow inputting wrong parameters, provides ways to get back to previous stages and saves the design content.

On **data-driven flow** criteria, regarding its *interoperability*, it is based on three.js as well, which allows data exchange. Regarding its collaboration, workflow among different stakeholders in the only met sub-criteria. The comprehension of the information among the different stakeholders attends all criteria. *Giraffe* manages social, environmental, perception and economic data.

On **design process**, *design generation*, it meets all the defined criteria as well as those for *design performance evaluation and decision-making*. However, it does not include any *optimisation* algorithms in the native tool. Regarding its *integration*, *Giraffe* also attends all criteria.

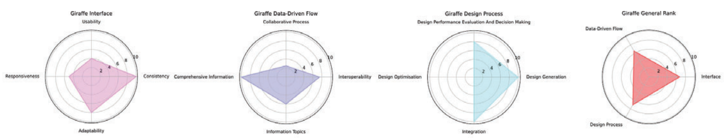


Figure 4. Giraffe Analysis.

4.4. SPACEMAKER

SpaceMaker **interface design** meets all the sub-criteria regarding its *consistency*, *responsiveness* and *adaptability*. As for its *usability*, it offers a set of tutorials on how to use the tool and is easy to understand even for beginners.

On **data-driven flow** criteria, regarding its *interoperability*, as the other tools, it is based on three.js, meeting data exchange and open standard. It also has a high level of *comprehension* among all involved stakeholders. *SpaceMaker* manages social, environmental, perception, and economic information. However, the only criterion met under *collaboration* was workflow among stakeholders.

On **design process**, regarding *design generation*, *SpaceMaker* meets all criteria. Under *Design Performance and Decision Making* the tool enables visual perception, environmental, and economic analyses and allows the exploration of multiple design alternatives. *SpaceMaker* was the only tool of those analysed that had *optimisation* algorithms embedded into its default platform. However, it does not allow multi-objective optimisation. Furthermore, it does not state what optimisation algorithm is being used, working as a black box for the users. Finally, in the demo version, projects cannot be imported. However, all the other sub-criteria are met for *integration*.

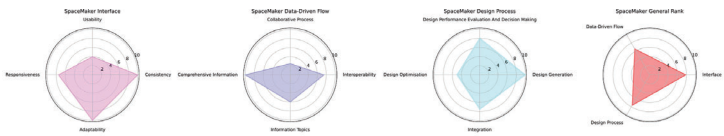


Figure 5. SpaceMaker Analysis.

5. Conclusion

This paper critically reviews urban design cloud-based and data-driven tools according to key evaluation criteria of interface development, data-driven flow and design process to understand how they can contribute to an integrated and holistic design of sustainable smart cities. In addition, the paper has introduced a conceptual framework for approaching smart cities as layered and time-dependent entities, with a focus on an urban design approach, to embed ICT in the occupation and networks layers. As can be seen, various cloud-based and data-driven urban design tools such as *Scout*, *Delve*, *SpaceMaker*, *Giraffe*, *Archistar.ai* and *Digital Blue Foam* have recently emerged as a direct impact of advances in generative design techniques and machine learning, a subset of artificial intelligence, that has contributed significantly to the automation and efficiency in the urban design process. These tools offer the ability to generate, evaluate, and optimise urban models from the early stages of design. They aid architects, planners and stakeholders to save resources, time and money, as well as to find optimal design solutions. Moreover, they promise to empower designers to design smart cities and neighbourhoods. Despite the potentialities of these new tools, a more holistic approach is still needed which should comprise social, environmental, and economic aspects, as well as behavioural and visual perception aspects of urban issues regarding the urban design interdisciplinary. Through this study, it has become clear that there has been a larger effort to develop novel tools instead of concentrating on improving their comprehensiveness. This will be crucial in further developments in order to make these tools more widely applied for urban design education and practice. Only then will this type of technology be able to achieve an impact on the more persistent urban layers and imprint a long-lasting, socially improving effect and steer cities into a smarter future from the bottom-up. However, this study is limited to the evaluation of demo versions of these tools, since the access to the full versions is still limited in most cases. The demo versions contain most of the features of full versions, but in most cases, there are resources only offered in the full versions. For instance, Giraffe offers integration with other microclimate analysis and parametric design tools which is available in its full version. A possible future step for this research is to evaluate full versions and consider more tools that were not included in this study. Furthermore, studies that apply these tools in teaching environments are needed to objectively evaluate their impact on the design process.

References

Batty, M., Axhausen, K.W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G. and Portugali, Y.: 2012, Smart cities of the future, *The European Physical Journal Special Topics*, **214**(1), 481-518.

Batty, M., Bettencourt, L.M. and Kirley, M. 2019, Understanding Coupled Urban-Natural Dynamics as the Key to Sustainability: The Example of the Galapagos, *in* T. Kvan and J. Karakiewicz (eds.), *Urban Galapagos*, Springer, 23-41.

Bettencourt, L.M.: 2014, Impact of changing technology on the evolution of complex informational networks, *Proceedings of the IEEE*, **102**(12), 1878-1891.

Dovey, K. and Pafka, E.: 2016, The science of urban design?, *Urban Design International*, **21**(1), 1-10.

Grassl, G. and Groß, P.: 2019, *Smart City*, München: Detail.

Holland, J.H.: 2014, *Complexity: A very short introduction*, OUP Oxford.

Kvan, T.: 2020, Data-Informed Design: A Call for Theory, *Architectural Design*, **90**(3), 26-31.

Marshall, S.: 2009, *Cities, design and evolution*, Routledge.

van Schaick, J. and Klaasen, I.: 2011, The Dutch layers approach to spatial planning and design: a fruitful planning tool or a temporary phenomenon?, *European Planning Studies*, **19**(10), 1775-1796.

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

Walloth, C.: 2016, Emergent nested systems, *Emergent Nested Systems: A Theory of Understanding and Influencing Complex Systems as Well as Case Studies in Urban Systems*, **1**, 13-17.

Yigitcanlar, T., Kamruzzaman, M., Buys, L., Ioppolo, G., Sabatini-Marques, J., da Costa, E.M. and Yun, J.J.: 2018, Understanding 'smart cities': Intertwining development drivers with desired outcomes in a multidimensional framework, *Cities*, **81**, 145-160.

Zheng, C., Yuan, J., Zhu, L., Zhang, Y. and Shao, Q.: 2020, From digital to sustainable: A scientometric review of smart city literature between 1990 and 2019, *Journal of Cleaner Production*, **1**, 120689.

Zvolska, L., Lehner, M., Voytenko Palgan, Y., Mont, O. and Plepys, A.: 2019, Urban sharing in smart cities: the cases of Berlin and London, *Local Environment*, **24**(7), 628-645.

OPPORTUNITIES AND RECOMMENDATIONS FOR LOCAL GOVERNMENTS DELIVERING SMART HERITAGE

DAVID BATCHELOR[1] and MARC AUREL SCHNABEL[2]
[1,2] *Victoria University of Wellington*
[1,2] *{David.Batchelor|MarcAurel.Schnabel}@vuw.ac.nz*

Abstract. The expansion of smart computer-led technologies into new disciplines enables local governments to design and manage their cities with novel smart discourses. Smart Heritage, the convergence of the smart city and heritage disciplines, offers local governments means to regulate and steer these issues. However, due to its novelty, currently, no research exists on the opportunities and trajectory of Smart Heritage within local government. Therefore, the here presented paper reports the opportunities and recommendations for Smart Heritage within local government, drawing on interviews with smart city and heritage advisors from three Australian local councils. It finds opportunities for smart computer-led technologies to design unique economic, place-making, and governance experiences in cities and recommendations that normalise the delivery of local governments' regulatory duties by these technologies. The findings are significant for leading smart technologies further into the practical-political framework of local government and diversifying smart cities' scope while at the same time combining two separated policies.

Keywords. Smart Heritage; Heritage; Smart City.

1. Introduction

With the continual expansion of smart technologies into new disciplines, local governments can consider a growing range of computer-led solutions to design and deliver new experiences and address their cities' issues. Smart technologies are digital tools with autonomous decision-making capabilities that do not rely on constant human management. Local governments primarily benefit from smart technologies in their jurisdictions because they reduce staff costs and improve services' effectiveness, transforming it into a 'smart city' (Lara et al, 2016; Yigitacanlar et al, 2018). Smart city commentators report yearly increases in the number of local governments implementing smart technologies and a diversifying range of applications, including comprehensive data viewing and analysis platforms for traffic and parking management and environmental resource use (KPMG 2018; KPMG 2019). With the upsurge in and diversification of the smart city discipline, academic researchers account new 'smart' discourses resulting from novel convergences of computer-led technologies and traditional disciplines, primarily in community, social, and cultural sectors (Neirotti et al,

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 749-758.

2014; Boogaard, 2018). These new smart discourses follow the now-standardised 'smart' naming convention; as in the established Smart Mobility, Smart Infrastructure, or Smart Governance discourses (Joss et al, 2019; Smith, 2020; Govada, 2020).

One discipline at the forefront of this convergence with smart technology is heritage. Heritage is the subjective and dynamic concept that results from understanding and applying the past (Uzzell, 2009; Smith and Waterton, 2009; Winter 2012). Within a local government context, heritage concerns identifying, protecting, and managing historic places, sites, areas, and objects. In this context traditionally, it rarely intersects with technology outside of digital heritage applications in local government-run museums, where it uses passive technology on heritage material (Rushton and Schnabel, 2021). However, over the last seven years, the academic literature has gradually closed in on the notion of Smart Heritage through a patchwork exploration between heritage and smart technology.

Batchelor and Schnabel (2019) and Brusaporci (2020) are the first to recognise Smart Heritage as a distinct discourse separate from digital heritage. Batchelor and Schnabel and Brusaporci emphasise the active autonomy of the technology in engaging heritage, and employ the smart city's ecosystem lens to frame Smart Heritage as a ubiquitous tool within cities; where autonomous computer technologies lead citywide services, including scoping, management, and delivery. Batchelor and Schnabel describe Smart Heritage as a bridge across these two disciplines that enable them to 'intersect, converse, and find value' through convergence. Brusaporci discusses Smart Heritage as an experience of seamless interactions between the past and technology, resulting in heritage itself being shaped by technology while also mediating the technology through historical understandings. Therefore, Smart Heritage is the meshing of the past's subjective interpretation and valuation with ubiquitous and autonomous technology.

Analysing interviews with smart city and heritage advisors from three local councils in Australia, the paper illuminates opportunities and recommendations for Smart Heritage within local government. It applies an inductive analytical approach to illuminate these understandings then locates trends across the case studies that deduce generalised findings pertinent to delivering Smart Heritage in the local government sector. It contextualises the findings in a discussion section against academic literature on interdisciplinarity within organisations. Against this backdrop, approaches and challenges arise that inform the findings on the delivery of Smart Heritage within local government. The findings are significant as they signpost how computer-led technologies can further expand into local government and promote diversify smart cities' scope by introducing the novel Smart Heritage discourse.

2. Methods

The researcher analyses interviews with three Australian local governments to infer generalised findings. In each local government case study, the researcher interviews a Smart City Advisor and a Heritage Advisor on the opportunities and recommendations for Smart Heritage within their organisation. The researcher then formulates shared narratives to produce generalised findings for local governments. The interviews were semi-structured. The questions probed into the potential and practical of convergence of the smart city and heritage disciplines to produce Smart Heritage. The organisations chose the advisors, and they were all experienced in their roles. The researcher provides the monikers Smart City Advisor and Heritage Advisor. The interviews were during May and June 2020, approximately one hour in length each, and audio-recorded, then transcribed.

The local governments are Broken Hill City Council, an outback mining city; the City of Melbourne, the state capital of Victoria; and the City of Newcastle, a former coal and heavy-industry city. These cities all have Heritage and Smart City Advisors and respective strategies that guide these disciplines. They reflect the broad range of size, status, and capabilities of the 537 local governments in Australia (Australian Local Government Association, 2020). However, the small sample size is a limitation of the research, meaning that the findings offer merely an indication of the opportunities and recommendations for Smart Heritage within the local government sector. Regardless, this is the first investigation of its focus within the academic literature and, therefore, is a valuable initial study that advances the smart city discourse into new disciplines.

3. Interdisciplinary Opportunities

The following sections report the unique opportunities from each local government case study.

3.1. BROKEN HILL CITY COUNCIL

The Heritage Advisor for Broken Hill City Council recognised how Smart Heritage could support economic growth in the city and resolve the lack of local heritage expertise and public funds for staff. For example, smart technologies could provide self-guided tours of the historical outback mine sites, buildings, and artefacts around the city. Technology like QR codes, mobile phone tracking, and autonomous interpretation software could provide visitors with the ability to register and pay for tours remotely. It would then track and guide the visitors through the sites, and unlock and manage the historic assets, buildings, and artefacts during and after the tours. This technology would enable the vast historic mines with numerous assets to be unstaffed and flexible to seasonal demand, reducing high operational costs that are a significant hurdle in the outback city. The Heritage Advisor also suggested an online marketing platform to attract to Broken Hill and service tourists during their stay. Personalised advertisements would target likely tourists and, like in the example by Monteiro et al (2018), the smart technology would curate a personalised experience for each tourist based on their interests, available time, and interactions with their surroundings. It would provide digital nudges for local accommodation, museums and galleries, restaurants, and other attractions based on personal information. This platform would integrate with other civic information feeds and would encourage opportunistic and novel explorations of historical and civic sites, similar to urban exploration discourses. In the opinion of the advisor, the city lacked economic opportunities and sees an avenue for smart technology to converge with historic sites to create a novel and profitable tourist experience.

The Smart City Advisor for Broken Hill City Council recognised two opportunities. The first opportunity is to install smart street lighting citywide that dims at night when no pedestrians or cars are near to emphasis indigenous astronomical narratives; a critical aspect of Australian Aboriginal heritage. The advisor recognised that the remote location and small urban scale of Broken Hill provides an opportunity to explore unique outback Aboriginal heritage. While smart street lighting is typically a Smart Infrastructure provision for reducing electricity consumption in cities, the opportunity to create heritage outcomes from the technology is novel. The second opportunity is the installation of digital pedestrian trackers in waypoints and historical sites throughout the city. The trackers would automatically recognise the volume and direction of people who pass by. The resulting data would support understanding the effectiveness of tourist initiatives and align with the existing place-making in the city centre.

3.2. CITY OF MELBOURNE

The Heritage Advisor for the City of Melbourne proposed using smart technology to create more efficient processes and engagement in visualisation, data collection, and data application for archaeological heritage. The advisor considered there would be opportunities for economic development through a better activation of heritage sites via smart technology but found it difficult to ways to deliver it specifically.

The Smart City Advisor for the City of Melbourne identified opportunities for an ‘intuitive city’ system that monitors public squares and parks and redesigns them in real-time to enhance meaning and functionality. The advisor referred to Smart Mobility discourses that reallocate road space to accommodate traffic demand better. The advisor translated this to the Smart Heritage discourse, where public spaces could better accommodate historical narratives through changeable heritage symbols, artworks, and spatial arrangements of objects and information of historical significance. The Smart City Advisor also saw opportunities for Smart Heritage to make visible Aboriginal history, customs, and values in the cityscape. The advisor recognised that Aboriginal heritage is primarily non-tangible, which is not always respected by colonial governance processes and constructs. Recognising Aboriginal history and culture was part of an emerging strategic shift in the council, and Smart Heritage is an opportunity to deliver in this direction.

3.3. CITY OF NEWCASTLE

The Heritage Advisor for the City of Newcastle thought that smart technology could support the repackaging and promotion of heritage collections, historic buildings, old streets, and other heritage places to new audiences. Smart technology could deliver heritage on digital platforms and mesh historical narratives with new contexts in order to pique the interest of the public. The advisor prioritised the engagement of audiences as an opportunity for

Smart Heritage. When asked about other opportunities; namely economic, historical conservation, governance, and environmental sustainability; the advisor acknowledged that these were likely possible but could not substantively identify how they would work within their current role. The advisor noted that delivering these opportunities would require a shift in the operational vision for the advisor and cross-council team inputs.

The Smart City Advisor saw the potential for Smart Heritage to enhance current place-making initiatives by the council. Notably, with respect to historic buildings, the advisor proposed that smart technology would provide immersive, interactive, and delightful heritage experiences. The advisor desired to see a more ‘mediatised environment’ where sites in the city communicate in real-time in order to improve the user experience. For example, each site would utilise and analyse personal data and ‘big data’ to continually improve the experience of the sites for visitors. The assets could react to current trends and alter exhibitions and narratives autonomously. The advisor also recognised a benefit in the additive installation of smart technology across the city. Reflecting on the development of the smart city discipline in the council, they described how the technological advancements unveil new and more ambitious opportunities. Therefore, the continual process of advancement itself was an opportunity for Smart Heritage. Later in the interview, both advisors from the City of Newcastle considered there should be a continual review of opportunities and interdisciplinary innovations within the organisation. The Heritage Advisor noted that explicit convergence between the smart city and heritage disciplines should feature in the new heritage strategy that was currently in development.

4. Recommendations to deliver Smart Heritage

The following sections report the recommendations from each local government case study.

4.1. BROKEN HILL CITY COUNCIL

To deliver Smart Heritage in their organisation, the Heritage Advisor for Broken Hill City Council recommended that the council is required to allocate greater staff availability and funding to Smart Heritage as they do not have the capacity for new tasks. Currently, their primary workload is to assess development applications, with minimal time available for other tasks. The advisor also stated that many of the staff, such as the Smart City Advisor, work long hours already. However, the situation for the council is complicated as the council relies on state and national funding for heritage and smart city initiatives. The capacity of the teams can, therefore, only increase through successful grant applications to state and federal organisations for specific Smart Heritage tasks and projects. Additional grant applications that converge the smart city and heritage disciplines are then critical to delivering Smart Heritage in Broken Hill.

The Smart City Advisor also recognised a lack of workload capacity to deliver Smart Heritage. The advisor noted that this is a result of the small staff size of the council. The advisor stated that staff are required to hold multiple portfolios, which restricts their ability to be involved in all conversations. The advisor recommended regular meetings between the disciplines to improve communication. However, ideally, the council would have additional staff to converge the two disciplines better. Coincidentally, the advisor was to become the acting manager of the heritage team the following week, while maintaining their smart city role, and was interested in pursuing Smart Heritage. The advisor also recommended the council establish a formal process for cross-discipline initiatives. The advisor talked about how the staff regularly communicate due to the small size of the organisation. But the advisor endorsed a more structured approach to focus on the practical delivery of projects, including funding applications and architectural design.

4.2. CITY OF MELBOURNE

The Heritage Advisor for the City of Melbourne stated that Smart Heritage required endorsement by councillors and management for success. The advisor noted that the workload in the organisation is strictly guided by individual projects and permissions, restricting the scope for new interests like Smart Heritage. The advisor stated that the way to improve the delivery of Smart Heritage is to gain approval for a specific project. The advisor considered an increase in the capacity of the team, such as an additional staff member or allocated time for convergence, is highly unlikely due to more immediate demands on other ingrained projects such as COVID-19 recovery. Therefore, the advisor recommended that councillors and management become aware and supportive of Smart Heritage for its success and allocate it in the workload pipeline.

The Smart City Advisor for the City of Melbourne reported that their team was in ‘pilot mode’, where they are testing initiatives with any team who approaches them. As the heritage team had not approached them, the smart city team worked with other disciplines. The advisor recommended the heritage team contact them to start the convergence process. There had not been an initiative or directive to converge the two disciplines, and they were not aware of the strategic aims of each other. Addressing this issue, the Smart City Advisor recommended that the disciplines engage each other better to understand their knowledge, technical capabilities, and strategic aims so they can efficiently and effectively deliver Smart Heritage. However, while discussing the strategic alignment between the teams, the advisor considered that the disciplines strategically aligned because of a technology layer in all strategies, including the heritage strategy, encouraged interdisciplinary working. Therefore, strategically the council supported Smart Heritage but it required operational encouragement to occur. More effectively, both advisors also recommended the council structurally merge the smart city and heritage teams into a singular unit or deploy an executive directive that strategically converges the teams. The Heritage Advisor discussed how the teams currently have different directors within the organisation and how this structure reduced the prioritisation of convergence. The advisor considered the merger of the teams would address this issue.

4.3. CITY OF NEWCASTLE

The Heritage Advisor for the City of Newcastle recommended an expansion to the duties so they can encompass non-regulatory tasks. Currently, regulatory processes, such as processing development applications, dominated their workload. Also, the advisor described the heritage team currently existed within an admistrative-focused land development pillar in the council, which restricted their approved ability to proactively engage other disciplines, such as the smart city discipline. These operational and structural barriers hindered the convergence of the disciplines. The advisor recommended broadening their responsibilities within the council to include non-regulatory functions to increase their visibility of opportunities and ability to converge with the smart city team. The advisor was optimistic that the new heritage strategy, which was under development during the interviews, would improve the prioritisation of interdisciplinary convergence.

The Smart City Advisor from the City of Newcastle identified that high workloads restricted their visibility of opportunities with the heritage team to deliver Smart Heritage. As a result, they had not considered Smart Heritage as a distinct deliverable. However, they welcomed more collaboration with the heritage advisor as the smart city team sought to expand its operations across council disciplines. The advisor recommended that the smart city and heritage teams identity the mutual and relevant benefits from Smart Heritage and how they align with the strategic aims of the organisation, which may unlock the mechanisms to fund and resource Smart Heritage outcomes. The Smart City Advisor also recommended that the council adopt a flat organisational structure that encouraged more free and direct lines of communication and visibility between the teams. The advisor stated their team frequently tested different structures to generate agile and creative relationships and considered a new structure might be required to converge with the heritage team in this instance.

5. Discussion

The Smart City and Heritage Advisors reported a range of economic, place-making, and internal governance opportunities for Smart Heritage within their local governments. These opportunities are novel means to deliver each council's strategic aims and reflect their unique internal and external context. This finding aligns with the academic literature on interdisciplinarity within organisations, which states it enables organisations to address unique and often complex contexts and issues. Helga (2017) states that interdisciplinarity draws on tacit and explicit knowledge bases that were likely not connected previously, and the organisational framework provides the drive for their convergence and exploitation. Sousa and Gonzalez-Loureiro (2015) discuss how the creative socialisation and combination of knowledge within an organisation often produce practical but unrepeatable outcomes. However, Lauring and Selmer (2012) warn that disciplines must have complementary skills and relevant information to co-create a viable and productive outcome. Without complementary and relevant inputs, interdisciplinary convergence is impotent. Translating these academic insights into the research infers that the identified opportunities are theoretically viable, and encourages local governments to explore them sincerely. Local governments should consider Smart Heritage's novelty primarily a strength, rather than a hindrance, as it applies computer-led intelligence to complex cultural contexts and issues. These autonomous abilities present the tools to meet the increasing demands of our cities. Yet, these specific opportunities should not be carbon-copied across local governments due to various contextual challenges between councils. Instead, local governments should use these opportunities as clues for locating their specific opportunities. Each local governments must assess the case-specific relevancy of their disciplines' skills and information and the demands of their context and issues to ensure a productive outcome.

The advisors recommended approaches to enhance the adoption of Smart Heritage within local government. These approaches are predominantly greater staff availability and funding, endorsement by councillors and management, and an expansion of the duties to encompass Smart Heritage. This finding aligns with the academic literature, which states that interdisciplinarity demands process and structural change in organisations. Clark et al (1993) and Swan et al (2002) find that convergence between disciplines initiates a learning and reflection process that requires each discipline to self-evaluate its contribution and position in contrast against the other discipline. This process results in subtle and regular iterative changes. Lanterman and Blithe (2019) identify that through this process, individuals typically reduce the opinion of their discipline in light of the inter-disciplinary approach, as they are hesitant to overextend their discipline politically. Leeuw et al (1994) note that organisations as a whole become aware of knowledge silos and biases towards specific disciplines and their distinct perspectives. However, Nonaka and Tekuchi (1995) warn that resource changes can disrupt existing well-performing aspects within an organisation and sow distrust in existing processes and management structures, weakening the organisation. Boone and Hendriks (2009) also recognise that interdisciplinary opportunities require time-intensive management of political motivations and each discipline's communication preferences. Interpreting these academic insights into Smart Heritage in local governments deduces that, in the initial stages at least, the shortage of resources for innovation due to existing structures and process is expected. But to be successful, local governments must change resource supply. This change may demand reducing resources to other tasks and upset practical and political balances in the organisation. Therefore, managers should consider the impacts on the organisation and scale or temper changes to ensure that productivity remains acceptable. Nevertheless, in the academic literature, Smart Heritage requires a change in resourcing within local governments.

It is important to note that the advisors' opportunities and recommendations are theoretical, meaning that the effectiveness and feasibility of delivering them are yet to be proven. But, established smart discourses, such as Smart Mobility and Smart Infrastructure, indicate a positive likelihood that these and other councils can deliver and benefit from the opportunities and recommendations. In earlier interviews by Batchelor and Schnabel (2020), advisors from the case studies identified a gradual and ongoing process, including across multiples years and various editions of strategic documents, that delivered similar outcomes and changes. It is likely learnings from delivering these earlier smart discourses could support the delivery of Smart Heritage in local governments.

6. Conclusion

The paper presents opportunities for smart computer-led technologies to design and deliver unique economic, place-making, and governance experiences in cities, and recommendations that normalise the delivery of local governments' regulatory duties by these technologies. The findings are significant as they strengthen the business case for smart cities, digital heritage, and interactive environments. As discussed in the introduction, computer-led technologies are expanding further into local governments, and there is support for its success. So, understanding the opportunities and recommendations for adopting these technologies benefits this cause and signposts its trajectory. The findings also support the diversification of the local government's smart city delivery beyond now-established Smart Mobility and Smart Infrastructure discourses. The heritage discipline is mostly untapped by smart technology and presents significant opportunities to benefit councils due to its cultural value and dynamism. Local governments should, therefore, openly consider Smart Heritage in their operations and strategic futures. The research's small sample size discourages the complete translation of the generalised findings to other local governments and countries. However, support from the academic literature on interdisciplinarity within organisations aids the weight of the findings. Therefore, the findings set the tone for further research in this novel area intersecting the smart city and heritage disciplines.

References

"Australian Local Government Assocation" : 2020. Available from <https://alga.asn.au/> (accessed 25 August 2020).

Batchelor, D. and Schnabel, M.A.: 2019, Smart Heritage in selected Australian Local Government Smart City Policies, *Revisiting the Role of Architecture for 'Surviving' Development, (53rd International Conference of the Architectural Science Association (ANZAScA))*, Roorkee, 245–254.

Batchelor, D. and Schnabel, M.A.: 2020, Interdisciplinary Relationships, Influence, and Aspirations for Smart Heritage in Local Government, *Heritage*, **3**(1), 1402-1415.

Boogaard, L.: 2018, *I AmSMARTerdam: Revaluating the Smart City Concept through the World's Most Bottom-up Smart City*, Master's Thesis, Blekinge Institute of Technology.

Boone, C. and Hendriks, W.: 2009, Top management team diversity and firm performance: moderators of functional-background and locus-of-control diversity, *Management Science*, **55**, 165–180.

Brusaporci, S. 2020, Towards Smart Heritage: Cultural Challenges in Digital Built Heritage, *in* G. Pavlidis (ed.), *Applying Innovative Technologies in Heritage Science*, IGI Global, Hershey, 271–296.

Clark, P., Staunton, N. and Rogers, E.: 1993, *Innovation in Technology and Organization*, Routledge, London.

Govada, D.: 2020, Smart and sustainable city framework with smart cultural precinct as case study, *Urbanie & Urbanus*, **3**, 22-36.

Helga, N. 2017, Introduction: Investigation Interdisciplinarities, *in* S. Frickel, A. Mathieu and B. Prainsack (eds.), *Investigating Interdisciplinary Collaboration: Theory and Practice across Disciplines*, Rutgers University Press, London, 5–24.

Joss, S., Sengers, F., Schraven, D., Caprotti, F. and Dayot, Y.: 2019, The smart city as global discourse: storylines and critical junctures across 27 cities, *Journal of Urban Technology*, **26**(1), 3-34.

KPMG, initials missing: 2018, “Smart cities: a snapshot of Australia in 2018” . Available from <https://home.kpmg/au/en/home/insights/2019/12/smart-cities-snapshot-australia-2019.html> (accessed 5th May 2020).

KPMG, initials missing: 2019, “Smart cities: a snapshot of Australia in 2019” . Available from <https://home.kpmg/au/en/home/insights/2019/12/smart-cities-snapshot-australia-2019.html> (accessed 5th May 2020).

Lanterman, L.J. and Blithe, S.J.: 2019, The benefits, challenges, and disincentives of interdisciplinary collaboration, *Commoning Ethnography*, **2**, 149–165.

Lara, A.P., Da Costa, E.M., Furlani, T.Z. and Yigitcanlar, T.: 2016, Smartness that matters: Towards a comprehensive and human-centred characterisation of smart cities, *Journal of Open Innovation: Technology, Market, and Complexity*, **2**, 8–13. .

Lauring, J. and Selmer, J.: 2012, Knowledge sharing in diverse organisations, *Human Resource Management Journal*, **22**, 89-105.

Leeuw, F.L., Rist, R.C. and Sonnichsen, R.C.: 1994, *Can governments learn?: comparative perspectives on evaluation and organisational learning*, Transaction Publishers, New Brunswick.

Neirotti, P., De Marco, A., Cagliano, A., Mangano, G. and Scorrano, F.: 2014, Current trends in smart city initiatives: Some stylised facts, *Cities*, **28**, 25-36.

Nonaka, I. and Nonaka, H.: 1995, *The Knowledge Creating Company: How Japanese Companies Create the Dynamics of Innovation*, Oxford University Press, Oxford.

Rushton, H. and Schnabel, M.A. 2021, Immersive Architectural Legacies: The Construction of Meaning in Virtual Realities, *in* E. Ch, V. Gaffney and H. Chapman (eds.), *Visual Heritage in the Digital Age. Springer Series on Cultural Computing*, Springer, London, pgs. 28.

Smith, S.: 2020, Smart infrastructure for future urban mobility, *AI Magazine*, **41**(1), 5-15.

Smith, L. and Waterton, E. 2009, The envy of the world? intangible heritage in England, *in* L. Smith and N. Akagawa (eds.), *Intangible Heritage*, Routledge, London, 289-302.

Sousa, M.J. and González-Loureiro, M.: 2015, Knowledge vision on formalisation versus tacitness of sharing knowledge in innovative large organisations, *Independent Journal of Management & Production*, **6**, 182–202.

Swan, J., Scarbrough, H. and Roberton, M.: 2002, The construction of communities of practice in the management of innovation, *Management of Innovation*, **33**, 477–496.

Uzzell, D. 2009, Where is the discipline in heritage studies? a view from environmental psychology, *in* M.L.S. Sorensen and J. Carman (eds.), *Heritage Studies: Methods and Approaches*, Routledge, London, 326–333.

Winter, T.: 2012, Clarifying the critical in critical heritage studies, *International Journal of Heritage Studies*, **19**, 532–545.

Yigitcanlar, T., Kamruzzaman, M., Buys, M., Ioppolo, G., Sabatini-Marques, J., da Costa, E.M. and Yun, J.J.: 2018, Understanding ‘smart cities’: intertwining development drivers with desired outcomes in a multidimensional framework, *Cities*, **81**, 145–160.

Index of Authors

In a time of unprecedented global challenges, the need to reflect on our changing society has rarely been more obvious. As the pandemic highlights the precariousness of our fragile climate, limited resources and unequitable urban areas, there is a new mandate for new technology-enabled processes that positively impact our profession, communities, and planet.

'PROJECTIONS' focuses on recent research around computational methodologies in architecture and urbanism, reflecting upon the different ways innovation will impact the future. A collection of 149 papers, selected through a rigourous double-blind peer reviewing process, highlights the challenges and opportunities around the current status of computer aided research and design.

ISSN 2710-4265
www.caadria2021.org

ISBN:978-988-78917-6-5

9 789887 891765