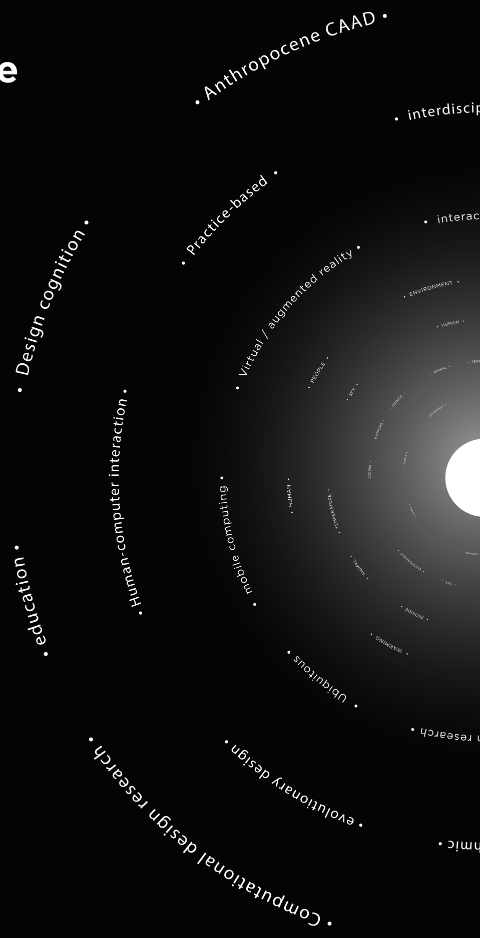
CAADRIA2020
RE: ANTHROPOCENE
Design in the Age of Humans

25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia



VOLUME 2

EDITED BY:

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Walaiporn Nakapan
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RE: Anthropocene, Design in the Age of Humans

Proceedings of the 25th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2020)

Volume 2

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25th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2020)

5 – 6 August 2020
Faculty of Architecture
Chulalongkorn University Bangkok, Thailand

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

ISBN: 978-988-78917-4-1

Cover design and cover image: The supersub Co., Ltd

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 *RE: Anthropocene, Design in the Age of Humans* – 25th International CAADRIA Conference, hosted and organised by the Faculty of Architecture at Chulalongkorn University Bangkok, Thailand. 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.

Against the backdrop of a year that many count among the most difficult in recent history, the conference organisers and the broader CAADRIA community have shown great resolve, passion, and commitment, resulting in a body of work of highest international standards. Calls for papers in July 2019 led to the submission of 466 abstracts. These were blind reviewed by the Paper Selection Committee, which invited 311 abstracts for further development. Of these, 233 full papers were submitted to the full paper review stage. A team of 91 international reviewers assisted us in this stage. Two-to-three international reviewers carried out a double-blind review of each submitted paper. Following the reviewers' recommendations, we were fortunate to be able to accept 183 papers. The travel restrictions caused by the global pandemic required changes, both to the conference date, as well as its format. We are very pleased that 158 papers ultimately got included in these conference proceedings, in particular given the fact that CAADRIA 2020 is being run as a virtual conference. We congratulate the authors for their accomplishment.

Next to the authors, the reviewers, who volunteered valuable time and effort, deserve our sincere thanks and acknowledgements. We thank the Organising Team and hosts at Chulalongkorn University in Bangkok for hosting the 25th International CAADRIA Conference online.

We extend absolute special thanks the ProceeDings team, and in particular Gabriel Wurzer, for his relentless support with customizing the submission and review system to the needs of CAADRIA from the full-paper submission stage all the way to production. On the following pages, we acknowledge and thank those who contributed to the production of this volume. In closing, we sincerely like to thank the CAADRIA community for offering us the honour to serve as members of the Paper Selection Committee for *RE: Anthropocene, Design in the Age of Humans, the 25th International CAADRIA Conference 2020.*

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CAADRIA 2020 Theme
RE: Anthropocene, Design in the Age of Humans

What if we are already in the Anthropocene epoch where the function of the Earth system is being impacted by human activities? What if our actions indeed are significant enough to have a critical force on the Earth as a system? The term Anthropocene (the Age of Humans) has gained increasing recognition as a description of a crucial geological stage of our planet as we face the consequences of our own events on the earth's ecosystem. While we are beginning to address the predominant challenges of sustainability and ecology, the environments we built have also shaped our behaviors.

To celebrate CAADRIA's 25th Anniversary, we challenge ourselves with these questions, asking what we want our future to look like in the next 25, 50, or even 100 years from now? If human creations are substantial enough to start a new geological epoch, what does this imply for our explorations of the realm of computational design and how will advanced technologies shape our future?

With the theme of RE: Anthropocene, we ask our contributors to REgard this new geological age as the main meaningful site for exploration into the future, REthink what our planet could become, REvisit our actions and behaviors to foster the REsponsibilities for the planet existence, and perhaps & importantly, REspond to whatever magnitudes happen to the built-environments and other planetary beings.

As the CAADRIA 2020 organizing committee, the beginning of 2020 has been quite challenging as we faced the COVID-19 pandemic in midst of conference preparations. We too, have been faced with disruptions and had to REthink, REvisit and REspond to the original format of the conference as we explored virtual possibilities. The resilience of people has never seized to surprise us and we are proud to present CAADRIA 2020 as the very first virtual conference in CAADRIA history. The essence of CAADRIA has always been and will forever be centered around the community and for that we thank all contributors for making this possible.

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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, 24 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 25th anniversary conference, in 2020, is hosted by Chulalongkorn University in Bangkok, Thailand. CAADRIA2020 is held as a virtual conference for the first time in the history of the Association to bring together researchers, practitioners and schools of the pacific region even at a time of global Covid-19 related travel restrictions.

Proceedings of CAADRIA conferences are available online at the open access cumulative database *CumInCAD* (http://papers.cumincad.org). CAADRIA is one of the four founding organizations of the *International Journal of Architectural Computing* (IJAC), and co-edits one issue each year. IJAC is published by SAGE in both paper and electronic versions.

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Smart Buildings/Cities/Regions

DYNAMIC TRANSLATION OF REAL-WORLD ENVIRONMENT FACTORS AND URBAN DESIGN OPERATION IN A GAME ENGINE

A Case Study of Central District in Tiebei New Town, Nanjing

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Abstract. The building and its urban environment are complex and dynamic data systems. Designers, who make design decisions, need the design tools to simulate the built environment, to estimate the feasibility of the design. However, the static modeling software, widely used nowadays, restricts the linkage relationship between the actual data environment and the simulation model, which lacks the dynamic constraint relationship and the construction of the loop order. Different from traditional modeling and analysis tools, simulation games, with dynamic constraint rules and real-time feedback operations, provide a new way of thinking and a perspective to observe the urban, which makes the simulation game be seen as a simplified analog system, to some extent. Therefore, this paper plan to builds a city model, based on an urban design project of an urban district of Nanjing as an example, by using the Cities: Skylines, a city simulation game with priority of traffic and zoning concept. Based on this dynamic model, the next step will evaluate the original project and carry out further optimization operations in real-time.

Keywords. Real-time interaction; dynamic process simulation; urban environment; city simulation system; simulated game.

1. Introduction

With the constantly emerging urban problems under the progress of urbanization, people have gradually realized that cities are a complex data and information system. In response to complex urban problems, professionals separately constructed simulation systems under various environments in each fields. Ruiz-Tagle, J. has classified the development phase of simulation models into static model stage and dynamic model stage. In the group of static models, which come from the generation of generic scientific models and from the theoretical contributions of systems theory, are more focus on the constraints or spatial relationships that constitute the environment at a certain time, such as physical and environmental geography models, social models, urban and architecture models, and so on. In the second group of dynamic models, with the development of

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 11-20.

computer science and system dynamics theory, are combined with the time to observe the dynamic relationship between various factors, such as optimization models, control models, and simulation models. The system dynamics theory, originally proposed by Forrester in the field of industrial engineering, has the characteristics of complex, multi-factor, dynamic, and non-linear. The model base on this theory can not only simulate the real environment of the city, but also predict a variety of possible results based on different strategies. Therefore, the model combined with dynamics theory is used by scholars to simulate the relevant design practice in a real environment and to get multiple possible results.

With further study in cities theory, scholars focus on the way of intervention in multiple fields of knowledge in order to solve complex problems. Related scholars devoted to study on comprehensive city simulation models and proposed to build a planning support system, based on dynamic models, featuring data integration and visualization. They pointed out that such an urban model based on the concept of dynamic simulation and multi-factor evaluation is helpful to solve the problem of lack of openness in early models. In recent years, a number of open source or commercial city simulation systems have emerged, such as UrbanSim (Waddell, Borning), SWARM (Ligtenberg, etc.), SLEUTH (Arthur-Hartranft, etc.), and Eris's ArcGIS and CityEngine. At the same time, for the attempt to use the model for design practice, JA Sokolowski and CM Banks summarized a four-step workflow that uses simulation models assisting design: model, simulation, results, and insight.

However, some shortcomings of the existing simulation models limit the dynamic model as a tool for design practice, such as being too complicated, lack cross impacts, difficult to interact, and lack accessible human-simulation-interface. With the development of computer technology and game theory, game simulation environment becomes more objective. At the same time, game has the property of easy operation, real-time feedback and dynamic interaction, which have inspired the discussion on the feasibility of using games as design tools. This article will also use a game to conduct a design practice, to simulate the city environment and to assess the design strategy. Furthermore, the application of simulation model with real-time interaction and dynamic simulation theory is intuitively demonstrated, with the help of game tools, in a design practice.

2. The Background Concepts of Game as a dynamic simulation model

Compared with scientific or professional analysis tools, (electronic) games mainly focus on the player's experience. With the pursuit of authenticity, today's urban construction games have provided players an interactive and dynamic urban model, with more scientific, accurate and objective, including urban systems such as production, transportation, and public facilities. Therefore, with the development of game mechanics, scholars have begun to focus on the potential by using the simulation games to deal with complex reality problems. This interactive system and city simulation system, simplified, can quickly help users experience the data between reality and design work and establish the concept of it. Some scholar even optimistically predict that simulation games can replace some of the design assistance software. P.C. Adams and J. Gaber and others have used

SimCity games for several teaching and research attempts, and B.Bereitschaft and other discussions on using “Cities: Skylines” for teaching. Some have further proposed that game-based simulation experiments should not be narrowly viewed as “playing games”, but rather as a design talk and logic training using game mechanics. The advantages, like comprehensive evaluation mechanism, real-time interactive feedback, perfect simulation system and more reality content, prompted this experiment to use urban simulation games as an experimental tool to study the utilization of urban environment simulation system, based on real-time data analysis, in design practice.

Games involving urban problems can be traced back to the ancient Greek board game “polis”. With the development of computer technology, urban simulation games have gone from similar traditional turn-based chess game based on the concept of dynamic generation, which is now more liberalized and authentic. The content of the game is to choose a site to build and manage a city. First,build the city from the “architect’s perspective”. Next, in the course of operation, from the “mayor’s perspective”, scoring of existing “chess” interaction behaviors in time and corresponding the feedback of result under existing rules, evolved over time. The operation process is from simple target, to meet a higher score, to achieve the dynamic comprehensive by evaluation result to satisfy the needs of citizens and improving the city operation condition, right now. The feedback process from the initial chart to the present dynamic model combination of civic activities and the building models in game. With the diagrams simulation games are more realistically reproduces the urban environment, the work of the designer and even the work of government.

3. Translation of game tools and experimental methods

Due to the relevant features of the game system, we decided to use the game, Cities: Skylines, instead of the existing dynamic simulation models. The paper expect to discuss how to use game as a tool in design practice through the operation process of this kind of dynamic simulation model.

3.1. AIMS AND METHODS

In the design practice using dynamic simulation models, we expect the design process could reflect the features of real-time feedback and dynamic simulation of the tool, so we decided to use game to optimize a project of an urban area that has been designed by traditional design methods. The results of the experiment hope to find problems of the existing plan based on dynamic rules, so as to obtain better solutions and summarize the possible impact of tool’s real-time feedback characteristics on the design process.

The experimental process is divided into four steps, based on the process of “analysis-modeling-operation-evaluation”. First, analyze the rules of the game, then extract the corresponding impact factors, get the data structure of the existing sites. Secondly, establish city model based on the original project and the actual environment, then dynamically run in the game to obtain the initial evaluation results. Third, set improvement aims and propose design strategies based on the evaluation results. Fourth, implement the evaluation operation process, based on the expression of built-in data visualization tool, and adjust the strategy timely according to the set goal. Finally translate the optimal game result to the design conclusion.

It is necessary to analyze the game operation mechanism and influencing factors, in order to ensure that each segment of the experiment could be controlled and avoid the uncertainty of experimental results caused by technical black box.

3.2. TOOL

This research chose “cities: skylines”, a software called city simulation games. The game’s features such as city’s dynamic model, evaluation rules, and multi-dimensional expressions, allow us to evaluate the feasibility of urban design projects in various scenarios.

The operation mechanism of the game focuses on the transportation system and the building units need to be built according to the road, which means the road network requires to be planned first. The game has the comprehensive road system from sidewalks to multiple road levels as well as the public transportation system based on the mechanism like the flow of traffic, specific to individual citizens. Secondly, the dynamic characteristics of the game rely on inherent dynamic rules and dynamic agent mechanisms. Dynamic rules are reflected in the concept of dynamic model database and land use zoning. Similar to the concept of function zoning and landmark building in the real world, the game mechanism divides urban architecture into two types: dynamic model and solid model. The dynamic model is “generated” in the form of zoning, including residential, commercial, office, and industrial areas. Like the CA model, it dynamically “grows” over time based on land-use attributes, and dynamically replaces models in the agent database as the environment changes. The solid model will not change once constructed, includes municipal buildings, hospitals, parks, and other urban service facilities. In addition, the game’s other concepts, including urban area and policy tree, are effective supplements in simulating the real urban environment.

The game contains data visualization tools, which could provide real-time feedback on the operation of the city model. These include 2D charts and 3D analysis diagrams based on the city model, covering environment, energy consumption, population, transportation, public services, economy, disaster and other aspects.

3.3. RULE AND AGENCY MECHANISM

The game relies on dynamic rules to evaluate the urban model in real-time, which prompts players to improve the model, further. The game’s evaluation system takes each agent as a simulation unit. The agent unit, are independent systems that affect each other, can be a single citizen, a vehicle, or a building or even an entire city.

Just as citizens in the real environment need various facilities to meet their daily demands, the dynamic rules of the game (Figure 1) is to solve the demands of the citizens by building modules, so as to improve the comprehensive indicators, like happiness and land value, promote the environmental score, and thus affect the dynamic growth in the zoning. The buildings will bring positive factors such as demand satisfaction, convenient travel, and environmental improvement and so on. On the other hand, side effects such as pollution, noise, fire hazards, and congestion and crime rates, as residents move in, will reduce the score, leading to a downfall in zoning.

The static building module be built or “generated” dynamic module uses its parameters, as a influencing factor, to regulate the game’s rule. In addition, the policy system serves as a catalyst to accelerate or slow down the appearance of results. In the dynamic model as a part of zoning, the only parameters that can be set are the population ceiling. The score of the game’s operation determines the specific number of people in each tim and the weighting of each individual’s index determines the final amount of data in the zoning, then the building model is replaced in real-time from the agent database, according to the final evaluation result. As a solid model of city service buildings, the general data, common to all buildings, and type data, that changes according to different types of buildings, can be set. The setting process can be completed in the game’s editor, or will use the default data without setting.

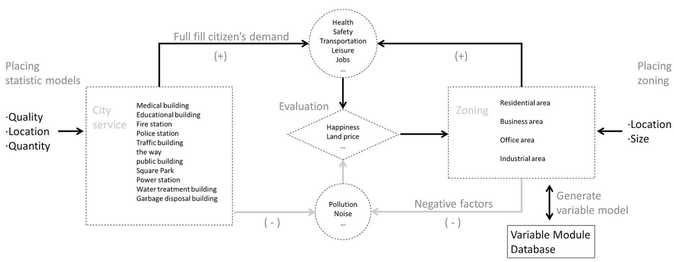

Figure 1. Game Rule.

4. Game Play

In order to test the aim of this experiment, a segment of the city is selected to build a model in the “cities: skylines”. The sample of this experiment selected the key area of “Tiebei New City” in Nanjing. As the edge of Nanjing’s downtown, Tiebei is far from the old district and has good traffic advantages, such as railway, railway station, subway station and urban main road passing through. The area is undergoing a transformation of urban functions, from an industrial area to a new urban center dominated by commercial offices with a small amount of residential land.

This area has been designed according to the traditional urban design method, relying on an urban landscape axis to achieve the transition from commercial to residential along the axis. However, it is not known whether the existing project obtained from experience is the optimal solution in this site, so we need to optimize it with the help of dynamic model and real-time feedback mechanism.

4.1. FIRST STEP- URBAN MODEL CONSTRUCTION

The first step is to collect relevant data for building a city model. In order to build a city model, relevant data in the original project should be collected: terrain data, road network information and other transportation infrastructure data, public transportation system information, economic indexes, residents and employment indexes, and land use zoning.

The next step is city modeling. In the game, the construction of the urban building model is divided into two steps. First, the terrain model is produced, and then the urban building model is built on the basis of the terrain model. 1. Create a terrain model. In this step, in this step, the DEM map in PNG format can be imported, then terrain can be generated automatically with the generation tool inner the game, or the terrain modification tool in the game can be used to manually fill and dig. Then establish the access interface of the main transportation network, cover the channels, routes, railways, and urban trunk roads. 2. Building a city model. The mechanism in game, building units in the game must along the road, determines the building model requires deepening the road network on the existing connection. Then laying infrastructure, such as municipal pipe network power grid, etc. After completing the road network and infrastructure, the next step is to "generate" or "place" building models. According to the above problems and the classification concepts of dynamic model and solid model, "smear" function zoning and "place" public service facilities, respectively, and finally generate the city model evolve over time under the influence of game rules.

4.2. SECOND STEP- THE GAME PROCESS

4.2.1. Origin project analysis

After establishing the urban dynamic model of the initial state according to the original design project, firstly run the model in the game, test it according to the dynamic rules, find possible problems, and improve the design based on it. Preliminary results are shown in Figure 2. By selecting noise, traffic volume, and land price as the factor for analysis, it can be seen that under the origin plan, part of the road traffic pressure cause congestion. The land scale is larger, resulting in insufficient land utilization. And excessive noise from commerce and roads. The above factors ultimately result in low level of land price, indirectly reflect the less attractiveness of existing district to citizens.

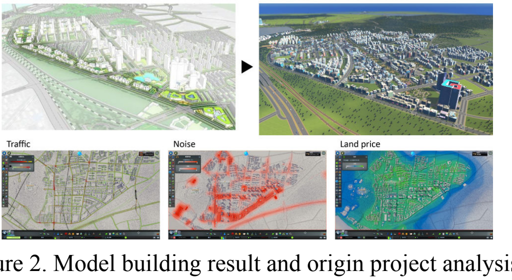

Figure 2. Model building result and origin project analysis.

According to the experience and the theory of urban design, some kinds of operation methods are proposed against above problems. Combined with the game's rules, the above operation methods are translated and organized into operation modes in the game (Figure 3). In order to increase the comprehensive index of "land price", it is hoped to establish inter-block connection, increase vitality, and reduce noise and traffic congestion. These are finally refined into two scales, namely, the urban and the block, which are respectively adjusted in three aspects: the pedestrian road, the function zoning and the green space for public activities.

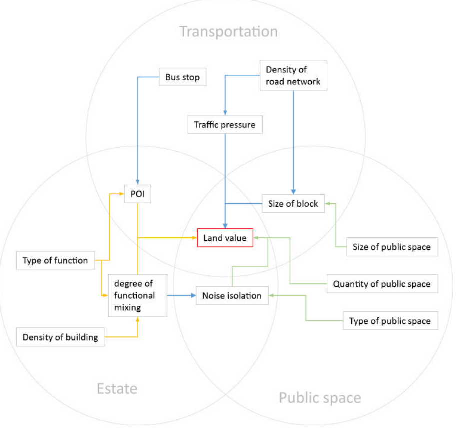

Figure 3. Optimizing strategy.

4.2.2. Intervention 1

In terms of urban scale, adjust the road system on the site. Adjust urban roads, partially, and add multiple walking roads. It is expected to appropriately reduce the block size, reduce the traffic pressure, and increase the vitality of some closed blocks by introducing people flow.

- Result 1

As shown in the Figure 4, in the game, according to the traffic volume feedback, the urban roads placed in some blocks are finally retained, after compared several operations, on the premise of minimizing the interference to the original urban road system. The newly installed urban roads reduce the block scale near the main urban roads and relieve the flow pressure at the junction and the main urban roads. At the same time, the newly placed pedestrian roads break the closed block property of the land and increases the vitality. The pedestrian road also replaces part of the locomotive travel, which also relieves the traffic pressure. These processes eventually lead to the increase in land prices.

Figure 4. Process of intervention 1- Adjust road network.

4.2.3. Intervention 2

On the scale of the block, adjust the functional zoning within the site to increase the degree of functional mixing. Improve the vitality of office and business function zones, which originally have a single function and lack of vitality in the area away from the crowd.

- Result 2

After operating in the game, we can obtain the most suitable location for the development of commercial, office and residential zoning, and, based on the results, adjust the original functional zoning to optimize the functional zoning. As the relevant dynamic analysis diagram express that the mixed function block brought about a few “land price” increase. The change may probably due to the function replacement of residential by commercial plots, which the land price being higher than the residential ones. At the same time, the influence scope of the noise also spreads through the site with the mixing of functions, because the large amount of noise brought by business activity. (Figure 5)

Figure 5. Process of intervention 2- functional mixed.

4.2.4. Intervention 3

On the scale of the block, new public green spaces are placed in the site, which can directly increase land prices. But in the original planning, the green space is concentrated on the central green axis that is isolated by urban roads and the block lack of relevant public activity space inside. On the other hand, due to these green spaces have a function of noise isolation, by which is expected to reduce noise pollution, appropriately.

- Result 3

Under the constraints of the overall area index, various operations were made based on the area, quantity and location of public green spaces placed in the block, and selected the most appropriate evaluation results, finally. As results show that land prices will increase, no matter how the public green space is placed. Compared with a single central green space, the scattered green spaces form a chain reaction, which will promotes the land price further. At the same time, the green space interspersed in the functional area well isolates the noise from the road or the functional plot, and reduce the noise impact range, which is also the reason for the increase of land prices. (Figure 6)

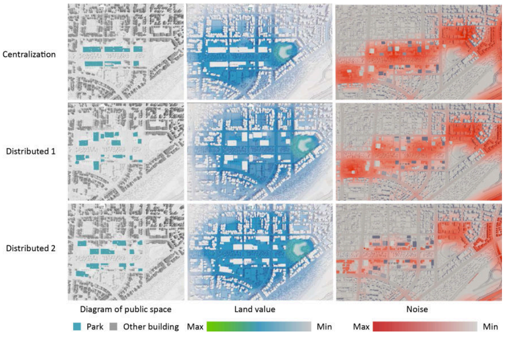

Figure 6. Process of intervention 3- insert public space.

4.2.5. Final result

After several operations of each intervention, then integrate above three methods in the game to get a comprehensive effect. Unexpectedly, the operation mode of functional mixed also activated the site price combine with the inserted green space, because the green space can properly isolate the noise. Adjust the original plan according to the selected operations, which are evaluated in real-time dynamic model, and finally get the adjusted design project. Considering the limitation of article length, only the final and appropriate results are displayed for each intervention method, and the comparison and selection process of the interference factors under the same operation, such as quantity, orientation, influence range and other factors, is omitted.

5. Conclusion

This paper demonstrates the feasibility of using simulation games as a dynamic simulation system for design practice. The results show that dynamic model effects can simulate the actual urban environment during operation and intuitive display the trend of data flow during the urban work, which makes problems once overlooked can be directly observed. Secondly, based on system's features of interactivity and real-time feedback, the impact of design operations can be directly demonstrated, such as the feedback of intervention results in real-time in this practice, which lead to the adjustment of design strategies. To sum up, the game-based dynamic simulation model can assess whether the current operation is appropriate and adjust it in real time. On the other hand, the game lowers the threshold for users to participate in urban practices, allowing more non-professionals to participate in their own community construction.

However, compared with the scientific modeling software, simulation game's feature of closed source, which limits the connecting with other software and the output of the results. And for the specialty in gameplay, the dynamic constraint framework between factors in the real environment is simplified in game, affecting the accuracy of the results. So, using simulation games, a kind of real-time feedback dynamic simulation model, instead of simulation tools needs a further study. On this basis, we should not limit ourselves in using games instead of any scientific design tools. Take the advantages embodied in simulation games, we should integrate these into existing simulation models in the next step, so as to obtain a more mature dynamic simulation model.

Acknowledgement

This research work is partially supported by National Natural Science Foundation of China (NSFC), Research on the Generative Design Method of the Traditional Architecture and Settlement Conservation Planning Based on the Digital Chain System (No. 51778118).

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A MACHINE LEARNING-BASED METHOD FOR PREDICTING URBAN LAND USE

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Abstract. Land use is one of the most basic elements of urban management. In urban planning and design, land use is often determined by experience and case studies. However, the development of urbanization has led to a combinatory trend for land use, and the land use of a plot is always impacted by the surrounding environment. In such a complex situation, it is difficult to find hidden relationships among types of land use by humans alone. Within artificial intelligence, machine learning can help find correlations among data. This paper presents a new method for learning the rules relating the known land use data and predicting the land use of a target plot by constructing an artificial neural network. We take Nanjing as a specific case and study the logic of its land use. The results not only demonstrate associations between the surroundings and the target but also show the feasibility of a combinatory land use index in urban planning and design.

Keywords. Land use; Urban planning and design; Machine learning; Artificial neural network.

1. Introduction

In urban planning and design, the determination of land use in the early stage is crucial. In the past, designers completed this task empirically. With technological development, designers began using new tools, such as geographic information systems (GIS), to quantify the surrounding environment to analyze the land use of the target plot. Although the tools have changed, the final determination of land use still depends on human judgment. However, the city is currently a complex system that is becoming increasingly spatiotemporally flexible. Meanwhile, land use has also developed from single to combinatory. In this case, it is almost impossible for humans alone to find detailed rules among data, while computers have the potential for solving this problem.

Within the field of artificial intelligence (AI), which is a general term for technologies using computers to solve intelligent problems as humans do, machine learning (ML) can automatically improve model performance through experience (Jordan and Mitchell, 2015), or as we say, through learning the correlations among data. Neural networks (NNs) are one of the most popular types of ML algorithms.

In urban planning and design, many studies using digital technologies involve land use. In computational urban design, land use is only part of the design; it

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 21-30.

is often initially given directly (Wilson et al., 2019) or simulated and optimized based on a goal during the design process (Nagy et al., 2018). In either case, the important aspect is the detailed functional organization, and the macro land use is always determined in advance. Urban planning takes more account of land use and cover change (LUCC). Planners use various models, such as the RPA econometric model (Wear, 2013) and the CA-Markov model (Al-sharif and Pradhan, 2013), to simulate and predict long-term LUCC dynamics. The applications of NNs to LUCC fall into two main categories (Wu and Silva, 2010). First, NNs are used for the classification and pattern recognition of land use for high-resolution satellite maps (e.g., Luus et al., 2015). Second, artificial neural networks (ANNs) are used to seek suitable parameters for CA models (e.g., Guan et al., 2005). These studies have wide study areas and rough classifications (including built-up areas, agricultural areas, forests, rangelands, water bodies, wetlands, wastelands, etc.).

This paper falls between the two urban fields; the goal is not to design detailed functions at the micro scale or to simulate urban growth at the macro scale, but to predict the land use of a certain plot based on ANNs. It is undeniable that the factors affecting land use are complex, including the land use of surrounding environments, topography, climate, policies and so on. Tobler's first law of geography ("Everything is related to everything else, but near things are more related to each other.") emphasizes the influence of neighboring space. Therefore, as a preliminary study, this paper takes the surrounding land use as a major factor in the research. We build an ML model to explore the impact of the surroundings on the target plot. As a result, the computer can learn a city's logic of land use and output a land use reference for a target plot based on known urban data and logic.

2. Modeling

The prediction model includes three modules-data definition and collection, dataset processing and model training-the functions of which are to collect the raw land use data, obtain the input dataset of the neural network, and train the final model. Figure 1 shows a concise research workflow.

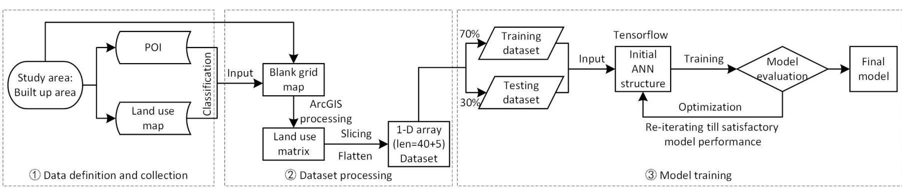

Figure 1. Research flowchart.

2.1. DATA DEFINITION AND COLLECTION

Since each city's logic of land use is quite different, and the functions of urban built-up areas are usually fully mixed after years of development, mining such data may guide urban construction and transformation. Therefore, we define the data collection area as a built-up area in a city to learn its unique logic.

Rough land use data can be obtained from current urban land use maps, which are usually out of date and cannot match reality; additionally, the classification is not fine enough to show the regional mixed status. Then, we considered points of interest (POIs), each containing up-to-date information about the name, coordinates and detailed function of a point on the map. However, using POIs still leads to a problem; for functions with a single use but large area, such as universities and industrial areas, one point obviously cannot cover the actual area. Therefore, we take the current land use map as the base map, and the real-time POIs we crawled as the basis for refinement, combining these two approaches to obtain accurate raw data.

2.2. DATASET PROCESSING AND NEURAL NETWORK SELECTION

Raw data must be processed and format-converted to generate the model input. Only by selecting a suitable representation of the data features and a suitable type of neural network is it possible to build a satisfactory model.

This paper classifies land use into five basic categories: commercial and business facilities (B), industrial (M), administration and public services (A), residential (R) and green space (G). Table 1 presents details about this classification, referring to GB / T 21010-2017 "Current land use classification".

Table 1. Land use classification.

ID	Code	Land use	Description
0	B	Commercial and business facilities	Entertainment, restaurants, shopping, hotels, business
1	M	Industrial	Industrial parks, factories
2	A	Administration and public services	Medical, educational, cultural, sport
3	R	Residential	Residential area
4	G	Green space	Parks, scenic spaces, city squares

We grid the study area at a certain scale, match the land use data to each corresponding grid, calculate the proportion of each of the five categories and obtain a matrix. Here, considering the land use complexity, in order not to lose too much information, we use the proportion data to represent the entire grid area instead of finding the maximum value to obtain a single dominant category.

We use supervised learning, so the input data require corresponding "labels" to be compared with the prediction results. We slice the matrix at a fixed size, such as the most basic 3 x 3 grid in Moore neighborhood theory, and create two 1-D arrays to store the data of each slice. One array stores 40 proportion values in the surrounding 8 grids as input data, and the other array stores 5 values in the middle grid as the labels. By this step, an input dataset has been generated.

Regarding the selection of the NN, the models commonly used in the urban field are convolutional neural networks (CNNs), generative adversarial networks (GANs), and ANNs. The first two models process image input, and ANNs process numerical input. Since the proportion data are more suitable to be expressed in numerical form than in image form, we select an ANN, which is one of the most basic neural networks, as our main model framework.

2.3. CONSTRUCTION, TRAINING AND OPTIMIZATION OF THE NETWORK

We use Python to construct the ANN model based on TensorFlow, which is an open-source ML platform. A neural network normally has an input layer, one or more hidden layers, and an output layer. We need to define the number of hidden layers, the number of neuron nodes in each layer, the learning rate, and other hyperparameters. We also need to select an appropriate activation function, optimizer function, and variable initializer function. It is usually impossible to find the most appropriate settings for optimal model performance initially, so continuous adjustment and optimization are necessary.

In a common NN learning task, a training set and a testing set are required. The training set, which is "known" to the network, is used for repeated learning, and the testing set is used to test the model performance on the "unknown" new data. The whole dataset is randomly divided into a training set and a testing set at a ratio of 7:3 and input into the model to train for a certain number of epochs (one epoch means training once with all samples in the training set). Meanwhile, evaluation functions are used to evaluate the model performance, functioning as the basis of adjusting and optimizing the parameter settings.

Evaluation functions usually calculate the loss and accuracy of the model.

A loss function calculates the degree of non-fitting of the network to the supervised data, and the larger the function value is, the worse the performance is. The network takes the value as a metric to automatically seek the optimal weight and bias parameters in the training process. Here, the cross-entropy error function is used as the loss function.

An accuracy function can assess the model performance directly. Different tasks define different functions. In computer science and statistics, we can calculate accuracy by judging if the prediction is equal to the label. However, urban issues are complex, and there is usually no absolute right or wrong. Rather than exact equality, we are more concerned about whether the prediction is approximately consistent with the label within a certain error range. Therefore, we combine qualitative and quantitative methods and define a validity score function:

$$S_1 = \frac{C_a \cdot 1 + C_b \cdot 0.7}{C} \tag{1}$$

$$S_2 = 1 - variance(Prediction - Label) \cdot 5 \tag{2}$$

$$S = S_1 \cdot 0.3 + S_2 \cdot 0.7 \tag{3}$$

C_a represents the sample count of the main category in the prediction matching the label, C_b represents that of the secondary category matching the label, and C represents the total sample count. S_1 calculates the matching degree between the dominant category of the label and the first two categories of the prediction. S_2 calculates the variance of the difference array between the prediction and label data to indicate the degree to which the prediction deviates from the label. S_1 and S_2 account for 30% and 70% of the final score S, respectively.

We compare and adjust each parameter that may affect model performance. When the validity score and loss value reach a relatively satisfactory level, we end the training process and obtain the final prediction model.

For a target plot of unknown land use, we can load the final model and input the surrounding land use data to generate the proportion as an auxiliary reference in the early stage of planning and design. Considering the differences in the logic of different cities, we only apply the model to areas of the city from which we collected data, rather than a different city.

3. Case study

3.1. DATA DEFINITION AND COLLECTION

This paper takes Nanjing, Jiangsu, China, as a case study and its old town as the study area (figure 2); the old town is surrounded by old city walls and covers an area of approximately 43 square kilometers. The old town's land use has been fully mixed over time, and we believe it is worth studying. Figure 3 shows the key steps in data collection. We used web crawler algorithms in Python to collect the data. We crawled the current land use data (2018.02) of Nanjing from Baidu Map (3a) and POI data (2019.11) from Tencent Map (3b). After the reclassification, the number of the five categories of POI data are 36398, 795, 20218, 8402 and 693.

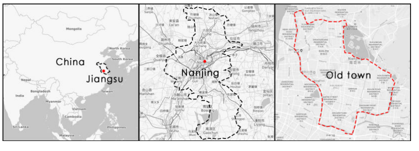

Figure 2. Study area.

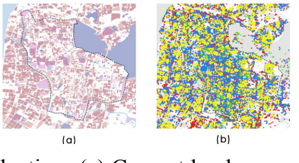

Figure 3. Raw data collection. (a) Current land use map. (b) POI data map.

3.2. DATASET PROCESSING

Figure 4 shows the key steps in dataset processing. We grid the study area at a 100 m x 100 m scale (4a) and superimpose the data on the grid to obtain a land use grid map (4b). For each grid, we create a 1-D array to store its proportion data in the order of B, M, A, R, and G and obtain a matrix. The matrix is then sliced at a size of 3 x 3 and divided into input data and label data (4c) to generate a dataset for the following learning process.

However, the existence of entities, such as roads and rivers, results in incomplete data coverage of the study area. There are still some grids with no land use data. Therefore, when sliced, only samples for which all 9 grid squares have proportion data that sum to 1 are stored in the dataset. Out of the 4373 grids in the old town area, 4049 have data. Finally, a dataset with 2902 samples is generated.

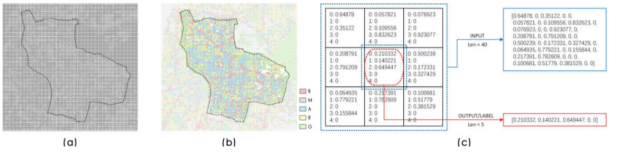

Figure 4. Dataset processing. (a) Blank grid map. (b) Land use grid (the color represents the dominant category). (c) Matrix slicing and conversion to a 1-D array.

3.3. CONSTRUCTION, TRAINING AND OPTIMIZATION OF AN ANN

After constructing an initial network, we randomly divide the dataset into a training set and a testing set at a ratio of 7:3 to input into the model. The parameters are repeatedly adjusted and optimized based on the validity score and loss. Figure 5 shows the final structure and settings of the model. We construct only one hidden layer, and the node numbers of the three layers are 40, 80 and 5.

The final training process has 1500 epochs. The validity score on the training set and testing set reaches 72.21 points and 61.07 points, respectively, when it stabilizes, and the loss value is 1.078 (figure 6). Judging by the model performance, we believe this model is legitimate and effective to a degree.

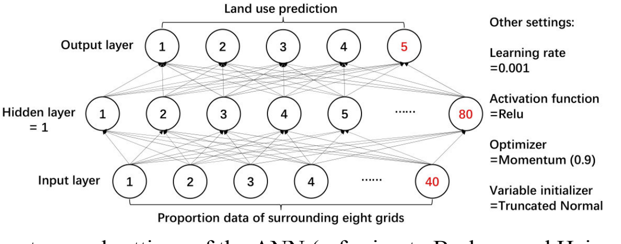

Figure 5. Structure and settings of the ANN (referring to Basheer and Hajmeer, 2000).

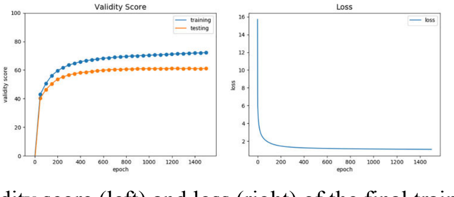

Figure 6. Validity score (left) and loss (right) of the final training process.

4. Result analysis and discussion

4.1. LEARNING PROCESS ANALYSIS

To explore how the NN is “learning”, we output the predictions of the training set at certain epoch intervals and analyze their changing trends in the whole process with a vertical comparison. Figure 7 shows four examples of the analysis.

As shown, in the beginning, when the parameters have just been initialized, nothing has been learned, and all the values are in a completely random state. During the first 300 epochs, the random initial value changes rapidly to approach the target value. When epoch = 600, an approximate proportional distribution has been formed, and the score has reached a high level. Then, the value change tends to slow, undergoing only some fine-tuning. This trend is consistent with that of the validity score and loss. This result indicates that the model learning process is to first quickly determine a wide value range based on the target and then to perform fine adjustment and optimization in a small range to approach the goal.

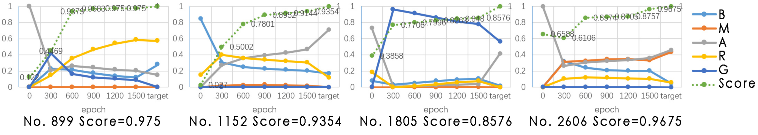

Figure 7. The change of the prediction value at different training epoch intervals.

4.2. MODEL PERFORMANCE ANALYSIS

The final model is applied to a testing set with 871 samples. We calculate the score distribution of the predictions (table 2) and select one sample from each score range for display (figure 8). As presented, 60.73% of the samples are above B-level, 22.39% are in C- and D-level, and the remaining 16.88% deviate largely from the labels. This result shows that the computer can learn reasonable relationships among most of the data. In general, the model performance is satisfactory.

Table 2. Score distribution of the prediction results.

Score	Number	Level	Proportion
≥80	376	A	43.17%
60-80	153	B	17.57%
40-60	111	C	12.74%
20-40	84	D	9.64%
0-20	59	E	6.77%
≤0	88	F	10.10%

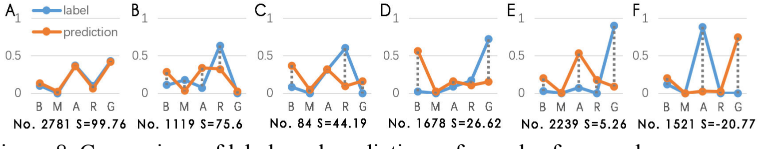

Figure 8. Comparison of labels and predictions of samples from each score range.

To explore on which types of samples the model performs well, we calculate the average land use proportion of the surrounding grids in different score ranges (figure 9). As shown, the prediction performance is better for samples with relatively low G proportions and relatively high A proportions in the surrounding plots. This result suggests that G data are uncertain and that it is difficult for a computer to learn their rules, while among A data, rules are easier to find.

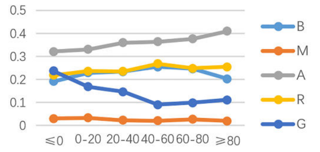

Figure 9. Average land use proportion of the surrounding plots in different score ranges.

4.3. RULE ANALYSIS

Therefore, what rules does the neural network find? We analyze the A-level samples with the best performance. Table 3 presents samples grouped by the dominant land use of the prediction. The proportions of the surrounding and predicted land use and the average validity scores are calculated for each group.

Table 3. Data statistics of A-level samples.

	Dominant land use	Proportion of surrounding land use B	M	A	R	G	Proportion of predicted land use B	M	A	R	G	Average Score
Level A	B	**39.90%**	2.08%	36.12%	15.52%	6.38%	**52.16%**	2.39%	28.33%	14.48%	2.64%	92.46971
	M	12.72%	**21.50%**	**34.29%**	23.61%	7.88%	6.85%	**55.82%**	28.94%	5.19%	3.20%	**85.57333**
	A	19.84%	2.36%	**54.31%**	16.75%	6.74%	18.71%	3.03%	**56.51%**	16.04%	5.71%	91.58159
	R	17.22%	1.17%	28.05%	**48.33%**	5.23%	17.35%	1.07%	22.64%	**56.43%**	2.51%	91.82046
	G	14.78%	0.99%	18.59%	14.60%	**51.05%**	5.53%	0.36%	11.23%	6.19%	**76.70%**	94.77

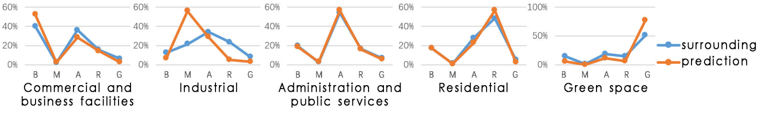

Figure 10. Comparison of surroundings and predictions for each group.

Several rules are derived from the prediction results:

- All kinds of land use tend to cluster; this is particularly obvious in M and G.
- G has a strong tendency to be away from M.
- B, A, and R are somewhat mixed with each other.
- A is relatively scattered, occupying a certain proportion of other categories, and M is only compatible with A.
- G is relatively isolated and less mixed compared with other categories.

These rules are consistent with our common knowledge, showing that the computer can truly learn from the data. However, it must be emphasized that only with sufficient high-quality data can we make full use of machine learning.

We compared the land use proportion between the surrounding areas and the prediction for each group (figure 10). As shown, except for the M-dominated condition, the two lines almost coincide, and the proportion of the dominant category is scaled up compared with surroundings. This surprising similarity between the two lines may be one of the computer's prediction principles.

The M-dominated prediction deviates largely from the surrounding conditions, and the score of the M-dominated group presented in table 3 is lower than that of the other four groups; perhaps the reason is that the industrial sample size is too small. Enlarging the dataset may improve performance on this part of the task.

We also perform the same statistics on the worst-performing F-level samples and compare them with the A-level (figure 11). As shown, the surrounding land use of the F-level is more evenly distributed than that of the A-level, and the dominant category is not so prominent (11a). However, the prediction distribution is similar to that of the A-level, and the proportion is also exaggerated (11b).

Perhaps the dataset is too small for the computer to learn deeper rules. Perhaps the computer is making reasonable predictions according to the rules it has learned, but reality is not consistent with the rules. Whatever the cause, we need to know that a city is affected by various unpredictable factors. It will not always develop according to a fixed rule, as a computer does. The input data are limited anyway, and a computer cannot go beyond the dataset to learn other factors in reality.

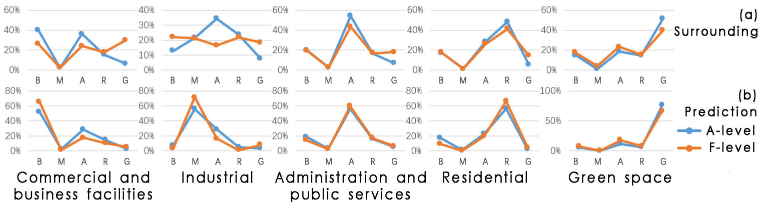

Figure 11. Comparison of A-level and F-level samples.

4.4. POTENTIAL APPLICATION

Figure 12 demonstrates a model application. We assume a simple surrounding condition of [G, A, R, G, B, R, R, B], load and run the model and get an output of [0.2177, 0.0859, 0.0166, 0.6635, 0.0163], predicting that the dominant land use is R. Currently the model can only predict one unknown grid at a time. We will try to expand the application area to more grids to make the model more practical.

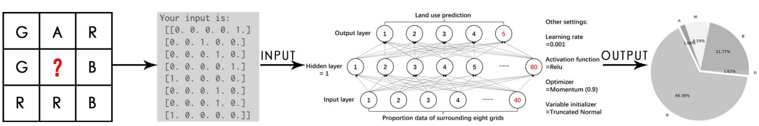

Figure 12. Model application demonstration.

5. Conclusion

Cities are currently very complex, and land use also tends to be combinatory. It is difficult to find all the associations among land use data by humans alone. This paper applies ML methods to urban areas, building an ANN model to predict the land use of a target plot based on the surrounding environment. We combine POIs and current land use data to obtain a relatively accurate land use grid in a GIS, which is then converted into a matrix and sliced. The data are finally input into the model as 1-D arrays for subsequent training, testing, and optimization processes. We take the old town area of Nanjing as a case study and obtain a relatively satisfactory model. The results show that the computer has found certain rules relating the surroundings and the target. In addition, a feasible research workflow for combinatory land use prediction has been established.

However, reality is complicated. Even if a model is perfect, it cannot perfectly cope with rapidly changing cities. Therefore, at least for a long time, AI will not be able to replace humans in directly making decisions. Functioning as an auxiliary reference tool, our model provides a new choice in machine logic for urban planning and design, and this is exactly what we currently want.

As a preliminary study, this paper uses simplified methods in the workflow, leaving room for improvement. The following aspects are considered for improving our research. First, we will collect data from other cities and generate corresponding models, comparing and analyzing different logics of land use. Second, we will improve the model structure, changing the value of variables, such as grid scale and slicing size. Third, we will add other influencing factors to the data input, such as topography and climate. In the future, we will continue this research to build a more effective and comprehensive prediction model.

Acknowledgments

This research was supported by National Natural Science Foundation of China (51578277) and Major Program of National Natural Science Foundation of China (51538005). The authors wish to thank Hao Zheng for his helpful advice, and to thank Chuanjia Gong and Yu Luo for their help in data collection.

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COMPARATIVE STUDY ON URBAN VIRTUAL MODELING PLATFORMS FOR URBAN PLANNING AND DESIGN PRACTICE

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Abstract. This paper examines urban virtual modelling platforms (UVMPs) to be used for urban planning and design practice, thus following points are revealed; firstly, comparing existing platforms in the case study, capability of each platform is pointed out. Secondly, potentials of UVMPs for urban planning and design process, including A) Collaborative Design, B) Simulation-based Design and C) AI-involved Design are also tested in the case study. Consequently, a possible system with above potentials is tested and the workflow for urban planning and design practice using UVMPs is suggested.

Keywords. Digital Twin; Urban Planning; Collaborative Design; Simulation-based Design; AI-involved Design.

1. Introduction

3D modeling technology in city scale has been developed recently and even building submission with BIM model has been implemented in advanced countries and regions such as Hong Kong, Singapore and Northern European countries (McAuley et.al, 2017). ‘Virtual Singapore’ (Nrf.gov.sg, 2018) project is one of the case studies in which detailed 3D building models of the entire city are imported to data platform run by several public authorities as “Digital Twin City” and various simulations, such as wind, flood and evacuation analysis are implemented on the platform by several public authorities. Virtual Singapore project implied several potentials of Urban Virtual Modeling Platform (UVMP), that is defined in this paper as browser-based city-scale 3D modeling application, for urban planning and design practice. The first potential is A) Collaborative Design. Sharing the urban virtual modeling platform, several planners and engineers can study new interventions and implement multiple types of analysis and simulations simultaneously. Typically, in the past, the administration of streets, parks and public buildings were often maintained by different parties. Projects of one party

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may not be recognized by other parties. With sharing the urban virtual models among related parties, planners can recognize the projects of other parties. The communication and collaboration among them can be enhanced.

The second potential is B) Simulation-based Design. Considering existing buildings and urban context, various options for planned buildings/urban configurations can be studied and evaluated with multiple analysis such as CFD, solar radiation, shadow and multi-agent simulation. However, in order to obtain the result of these studies, the analyses/simulations of design options require multiple times of large-scale calculation although most of the unselected calculations are not necessarily used. Besides, sampling the analyses of studies with random seeds or metaheuristic methodology such as Galapagos (Rutten, 2013) on Rhinoceros (Rhino3d.com, 2019) and Grasshopper (Grasshopper3d.com, 2019) are not efficient since the calculation each time is very time-consuming.

Therefore, as a hypothesis, the third potential of urban virtual modeling platform, C) AI-involved Design, can be considered to feed the results of the analyses to machine-learning process. This enables possible analytical suggestions of changing geometry during the process of searching design options. Based on the previous data collected during the process, this method can dramatically reduce the number of necessary samples during the decision-making process.

Thus, this paper aims to examine the above three potentials of urban virtual modeling platform to be used for urban planning and design practice, especially in the early phase of master planning or large-scale development when several urban scenarios and urban configurations are tested and discussions and communications with multiple stakeholders are required to decide a clear direction before proceeding to the drawing and documentation phase. Therefore, in this paper, the necessary functions of platforms are evaluated based on studies at building volume level but not detailed modeling level.

2. Background

In the field of architecture, urban planning and design practice, Rhinoceros, Revit, AutoCAD and Sketchup are the currently popular software for 3D modeling. However, a key constraint of them is that these software products are localized. In short, they operate on remote desktops, and files are stored on private servers. (Leung et al. 2018). Thus, there are several examples of browser-based platforms that allow collaboration for architecture, engineering and construction (AEC) industries. Redback BIM (Leung et al. 2018) focuses on developing a 3D modeling web application which allows browser-based, real-time collaboration among multiple users. It also intends to be an open-source application. However, it is still under development and does not yet support analyses and simulations for large city scale. Speckle(Speckle.systems, 2019) is an open source data platform for AEC industries, which is operated on the cloud and allows for data transfer not only from one software to another on a local machine such as Revit, Dynamo, Rhinoceros and Grasshopper, but also across networks and various web platforms.

Considering the process of urban planning, working on geo-located environment is another important aspect to locate models from different parties.

3D EXPERIENCity (Dassault Systèmes®, 2019) is a browser-based, geo-located platform which is used as a base system for Virtual Singapore project. As shown in the Singapore case, it allows collaborative modeling among different parties and implementation of analyses and simulations on the platform. ArcGIS Urban is an immersive 3D experience designed to improve urban planning and decision making (Esri.com, 2019). It is browser-based, and allows for storing geo-located information including plans, existing building models and new projects. ArcGIS Urban is used in several case studies in Boston, San Francisco and Zurich in Switzerland for urban planning. Giraffe (Giraffe.build, 2019) is a different type of platform which allows parametric modeling in geo-located environment in Mapbox(mapbox.com, 2019) based on Rhinoceros and Grasshopper system. It is also an open-source platform which allows for programmers to create their own apps that work in the platform for any modeling and analysis functions. Spacemaker(spacemaker.ai, 2019) is a browser-based application that works especially for residential industries currently. It allows parametric installation of pre-defined urban settings in the site based on the machine-learning solution of existing residential plans. After the selection of possible urban setting by developers and planners, multiple preset analyses including visibility, solar radiation and daylight are able to run on the same platform. Although it shows certain potentials to be used in urban planning and design process, Spacemaker is not yet an open-source platform and thus not able to be tested in this paper. Since our goal is to explore the aforementioned three potentials of UVMPs, 3D Experience, ArcGIS Urban and Giraffe are selected as platforms to be examined in the case study to find out the procedure and possibilities of UVMPs to be used for urban planning and design practice.

Table 1. Comparison of browser-based modeling platforms.

	Platform	Browser-Based	Open-source	Analysis and Simulation	Geo-located
1)	Redback BIM	○	○	X	X
2)	Sparkle	○	○	△	X
3)	3D EXPERIENCity	○	X	△	○
4)	ArcGIS Urban	○	X	△	○
5)	Giraffe	○	○	○	○
6)	Spacemaker	○	X	○	○

3. Problem Statement and Proposal

3.1. PROBLEM STATEMENT FOR THE CASE STUDY

For volume study for urban design, various simulations in a large scale have to be implemented repeatedly. For instance, in this case study in Marunouchi Area of Tokyo Japan, the following simulations have been tested on Giraffe (Giraffe Technology, 2019): Radiation analysis for reducing heat gain, CFD (computer fluid dynamics) for analysis and visualization of wind flow, agent-based simulation for pedestrian flow in order to enable more activities and higher efficiency of route for connectivity. Three existing problems of inefficiency have been listed as follows: 1) Problem statement for Collaborative Design - A number of software is used for one project. In an economic-driven society, this situation may not change. However, on the other hand, there has been ardent desire to have a universal standard for them to be used widely. Browser-based modeling applications (BMAs) could be one of the potential solutions to realize true collaborative design. 2) Problem statement for Simulation-based Design - The amount of computation is huge and the process is time-consuming. This is simply because urban design has a larger scale than architecture. In the case of the urban district planning, although only one small part of the urban tissue has been changed, however, the rest of the model which remains the same is repeatedly tested. The greater part of the calculation tends to be overlapped. Thus, a huge amount of calculations and simulations is always wasted. 3) Problem statement for AI-involved Design - In current workflow of design practice, most of the time the analyses, such as wind or light analysis, etc., are outsourced to vendors or consultants. This way of working helps designer to rediscover the design by having it evaluated by a third party to obtain a different point of view. However, this procedure costs both time and labor for transferring information. This AI-involved may enable a prompt and speculative design procedure.

3.2. REQUIRED SPECIFICATION OF THE SYSTEM

The following conditions are suggested as the required specifications for the case studies corresponding to the problem statements A, B and C. 1) To implement Collaborative Design - the platform should be browser-based to cater for multiple users Common rules such as the use of geo-referenced CAD or BIM data, level of details and data formats are also required. 2) To implement Simulation-based Design - the platform should enable multiple simulations such as wind, heat, etc. to be operated directly on the same platform or closely linked (does not mean physical space) with other simulation engines. It should also allow for prompt evaluation of various design options. 3) To integrate AI-involved Design - recent development of machine-learning related technology has provided new opportunities and some AI-like system is expected as a partner or partners for speculative design. This AI may return answers or suggestions as draft to connect with the above specification 2).

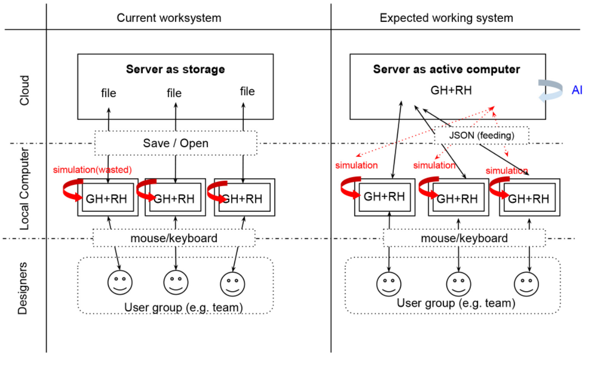

Figure 1. Proposing System Diagram.

This proposing AI simulation and suggestion system enables architectural designers to grasp the real sense of time. For instance, when a designer drafts a footprint of geometry on Giraffe, surrounding wind speed will be estimated in real time. Design scheme can be reviewed immediately as a result. This helps reduce the number of schemes and enhances efficiency by narrowing down the design schemes in early stage of architectural planning and urban design.

3.3. PROPOSING AI SUGGESTING SYSTEM

In parametric modelling, designer has to search for better design, but should avoid round-robin evaluation as it is almost impossible in practice due to time constraint. Hence, authors assume that this system should have some strategies to find out the better design following better simulation method other than limited number of sampling by humans. This case study proposes a 'weak' artificial intelligence (AI) approach, that is, using neural network model developed by Lunchbox (Proving ground, 2012-), a plug-in of grasshopper (GH), to solve the following issues. P1) This online system must have a function to suggest an estimated result to users in real time. Immediate response of system may improve interaction with other designers as well as with AI. P2) Artificial Neural Network (ANN) is selected to be used in the case study. The method that consists of both heavy and meta-heuristic simulation is not effective in this case as one generation of calculation is too heavy and time-consuming even under effective solving mode. Random sampling method does not give reliable result, too. P3) If the design team is consisted of multiple designers or architects, the system should not waste their design attempts, and the simulation results. Proposals from professionals have contained useful information from their experiences. This system should collect this information as feeding data to possibly generate an estimated design that may not be experienced before.

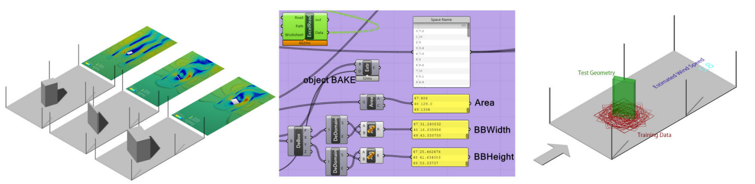

Figure 2. Execution window pictures.

Figure 2 shows the experiment settings. The data on the left is the training data, the one on the right is the testing data. Currently this system is working as a 2-dimensional system. The current feeding elements are wind speeds at 7 matrix-ed points on the field. (Fig.2) Also current design parameters are footprint of a architecture-like obstacle, areas of footprint, the width of the bounding box of footprint and the depth of bounding box of footprint. There could be more efficient parameters, such as sharpness of corners. The result of this experiment may help to figure out effective geometric parameters. In this experiment, we connect to Excel read plug-in and, reading temporal file from RhinoCFD (Cham 2017).

4. Methodology

4.1. CASE STUDY

To examine A) Collaboration Design and B) Simulation-based Design process of the platforms, Marunouchi area, a 120ha CBD of Tokyo, is used as a case study and each platform is tested in 3 phases. 1) Existing context data including base maps, digital elevation model (DEM), 3D buildings with different level of details (LOD) obtained from both public and private parties are imported (Table2). 2) New project model is imported to and sketched on the platform to understand the usability and parameters during modification process. 3) Possible analyses/simulations implemented both directly on the platform and in the external application are tested to understand the flexibility and the exchange process between applications.

Table 2. Imported data in the case study of Marunouchi District.

	Data Type	Format	Data Source	Detailed Explanation
1)	Base Map	Shapefile	Geospatial Information Authority of Japan	Base Map as a guide to import 3D building models
2)	Aerial Image	JPG	Geospatial Information Authority of Japan	Surface of terrain model
3)	DEM	GeoTiff	Geospatial Information Authority of Japan	Terrain model
4)	3D buildings (LOD1)	OBJ	Owned by auther	Extruded simplified volume model
5)	3D buildings (LOD2)	OBJ	Owned by auther	Extruded model with façade image mapped.
6)	3D buildings (LOD3)	OBJ	Owned by auther	Detailed building model
7)	Tree plot data	Shapefile	Owned by auther	Tree plot data within the district
8)	Tree elevation image	JPG	Owned by auther	Tree elevation data to display trees

In this paper, C) AI-involved Design process is examined only in Giraffe platform, since it supports customized applications in connection with Rhinoceros and Grasshopper system. It gives flexibility to the users to write their own code on the platform, while 3D EXPERIENCE and ArcGIS Urban are not open source and currently AI feature is not yet installed.

4.2. METHOD TO EVALUATE

In order to prove the efficiency of suggested system, firstly it is necessary to see whether this system can reduce time to return analysis results rather than having new simulation. Secondly, this ANN system has a certain degree of accuracy depending on the number of feedings which links to the quality of training. The proposed system has to be fast and precise enough to provide designer a tool for real-time interaction. For the calculation time, author uses profiler in GH which allows one to count how long it takes for the whole procedure of GH definition as well as part. For evaluating ANN's accuracy, the training geometries contain a combination of several parameters. The number of variations are more than 900,000. One hundred randomized patterns of training geometries are analyzed by CFD and wind speed data on the seven different points are stored. Based on this training data, ANN predicts wind speed for unknown test object. Five new typical test models are prepared to verify ANN's accuracy (but shown only two results, omitted because of space). The wind speed data for test geometries are predicted by ANN for every 10 piece of training data. They are also calculated by CFD. The gap between these data shows ANN's prediction accuracy. The basic ANN components are cited from lunchbox (proving ground 2011-), also the referring sample files are from website.

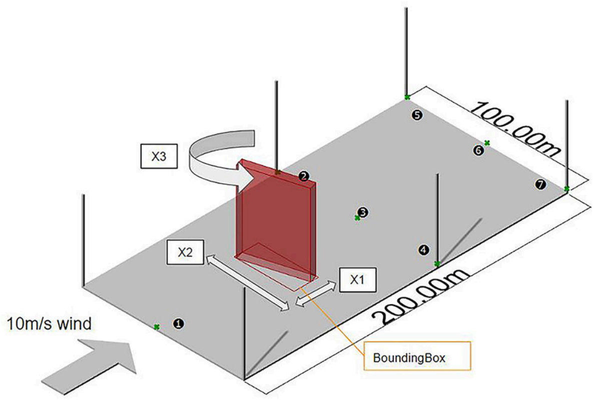

Figure 3. Diagram Experimental setting .

5. Result of case study

5.1. EVALUATION RESULT OF PLATFORMS

As a result of evaluating UVMPs in the case study of Marunouchi area, several features of each platform are extracted. 3D EXPERIENCity is good at extracting necessary information to be visualized from enormous and highly detailed models such as BIM models. On the other hand, in order to test new project within the urban models, it is only possible to import models and does not allow sketching directly on the platform. Visibility analysis works directly on the platform, while other analyses such as solar radiation and CFD are also available in other application within 3D EXPERIENCE package and to be integrated in the platform.

ArcGIS Urban works together with other ESRI package such as ArcGIS Pro(esri.com, 2019) and CityEngine(esri.com, 2019) It allows importing various types of data including Revit files. ArcGIS Urban uses procedural modeling (Müller et al., 2006) methodology. In the phase of testing new project, the models of possible options are able to be generated using predefined rules so that the design study process can be optimized. Type of analysis available on the platform is only basic and for further analyses. In most occasions, urban models need to be exported to external applications.

While the features of 3D EXPERIENCity and ArcGIS are dependent on the software provider and limited to customization to fit the workflow of urban planning and design practice, Giraffe allows flexibility to integrate any applications which can be run on Rhinoceros and Grasshopper environment. It means that it can implement not only analyses such as CFD, solar radiation, daylight simulation and shadow studies, but also multi-agent simulations to analyze people's behavior and genetic algorithm solver to find out optimized solution and AI-integrated machine-learning system.

Figure 4. Imported Result (Left: 3D EXPERIENCity, Middle: ArcGIS Urban, Right: Giraffe).

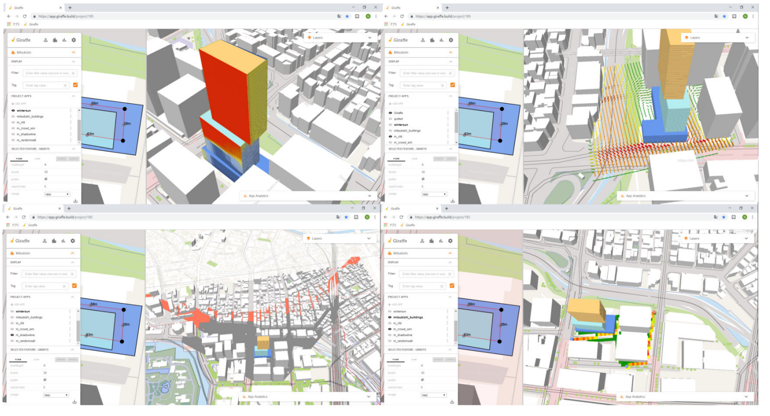

Figure 5. Analysis result in Giraffe (Top-left: Solar Radiation, Top-right: CFD, Bottom-left: Shadow study, Bottom-right: Multi-agent Simulation).

Table 3. Evaluation result of platforms .

	Platform	1) Import Data format	2) Insert new project	3) Process of analysis	4) Type of available analysis
1)	3D EXPERIENCity	SHP, OBJ, Image file	Import	Internal / External (3D EXPERIENCE)	Visibility (Internal) CFD, Solar Radiation, Shadow Study, etc. (External)
2)	ArcGIS Urban	SHP, GDB, OBJ, DXF, OSM, DAE, FBX, Revit and others (via ArcGIS Pro and CityEngine)	Import/Sketch	External (ArcGIS Pro)	Visibility, Solar Radiation, Shadow Study, etc. (External)
3)	Giraffe	SHP, OBJ, FBX, 3DS, and others (via Rhinoceros)	Import/Sketch	Internal	CFD, Visibility, Solar Radiation, Daylight, Shadow Study, Multi-agent Simulation, etc. (Internal, based on Rhinoceros+Grasshopper plugins)

5.2. EVALUATION RESULT OF AI SUGGESTING SYSTEM

The graph shows the difference between CFD-calculated and ANN-estimated wind speed with 10 to 100 training data. In general, there is a tendency of less error with more training data. The fastest case (e.g. model-1, figure 6), 20 feedings (simulations) are enough for predicting wind speed. However, in other cases like the oscillated case (e.g.model-3, figure6), it is not easy to predict the condition of the locations distant from the back of the obstacle. A wind simulation is recognized as a typical complex system, such as the widely known 'butterfly effect' in which local small changes may cause catastrophic change of the whole result. Thus, careful analysis of the result is expected. For 7 estimated points and 15 iterations, the calculation time for ANN is clearly faster than CFD analysis and meta-heuristics on computer in the current settings (Figure 6, below graph). When the case points are arrayed in matrix, calculation time may increase drastically with the increase of feeding numbers. Thus, the number of estimated points should be controlled, in order to use this system effectively.

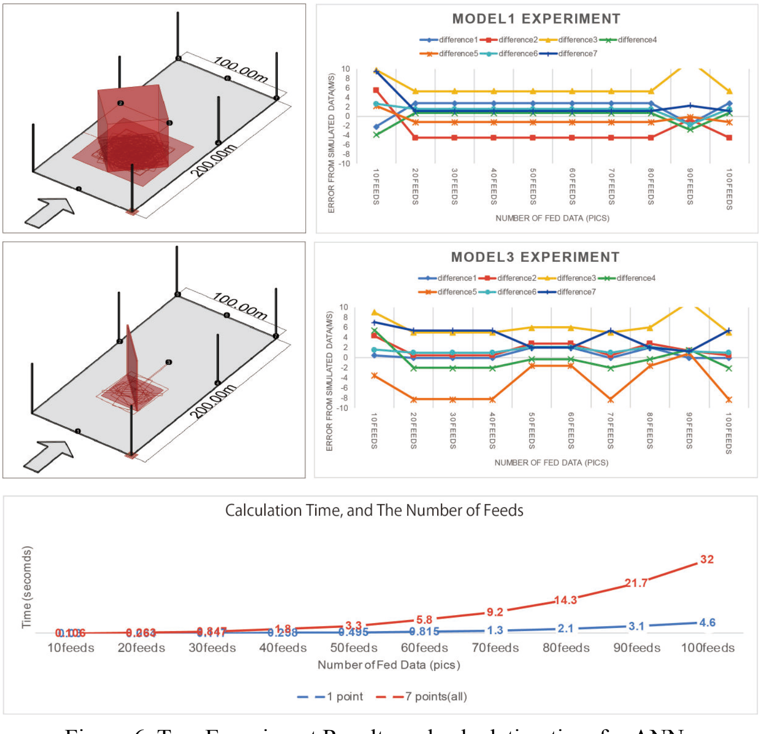

Figure 6. Two Experiment Results and calculation time for ANN.

6. Conclusion

This paper examined potentials of UVMPs to be used for urban planning and design practice. A) Collaborative Design with browser-based platform enhances communication and collaboration within the team and with other parties by sharing the information and recognizing ongoing projects shown on the platform. B) Simulation-based Design with implementing multiple analyses and simulations on the same platform shows the potential of modifying building shapes and receiving evaluation at the same time. Especially in the early phase of urban design practice, this workflow is able to optimize the design process and reach the best option faster. C) AI-involved Design, AI-involved suggestion system is proposed and worked on the BMAs (in this case Giraffe). The case study shows that wind flow could be estimated less than one second by using this system. Finally, the improvement of accuracy could be seen in this experiment. In simple scenarios when the wind is stable and steady, 20 feedings are enough to generate a decent result. The increase in feeding numbers does not improve the accuracy of the simulation. However, when the wind is in a non-steady state, the result is not accurate enough for useful feedback on design.

Acknowledgement

We would like to express our gratitude to Prof. M. Hank Haeusler; UNSW, and Mr. Rob Asher; Cox Architecture Sydney for their help and support of testing on Giraffe.

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HOPE IN PERTURBANISM

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Abstract. A fundamental assumption in this conference is that human actions in creating and modifying our constructed environments can be rethought and made better for the environment. There are few laboratories in which to conduct research; an isolated island system offers one such opportunity. This paper reflects on work that carried out in the past five years in the Galapagos Islands by a collaborative of researchers from five institutions. The research examines potential positive changes in urban settlements and their impact on a fragile ecology of the islands. In this work, we illustrate how small perturbations (disturbances) within urban systems can lead to changes not only within urban form but also in the citizen's environmental awareness and how these, in turn, can lead to positive changes in the environment. The paper discusses applications of models we developed using Python scripting, GIS, and agent-based modelling, as we applied them to design strategies, built outcomes and community awareness.

Keywords. Complex adaptive systems; urban design; CAS; panarchy.

1. Coupled urban and natural systems

By articulating an Anthropocene era, we are increasing awareness of the impact of human activity on the environment. Some suggest that the impact of human action on the environment can be best understood through the concept of coupled human-natural systems (CHANs) (Liu et al. 2007). While there is a growing awareness of the mechanisms by which we harm the natural environment, such as through pollutants and waste, the greater impact of human settlements is less examined and understood. Increasingly, insights call upon us to recognise that urban and natural ecosystems must be considered as coupled continuities (Batty et al 2019). Of particular relevance in this context, others have suggested that the environmental crisis is a design crisis (Van der Ryn and Cowan 1996). In the work discussed in this paper, we consider how design can engage with coupled urban-natural systems.

The term 'sustainability' is now over-used, devoid of meaning and has ceased to illuminate the path to secure a better future. There is no point in 'sustaining'

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 41-50.

what we have at the moment, we recognise that a dramatic change is needed to reset the framework (Karakiewicz 2016). But how do we introduce appropriate change without causing greater damage? Blastland (2019) tell us how we are still unable to admit to the fact that our knowledge is much weaker and less reliable that we think it may be. He also talks about our fear of uncertainty and gives us some advice how to deal with unavoidable uncertainty and still gain some credibility. One of his suggestions is: don't jump to conclusions. The other suggests that there are no "policy levers". And what we should do is to experiment and adapt if something will change. If we accept the believe that our future is full of uncertainties, and prediction are useless, and whatever we decide to do will be at least to some extend wrong, then we can assume that sometimes small disturbances or what we call small perturbation to the system might achieve better results than zoning, master planning and policy levers.

In our work we have been heavily relying on Complex Adaptive Systems (CAS) theories. CAS theory dominates many disciplines at the moment. And although CAS theory has originated in physical and natural sciences, there is now growing interest in the dynamic processes and global patterns that in many ways defy our believes and assumption about the world we live in (Eidelson 1997). In CAS, healthy systems require periodic perturbations that, in turn, allow systems to enrich themselves or reach the state of new complexity. This allows the system to be more resilient and more adaptable. Perturbations, or disturbances, can enable as disruptive innovations. We have supplemented our models in CAS with Cycles of Adaptive Change (Holling & Gunderson 2002) to illustrate the positive potential of perturbations that could lead to more resilient urban futures and positive changes in the environment.

2. Case study of Puerto Baquerizo Moreno

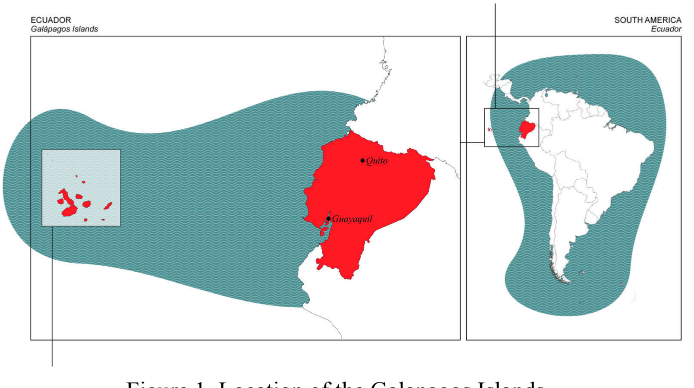

Figure 1. Location of the Galapagos Islands.

We chose to focus our work on the settlement of Puerto Baquerizo Moreno, the capital city of Galapagos Island, located on San Cristobal Island. The Galapagos Islands are located 1000 km from the South American mainland; therefore, it is relatively easy to consider the systems which operate in this extremely fragile and isolated environment (Fig.1). San Cristobal Island is relatively small, only 55,697ha, with a population of 7,330 people. Originally, Puerto Baquerizo Moreno was colonised for sugar cane and coffee plantations as well as cattle farming (Latorre 2001). While it depended heavily on farming, the fishing industry took over and by the 1970s fishing and tourism became to be leading industries. This resulted in many people moving from the farms, located in the island's hills, to the coast.

Today tourism is the main economic driver, with a few working the public sector, and very few people remain in the agriculture areas, consequently a majority of their food is import from the mainland. There has also been an increasing problem with invasive species since unattended fields provide a perfect place for invasive species to flourish, threatening this fragile environment. Another source of employment is in The Galapagos Science Centre (GSC), which was established in 2010 and now is an important centre for academic activities (Quiroga 2019).

The majority of the island is a protected national park. Human habitation is largely limited to the south west tip of the island. Here, the town of Puerto Baquerizo Moreno has 86.9 ha of surface area in all private and public ownership with a built footprint of 24.87 ha, which gives a ground coverage ratio of 29% (Lopez and Quiroga 2019). With such a low ratio and the challenge of an increasing population, there are many opportunities for densification instead of horizontal expansion. The urban area is defined by three main street running parallel to the waterfront, and one perpendicular road connecting the sea to the rural area. Most of the tourist activities are concentrated along the first two streets running parallel to the waterfront. The town is therefore compact with most parts, including the airport, readily accessed by foot or bicycle (Fig.2).

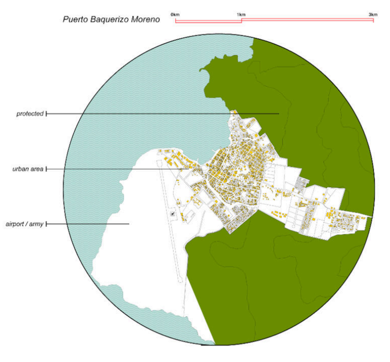

Figure 2. Puerto Baquerizo Moreno.

2.1. SETTING UP THE FRAMEWORK

We established the framework for our research and investigation, working with students and academics from the University of Melbourne, University of San Francisco de Quito, University of Chicago, University College London and the

Galapagos Science Centre (GSC), and aligning our work with that of the GSC by using CAS theory to examine urban change (Karakiewicz 2015, 2016).

In earlier work at the GSC had mapped the history of the islands onto Holling's cycle of adaptive change in order to show how major events through the history of the Galapagos Islands have led to regime shifts and allowed the islands to reconfigure to a new system (Gonzales at al. 2008). This depiction suggests that the islands are today in a unique position where there is no evident structure that emerges, despite several attempts from the Government, National Park, or National Special Laws, which were passed in 1998. Furthermore, there is clear evidence that the system may shift into undesirable stage if a favorable intervention is not made. This framed our design opportunity.

We used a framework based on panarchy model by Holling and Gunderson (2002) with three cycles of adaptive change operating at different speeds and scales (Fig.3). The functioning of, and signaling between, these cycles determines the survival of the overall system. In our model, the three cycles are: the environment (the biggest and the slowest acting), urban structure (the middle scale and the middle speed) and noosphere (the smallest and the fastest of all three cycles) (Karakiewicz 2019). The term *noosphere* is borrowed from Vernadsky (1945) and represents environmental awareness and the role of knowledge in society that informs and influence our actions. In this, we are particularly interested in the knowledge that is developed through our disturbances, or what we call perturbations within urban structure. What we want to find out is, how the conditions for a perturbation in the form of innovation are created and how knowledge emerges from this perturbation. If a proposed perturbation results in attitude change and the creation of new knowledge, the chances for another perturbation become greater and this, in turn, might lead to a transition towards a more resilient future.

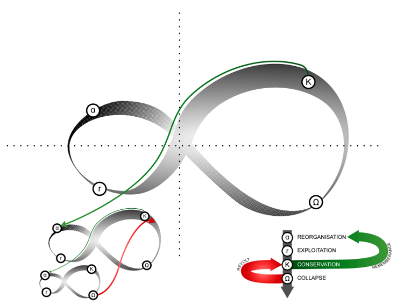

Figure 3. Reinterpretation of Panarchy model by Holling and Gunderson 2002.

In order to examine what perturbation might make a shift towards a more resilient future, we worked with the Batty model of coupled urban and natural systems. We were also aware that any perturbation we proposed should be recognized as positive. Changes are never easy and unless the population can perceive something of the value to them, they often fail. Therefore, we decided to add another element to the coupled system, that is, the noosphere of environmental awareness.

Through our models we are trying to find out how small perturbation could not only provide residents with possibility to reliable income, create employment for themselves and community, and in turn create economic benefit for many, but also how this perturbation could affect environmental awareness within community, create new knowledge, and new niches for more innovations and more perturbation to take place. We based our assumptions on theories derived from Bandura (1986), Kelling and Wilson (1982) and Bickhard (1992) who propose that the context can change human behavior. Amel et al (2017) and Klinenberg (2018) suggest that individuals have great potential in transition towards more sustainable futures through collective and collaborative actions through their connections, by forming networks, and find ways to support one another.

Identifying the most appropriate location for each perturbation within urban structure was therefore a priority. We wanted to make sure that our perturbation could benefit the largest number of residents by providing visible positive change towards a better quality of life, bringing new knowledge and expertise, key steps towards future development. We also wanted to make sure that our perturbations will become facilitators for building new networks for common benefit and mutual support.

The model was written in Python 3.x with an Object Oriented Programming structure in which the generic city parcel was the base unit (the Agent) to which parameters and attributes were associated, including the spatial location within an urban network model. Using a cellular automata approach, models were run iteratively and results visualised using a Grasshopper plugin for Rhinoceros 3d.

2.2. CHOOSING THE RIGHT LOCATION

As noted earlier, each of the cycles in the panarchy model works at a different speed and scale. Although the noosphere works at the smallest scale and the fastest speed, it is still very much dependent on the urban environment. Changing our context maybe more powerful way of shaping our behavior than trying to change our minds. So, if changing our context can influence our behavior the next question is what will be the best and most effective way to change this context, with limited or no resources? Furthermore, how to make sure that this process is not limited to just one event but instead creates a domino effect, which will continue for very long time, without final goal and ideal final condition.

In order to find the best location for our disturbances we started our work by mapping all the empty sites and sites with half-finished buildings (Fig.4). We mapped the location of all services, restaurants, hotels and other tourist accommodation. We collected data on pedestrian and vehicle movements in order to establish the most suitable sites for our perturbations. We established possible connections between variety of different functions, for example, how recycling water from the laundry can be used in hydroponic and aquaponic gardens, and how hydroponic and aquaponic gardens can support restaurant, etc. These connections helped students to define rules for their models.

3. Designing Perturbations

Our students focus was on understanding and applying a CAS approach and to design perturbations in the form of innovation that would redirect the urban landscape to a more desirable outcome. The computational model was designed as an agent-based model in which individual parcels of the city became the "agents". A network graph of the city was built in order to create relationships between all parcels such as connectivity and distance to each other. Each parcel would have its own set of attributes which came from the data that was gathered by the students through their in-person surveys of the city and provided digital information (public/private use, occupation of public space, interior public space, use, number of floors, etc.). The model was then programmed to work as a cellular automata model in which agents change their attributes based on the relationship to their closest neighbors and previous states. In this way, students could create their own logic and rulesets to define what would happen to a parcel if conditions around it changed. By having this framework in place, iterations of urban change could be introduced that would allow for a bottom-up gradual change over time to happen in the city.

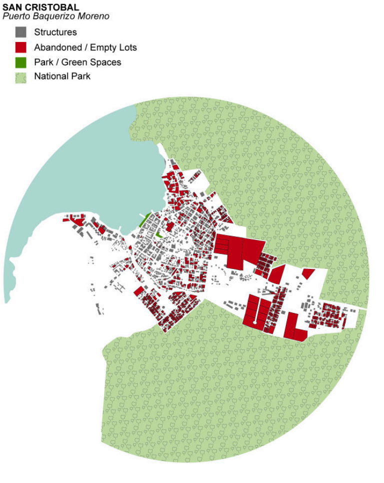

Figure 4. Location of empty lots within Puerto Baquerizo Moreno.

After determining the best sites for perturbation to take place, the next step was to design the best possible perturbations to happen on the particular site. As always, we relied on data and work which has been done by us and students previously. Students were able to work in groups with each group addressing one of issues that were considered as top priority by the government. These included: water, invasive species, food securities, waste, diversity of employment and dependencies on the mainland.

One of the perturbations proposed was the introduction of hydroponic and aquaponic growth kits on certain parcels of the city which, over time, would increase their income attribute and its demand of water (Fig. 5). A higher the demand of water in a neighborhood would incentivize the creation of decentralized greywater treatment facilities that would supply this demand. It will also allow the local population different forms of employment and create opportunities for innovation and experimentation to take place.

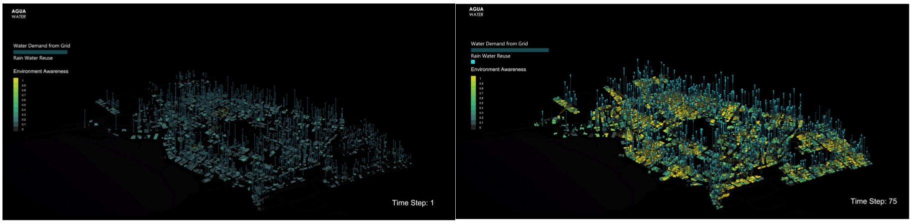

Figure 5. Effect of perturbation on water consumption and growth in environmental awareness
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Another example was a project in which decentralized tourist accommodations. Seeding certain parcels, this would create a gradual change over time and neighborhoods would start to develop as a network of tourist services that worked as a whole. This project also proposed to use guava trees as a building material. Guava trees are invasive spices and create huge damage to the environment. Eradication is very difficult, extremely expensive and so far, has not produce good results. In the same time guava trees could provide us with hard wood for construction via laminated cross-panels. Using guava trees as a building material will not only help in controlling guava trees grows and spread, but will also dramatically reduced import of building materials from the mainland and provide local population with new types of employment, which in turn could lead to more innovation and more job opportunities related to craft, furniture making etc. All these initiatives will contribute towards reducing imports and therefore possibilities of importing other invasive species into the islands.

A third project dealt with plastic recycling. Although the Galapagos Governing Council announced the plastic ban in April 2018, with different types of single-use plastic (straws, bags, takeout containers and bottles) being banned progressively over four months, there is still a lot of plastic being deposited on the beaches each day. Some of the plastics arrives from South and North America, but some drift in from Asia. Even if the Galapagos government stops all imports of plastic, it will still be deposited on the beaches each day. If this plastic is removed from the beach through community action, it ends up being transported by boats to the mainland. This not only costs money, it pollutes the atmosphere and water, and some is accidently lost and ends up back in the sea (Fig.6).

One of the ways to deal with this problem is add value to the waste, transforming the plastic deposited on beaches into a desirable material. This could be achieved through the provision of pulverisers and 3D printers in strategic positions within urban areas and providing residents with basic knowledge. A project suggested that first perturbation should start in schools, where young children could learn how to segregate different types of plastic, how to use pulverisers and additive printers, and to design useful objects from this material. If this idea works, it could then be moved into the more central location which will allow anyone to experiment and innovate, or even start their own business. One idea was to produced souvenirs, (which currently are imported from China) and sell them to tourists. In this way tourists will be paying for waste and taking it home with them.

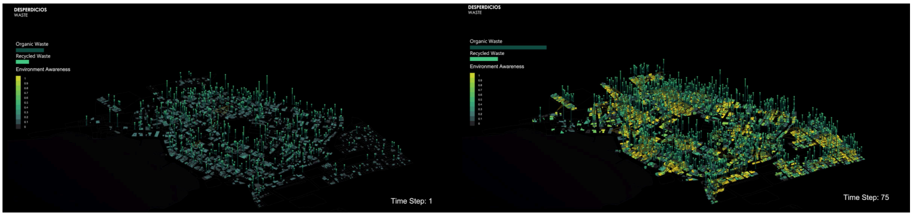

Figure 6. Effect of perturbation on recycling of plastic .

Over time the city would adapt, and school students would be able to see this change and fine tune the model and the initial parameters to test different outcomes. Figure 7 illustrates changes within urban structure and their effect on environmental awareness.

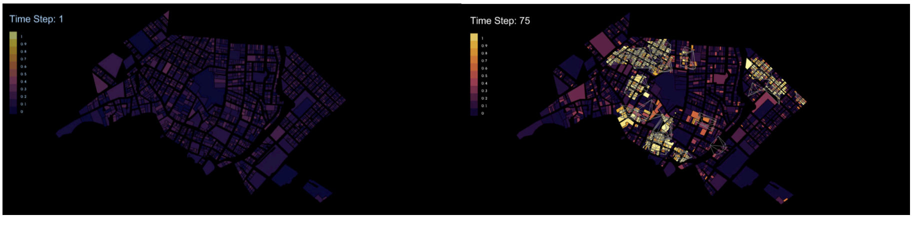

Figure 7. Changes in environmental awareness due to introduction of perturbations within urban system.

Unfortunately changes within the environment will not be visible for a long time. The only visible and measurable things within relatively short period of time could be extend of sprawl of invasive species, the demand for water, an increase in employment and economic benefits. All of these could be model with some degree of accuracy. However, what we are unable to model are things like the unexpected importation of new invasive species or the growth in volume of rubbish deposited on beaches, or any unexpected external innovation or disruption.

4. Conclusion

As mentioned above, in our work in the Galapagos Islands we have been using Holling's (2001) cycle of adaptive change. The model is useful to describe a process of change for one ecosystem function operating over a time period. Holling's model clearly illustrates that during periods of greatest uncertainty in nature, innovation and resilience are strongest, and in periods that are characterized by the strongest certainty, resilience and innovation are at the lowest ebb.

Therefore, if we are looking for innovation and want to create more resilient future, we should be investing in uncertainty instead of creating stability and certainty. This is counter to widely held assumptions that stability and certainty are the best foundation for resilience. Strategically, for this reason it is probably wiser to invest in small perturbations first if we want to change existing status quo.

Furthermore, we are very much aware that disturbed urban systems can recover and adapt much faster than disturbed natural systems. The impact of human intervention on a natural system is usually difficult to observed, it may take years to be noticed. At the same time, disruptions to urban systems might be difficult to accept for the general population. Humans do not respond very well to change, unless it is clear that this change brings some clear and fast benefits to them. If our actions benefit us but cause a negative impact on the environment, we choose to overlook this consequence.

In summary, we are always dealing with three interrelated systems: human, urban, and natural. They all respond to feedback loops and have reciprocal casual relations, they are all nonlinear, and have thresholds and therefore experience regime shifts, have historical path, are resilient (at least to some extend) and are heterogenous (Liu et al. 2007). Batty et al (2019) write:

...it is important to recognize that in most cases urbanization endows human dynamics with the ability for much “faster” dynamics and greater energy intensity (power) than is typical of natural selection. In this sense, human dynamics connected to urbanization are the fastest, driving influence on ecosystems, driving them into disturbed regimes that may indeed be unstable or prone to collapse as their ability to respond lag.

But there is also a small possibility that disturbance within urban structure can have positive impact on people’s lives and that this impact could be visible within relatively short time. Batty et al. describe the need to for a close, consistent, and continuing analysis of coupled urban-natural system in order to tell us about mutual interactions and adaptation over extended periods of time and that incorporates expectations for good and bad trajectories. Humans will always try to control natural systems but we might change the way we make decisions by understanding the dynamics and the impact of our action on the environment. There is a clear need for innovation within urban systems which are more synergistic and geared to improve resource flows and biodiversity in natural systems.

We postulate that if we can influence environmental awareness within tourists and local population, we will be able to have some positive effect of the environment as well. In the context of the Galapagos Islands, we will be able to reduce import from the mainland of construction materials, food, and other products and therefore, reduce possibility of other invasive species arriving onto the islands. will be able to control the spread of invasive species. We will be able to reduce water consumption, to create different jobs and diversify possibility of local employment, thus improving economic situation for majority of the population. Furthermore, will be able to promote innovation and create specific local knowledge. This knowledge could become another form of export. Maybe in the near future, the Galapagos Islands will focus on exports, not on tourism and imports. This maybe the way to more sustainable future of this amazing but extremely fragile environment.

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ENCOURAGING COMMUNITY PARTICIPATION IN DESIGN DECISION-MAKING THROUGH REACTIVE SCRIPTING

A general framework tested in the smart villages context

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Abstract. In governmental decision-making, centralised experts spending a society's resources benefit from the guidance of community participation, yet the most effective participation by individuals distributed throughout a community often relies on expert guidance. This co-dependency of centralised and distributed knowledge is a critical weakness in contexts, such as developing rural communities, in which opportunities for in-field expert engagement are limited. This paper proposes a novel computational framework to break this deadlock by taking into the field responsive expertise digitally encapsulated within accessible built environment simulations. The framework is predicated in reactive scripting for design apps that invite a citizen user to progress a model towards their ideal design by prompts that highlight exceptional, contradictory, mutually exclusive, or simply underwhelming outcomes or branching decisions. The app simulations provide a gamified context of play in which goals are not prescriptively encoded but instead arise out of the social and community context. The detailed framework, presented together with a proof of concept smart villages app that is described along with an integration and feasibility test with positive results, provides a model for better participatory decision-making outcomes in the face of limited availability of expertise.

Keywords. Community participation; built environment simulation; gamification; reactive scripting; smart cities and villages.

1. Introduction

Within society is an information gap in which knowledge of how best to prioritise resource use is held by the individual and not at a central source where planning, design, and related decisions might occur. Participatory feedback can help resolve this gap; its use, however, is impeded by the limited availability of expertise to develop and guide it in the field. This paper in response proposes a tripartite computational framework for community participation and collaborative design that minimises need for direct expert input. The citizen is prioritised by *reactive*

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 51-60.

scripting for design placing them as the 'designer in the loop'. They become an essential decision-making agent who guides self-referential, iterative digital workflows towards a preferred solution, operating in a modelling context that accentuates relationships over numbers and helps reveal knowledge that may be only implicitly known. Alongside, the engagement and visualisation techniques of gamification provide accessible built environment modelling simulation. Within the interaction of these sits responsive encapsulated expert contextual knowledge.

The paper begins with demonstrating the utility of the approach in a context of rural development of smart villages that display high social buy-in and whose issues when solved have benefits beyond the local. This demonstration is followed with some essential detail of the associated computational framework. A proof of concept software application, based on ongoing research in rural India, is presented as reification of the conceptual framework. The paper concludes with a discussion including future research directions.

2. The problem of centralised knowledge

Cities may benefit from immigration of villagers seeking a 'better life', such as through economies of agglomeration, but are increasingly stressed when required to boost the supply of utilities and services to their burgeoning populations against a backdrop of depleting resources. Concomitantly, these rural communities are left enervated by the drain of people and resources to cities.

There is a growing focus on smart cities solutions to some of the problems caused in developing Asian cities by rural flight to those cities, including the use of collaborative and collective design and governance techniques. Two notable programs are the *Indian Smart Cities Mission* and Ho Chi Minh City's *Smart City Masterplan*. There is no corresponding technology-enabled focus, however, on the issues within rural communities. This imbalance risks a bipartite, self-reinforcing and deleterious outcome: solving the problems of the cities, while necessary and worthy, increases the pull factor, and the abandonment of the rural only encourages the push factor to worsen.

Given a need for smart rural solutions, we may ask what are the conditions peculiar to rural situations to which they must respond? Doloi, Green, and Donovan (2018) pithily canvass rural development issues in their book *Planning, Housing and Infrastructure for Smart Villages*. They identify a central challenge in the nature of top-down governance: "every rural community is different, and it will take unique insider knowledge of the region's assets and customs to determine the most effective combination of policies" and "central government generally devises a single policy for all the rural communities under their jurisdiction which can be hundreds or even thousands of villages with differing cultural traditions, religious beliefs, employment opportunities and standards of living."

Arguing against a planned economy in his seminal 1945 work *The Use of Knowledge in Society*, the economist Friedrich Hayek illuminated issues of decision making within top-down governance. Hayek identified the "problem of the utilization of knowledge which is not given to anyone in its totality": useful knowledge is not pooled in singular form and is instead dispersed throughout society and possessed by separate individuals, and it is such individuals who might best judge the purposes to which society's resources should be put. He further noted that statistical information cannot adequately allow for the unique spatio-temporal considerations that may occur throughout a planning district, and that the "central planner will have to find some way or other in which the decisions depending on them can be left to the 'man on the spot."' To expand in a participatory context, why collect data to develop general principles or guidelines, and then shoehorn them into a specific community context, when one can work with the actual situation and preferences on the ground?

Resolving these knowledge issues in developing rural contexts is impeded by a communication gap arising from limited availability of expertise and the accessibility of remote subject communities (Cavaye 2001, Herbert-Cheshire & Higgins 2004, Hudson 1989). This gap arises from participatory deficiencies at the 'top' and 'bottom' of the governance hierarchy. At the 'top', experts have limited capacity to engage directly across the range of cultural and environmental contexts within their geopolitical service area and must make decisions on aggregated data that loses the nuance of diverse local knowledge and preferences. At the 'bottom', what local knowledge and stakeholder feedback that rural citizens can provide has by necessity limited guidance from expert input. A balance is needed despite the appeal of populist engagement in which, as Olszewski and Turek (2018) note, "local communities get all the power without the proper methodological support."

3. A framework for reactive scripted participatory community simulations with encapsulated expert knowledge

Participatory approaches in planning and design close such a knowledge gap and their worth is well established (Hasler, Chenal & Soutter 2017, Poplin 2012, Voinov & Bousquet 2010). Being closely bound, rural communities are ideal loci for participatory approaches in many respects. Foremost, an efficient participatory process relies on the ability of stakeholders to "communicate and exchange information and knowledge" and the social relations between them (Voinov & Bousquet 2010). Further, their social structure naturally addresses the hinderances to participatory processes summarised by Hasler, Chenal & Soutter (2017). This includes the usefulness of participants to be spatially and temporally co-located, disengagement among citizens, and the essentiality of supporting and encouraging interactions. When implemented, however, these approaches often rely on direct expert participation for guidance even in rural or remote situations where provision of such expertise can be difficult (Castella, Trung & Boissau 2005, Lagabrielle et al. 2010). Their useful replication - of even digital components - is thus limited by a finite and non-duplicable resource.

In response we propose a computational framework for participatory community simulations to facilitate informed decision making without on-the-ground experts. The framework is a tripartite synthesis: reactive scripting prioritises modelling that emphasises behaviour rather than data and engages the citizen as the essential 'designer in the loop'; abstracted expert knowledge is integrated as the expert's understudy; and rich visualisation and interaction comes via computer game techniques (Figure 1).

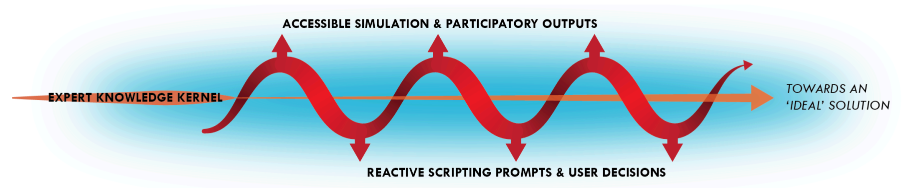

Figure 1. The tripartite computational framework.

The framework is predicated in work that extends *reactive scripting* to built environments design (Burry, Cruz & Kimm 2019). Reactive scripting, which originates within the computer science reactive programming paradigm, propagates information within a program's state through relationships linking reactions to events (Boussinot & Hazard 1996). In the methodology, broadcast and concurrency of events emphasise parallelism and simultaneity of program state change. As relationships may react to all events, and as reactions may execute while other reactions are running, modelling that focusses more on behaviour than on data is prioritised. Explicit interrupt commands may sequence event logic: a program may therefore query a user to update its state in response to the possibility for choice or deliberation. Burry et al. extended the methodology to preference a user as a 'designer in the loop', who connects and winnows relationships, to decide on matters with fundamentally competing considerations and associations that are not necessarily explicitly known or formulated. Reactive scripting for design, Burry et al. noted, enables "the possibility of human input to an otherwise fully automated model, allowing for adaptation and change to become part of the development of the system" with the non-expert stakeholder "brought more actively into the design loop as a bottom-up participant".

However, reactive scripting for design is not sufficient in itself for community engagement without direct expert involvement. The approach of Burry et al., when tested at a 2016 Galápagos Islands workshop, relied on expert guidance of multi-disciplinary participants to introduce variables and route connections to find mutual understanding of rivalrous economic, ecological, and experiential issues. In related work, a pedestrian-centric design strategy that used reactive scripting proposed only the designer as the human actor within the loop and they must exercise expert intervention to identify and manually isolate simulation elements from the reactive scripting loop (Huang, White & Burry 2017).

Core to reactive scripting as part of the design methodology is a stateful model of the design problem. The model must be dynamic and evolving: reactions cause data to propagate throughout the model according to relationships and those query events that engage the user can hence be generated. It is within this stateful model that an interrogative framework for encapsulation of an abstracted expert knowledge kernel is provided. Such a kernel, informed by appropriate GIS, social and other contextual information, must produce output that can direct the state of the model, and must accept and respond to user and other change of model state.

The precise technical implementation of a kernel is beyond this paper's scope; instead we note the established utility of AI techniques in built environment modelling including expert systems, generative and evolutionary computing such as genetic algorithms, and artificial neural networks (Kalogirou 2002, Dutta & Sarthak 2011, Pijanowski et al. 2009). Kernels may also be developed through their own distinct participative processes, such as fuzzy cognitive mapping that captures knowledge of abstract relationships (Özesmi & Özesmi 2004). A kernel thus integrated becomes within the framework the expert's understudy in the field.

Visualisation, interaction, and engagement techniques arising from gamification, but that are not explicitly gamification, make accessible to a user the abstracted expert knowledge within the reactive scripting model and design loop. In a widely-cited definition Deterding et al. (2011) gives gamification as "the use of game design elements in non-game contexts", and notes that a "game", with an explicit design objective to engage a user, and what is an "artifact with game elements" are not dichotomous. Encouraging user engagement within a reactive scripting for design model is essential if user feedback is to be captured, yet constraining rules or goals and directive engagement strategies such as points or awards defeat the purpose of uncovering nuanced or latent community preferences. In any case, users bring to a game their own "real commitments, expectations, hopes, and desires" that arise in their lived lives (Consalvo 2009). It is in this social context that the defining of the game, and hence the driver of engagement, may thus be extrinsic to the reactive scripting for design model itself; the social context and addition of shared goals and informal rules may turn a gamified application into a game (Deterding et al. 2011).

It is in this sense we argue reification of gamification for reactive scripting for design should tend more towards *paidia* than *ludus*. Caillois (as cited in Deterding et al. 2011) defines paidia and ludus as two poles of play. Ludus, or 'gaming', is characterised by rule-based activity and competitive goals, whereas paidia, or 'playing', is the expressive, improvisational fusion of meaning and behaviour. Caillois (as cited in Jensen 2013) observed there is an inevitable social drive for paidic activities to transform to ludic activities as implicit rules and constraints become explicit. Despite gamification being generally viewed as more a ludic activity, it is paidic play, with its freeform exploration, that is best suited to capture subtleties of community preferences, as well as latently-held attitudes and desires, in a reactive scripting for design model. That model seeks not to prescribe outcomes but instead to allow them to arise from a social context appropriately leavened with external direction or local non-expert guidance: "what's *your* ideal village layout?"

The above is not to suggest that game elements are to be excluded from reification of our model. Although we do not propose that reactive scripting for design should be manifestly formulated and presented as a game, and although we propose leaning to the paidic rather than ludic, appropriate borrowing and deployment of game elements is essential in its implementation and uptake. Taxonomies of game attributes, such as that by Bedwell et al. (2012) of 19 attributes such as representation, interaction, or progress, provide reusable and extensible kits of parts from which implementations may be built. Similarly, the established visualisation and engagement strategies of games, in addition to their mature development technologies, allow exploitation of game developers' knowledge of communication of ideas and human psychology.

Vital is the generation of actionable data through observation of play within a reified model. Whereas game design may derive performance metrics following identification of a ‘fun’ idea and play outline, gamification design develops these from identification of a business objective and only then proceeds to identification of a subordinate gameplay outline (Marczewski 2014). It is these metrics and the simulation state that may be captured as actionable outcomes. As gamification is not used here with clear objectives in a traditional sense, there is no set point when an outcome is finalised: it is an iterative process of interaction decided by the user (Figure 1). Data collection may be internal to the app, as in the proof of concept below, or in conjunction with the external processes that can occur in a community setting such as guidance by a non-expert local facilitator, in interaction akin to the Galápagos workshop of Burry et al.

4. Computational proof of concept

A proof of concept application (‘the app’) was developed in the Unity 3D game engine to test integration of the framework’s tripartite synthesis of reactive scripting, expert knowledge, and gamified simulation. OpenStreetMap crowdsourced mapping data gives road network and feature placement, and location services and 3D terrain information are by the Mapbox mapping platform. App state and user response capture is via AWS DynamoDB cloud storage.

The app’s geographical and social context is a village on the island of Majuli, Assam, Northeast India. Despite much recent economic progress in Assam, there is still great rural disadvantage. A causal factor is a lack of reliable, complete, and broad data available to government, and the resulting insufficiency of actionable insights that frustrates development goals (Doloi, Green, & Donovan 2018).

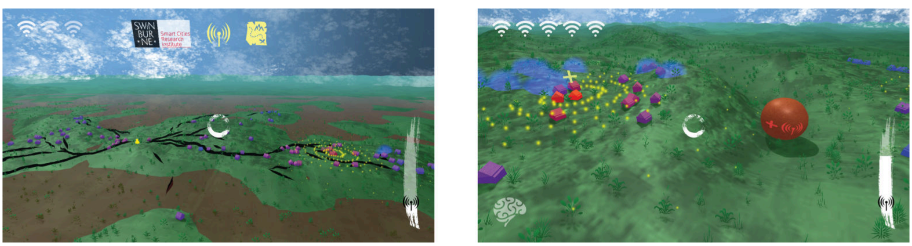

Figure 2. Two app interaction modes (left), and fixed node placement with topographical feedback alongside implicit and explicit reactive scripting prompts (right).

Two framework-user interaction modes were developed (Figure 2 left). First, dynamic community resource and infrastructure placement with accessibility illustrated, in the absence of fixed footpaths, by the display of animated desire paths that respond to flood scenarios and land use. Second, consensus on mesh networking node placement for communal internet access. The latter is here presented in detail. An object-oriented design of the embedded reactive scripting simulation engine allows easy addition of further interaction modes. The simulation in these modes, given cloud linkage, may also evolve collaboratively across user sessions; for example, a district may collectively identify and connect existing and potential circular economy and micro enterprise opportunities.

On opening the mode of mesh networking node placement, a user sees a single initial network node placed at a village house (Figure 2 left). The expert knowledge kernel undertakes complex modelling of mesh network signal strengths for current node placements; all houses are correspondingly coloured and signal strength and total node count and limit are displayed in a UI overlay.

In accordance with the framework, explicit objectives are not encoded directly within the app; instead, the simulated environment allows paidic play in response to immersive visualisation and feedback metrics. An implicit objective is supported: users may, when asked to select the number and preferred location of mesh network nodes, bring to the simulation those considerations not directly embodied within it. Users have unique local knowledge of special considerations allowed for in the model, including where and who is important in the village, budget and project prioritisation, and number and placement of nodes. To aid this, users may fix a node in position, such as at the location of a communal building, and user placement of nodes is guided by animated feedback including highlighted topographical signal interference (Figure 2 right). Full signal coverage that satisfies all considerations is not easy; users are thus invited to prioritise relationships in the model and give their own compromise: for example, should an important place have a fixed node if it will give a weak signal? The user, through winnowing and prioritisation, chooses from a solution space that might contain many optimal solutions those that are optimal for *themself* (Figure 3 left).

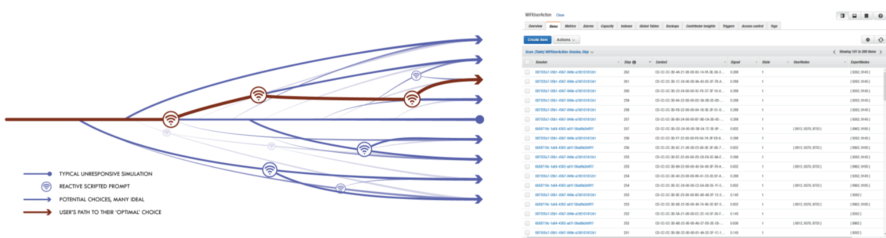

Figure 3. Conceptual overview of reactive scripting prompting a user towards novel outcomes (left), and app state and user outcome capture in AWS DynamoDB (right).

Reactive scripting prompts are provided to the user implicitly and explicitly (Figure 2 right). On change of a fixed node by the user, a genetic algorithm within the expert knowledge kernel responds immediately to reconfigure placement of all non-fixed nodes. Its exploration of the solution space, which otherwise would be near-instant, is slowed to human perceptual scale and concurrently displayed, along with a prominent ‘thinking’ brain icon in the overlay UI, so to suggest alternatives as it converges on an outcome. An explicit reactive scripting prompt is given when the genetic algorithm cannot dynamically update the simulation with a node configuration that gives a preferred level of signal coverage. In such a case, an interactive traditional ‘gulab jamun’ sweet (a local treat in a giant, whimsical form that rolls into the landscape) is spawned to enquire about adding a new node.

As a user develops their solution though iterative participation, they may flag results that best encapsulate their desires and local knowledge. Each is recorded to the cloud with specific design and contextual interaction data to assist decision-makers in applying these community preferences (Figure 3 right). Alongside, a traversable record of user actions is continually captured to allow interaction reconstruction as well as future machine learning and other analysis.

4.1. INTEGRATION AND FEASIBILITY TEST

In the face of inaccessibility of the Majuli subject site at the time of research, a limited study of the proof of concept app was undertaken to test the success of integration and feasibility of the proposed framework. The study was premised on success being indicated by acceptable usability of the app.

The usability of the app was evaluated with a survey of ten participants using the System Usability Scale (SUS) method (Brooke 2013). All users were Australian residents, and none had professional built environment experience. The widely used SUS method is reliable, robust, applicable to different technologies and platforms, and comparable across subject systems. Although the sample size was relatively small, small groups can be effective in usability testing with just 10 users potentially encountering at least 82% of problems (Faulkner 2003).

Users were tasked with designing their ideal village using the app taking community equity and limited resources into account. They were hence given direction that was not prescriptive of any particular design but did create rivalrous considerations, as would be expected of an in-the-field trial. The returned SUS score was 74.3, or ‘good’ on the adjective rating scale of Bangor, Kortum, and Miller (2009). The outcome indicates an acceptable level of usability and therefore that the proposed tripartite framework can be successfully implemented.

5. Discussion

The proposed framework for community participation through reactive scripting for design has been presented in this paper in both theory and implementation. While the proof of concept results suggest useful application, the outcomes and theory raise several aspects for further research.

We have proposed that nuanced response on a design issue should arise out of paidic play and a ludic drive. This was discussed in a rural community context of relatively high social capital buy-in and opportunity for users to communicate and exchange knowledge directly. Further research is needed including into the psychological motivation of a user responding in isolation or of a demographic which is disenfranchised within its own community. Of use here are theories of behavioural motivation, such as self-determination theory and locus of control, which are of established use in gamification.

The expertise modelling in the proof of concept is relatively fixed: the output is responsive to user decision, but its essential relationships do not meaningfully change. Implementations that respond more flexibly in their very structure to user input could afford more sophisticated community preference capture. The Galápagos Islands precedent tool of Burry et al. allowed workshop users to add, prioritise and balance relationships within a developing model. Similarly, community engagement methodologies such as role-play based participatory simulation allow rules to change and the model itself to develop within the process (Voinov & Bousquet 2010). Yet development of these models typically requires in-person expert guidance; their successful incorporation into our proposed framework would obviate this need. A flexible model can also allow personalised reactive scripting interaction that fundamentally changes the path and character of the participatory process. To illustrate, a random forest model could train on user choices over many sessions, and make suggestions specifically if it predicts a user might find them novel; a user is exposed to new ideas to inform their responses.

We note alternative approaches for suggestion in interactive built environment simulation, and certain approaches may be better suited to given participation and computational needs. For example, the CityMatrix precinct simulation employs heuristic search of future moves a user may take and illustrates on a user's 'turn' an optimal move within an engaging tangible user interface (Zhang 2017). Users may follow a suggestion or not, and when doing so may consider issues not embodied in the simulation itself. In CityMatrix, the AI offers only the 'best' next choice or step whenever computed and the simulation adjusts in response to user changes alone: suggestions drive a static model towards a preconceived optimisation. In our model, by contrast, a dynamic framework continually evolves through the expert kernel's response to user-set conditions. Reactive scripting prompts the user when exceptional outcomes are detected or branching decisions exist: the simulation itself is the driver of change as the expert's understudy and its suggestions are 'have you considered?' or 'what do you think?' prompts on an issue of note.

6. Concluding remarks

This paper proposes a novel contribution of community participation through reactive scripting for design in decisions that have major long-term implications. The framework addresses the use of digital built environment simulation with embodied, responsive expertise modelling to facilitate participatory processes in situations in which guiding expertise is of limited availability. By promoting the collection of data that is nuanced by diverse local knowledge and preferences, and through capturing actionable data on local matters directly rather than relying on statistical aggregation or generic models, the framework can afford far more credible responses to unique problems by centralised decision-makers. The villagers involved can be considerably more enfranchised in processes typically done for them by invisible others, or not done at all.

This research is based in a context of smart villages and rural development. While the integration and feasibility testing of the proposed tripartite framework is in itself valid, a real in-field study would need to be undertaken for full verification.

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SENSING THE DIVERSITY OF SOCIAL HUBS THROUGH SOCIAL MEDIA

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Abstract. As we continue to discover the potential of social media data as an insightful source for academic research, the majority of previous work tends to focus on the density of socio-spatial relations as the foundation for understanding urban phenomena. This paper extended those approaches by introducing the concepts of diversity and inclusiveness through an investigation of the 'differences' within the networks of relations that are inherent to social media data. The author constructs a diversity measure based on the variety of home locations of social media user visitors to each geographical location in the city. This home location, in its turn, is derived from each user's digital spatio-temporal footprint. This proposed method demonstrates that through the visualization of this diversity measure, 'social hubs' (which are frequently visited by different groups of people) were able to be located that would otherwise be overlooked in conventional data analyses that focus only on density. As such, this research expands the usefulness of social media as a practical tool to help understand urban processes by making the concept of diversity - a key consideration in many planning and design contexts - measurable and mappable.

Keywords. Social Media Data; Home Location Detection; Diversity Analysis.

1. Introduction

With the challenges of increasing urbanization, city officials and design professionals alike have focused on analyzing human behavior in urban environments to make more informed and sustainable planning decisions. Today, urban sensing strategies can leverage the sensing capabilities found in cell phones and geolocated social media platforms to conduct people-centric analysis at a much larger scale than previously was possible (Campbell, Eisenman, Lane, Miluzzo, & Peterson, 2006).

In recent years, social media data analysis has made insightful contributions to explore socio-spatial relations in a wide range of everyday urban processes (Shelton, Poorthuis, & Zook, 2015; Stephens, 2013). As we continue to discover the potential that social media data can offer as a source for academic research, it is critical to ground and contextualize data analysis with theoretical concepts and contextualization (Goodchild, 2007; Hossain et al., 2016). Furthermore, previous

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 61-70.

research with social media data has primarily taken a descriptive perspective and focused on the density of socio-spatial relations in the city. The goal of this research is to take this work a step further and look into the ‘differences’ within these networks of relations. As concepts such as diversity and inclusiveness are fundamental to urban design and planning for a city, I now bring these concepts explicitly into the analysis of social media data.

The context of the paper is set in Singapore’s neighborhoods. This research explores the neighborhoods’ underlying socio-spatial structure through analyzing a social media dataset, which contains all geotagged tweets sent in Singapore between July, 2012 and June, 2015, totaling approximately 24 million tweets (Poorthuis & Zook, 2017), combined with land-use programs to contextualize. To gain insight from this data - which effectively holds the spatio-temporal footprint of each user - I derive the home location of each user based on their mobility pattern. This home location is subsequently used as input in calculating diversity measures (i.e. the more people from different neighborhoods visit a place, the more diverse this place is) for places they have visited. By visualizing this diversity measure across Singapore, I identify ’social hubs’ in the city that might be overlooked in the conventional analysis only focused on density.

2. Related Work

Social media data has often been used to help decode an individual’s connections to different places that pose importance to that individual(McGee, Caverlee, & Cheng, 2013; Poorthuis, 2017; Schönfelder & Axhausen, 2003). This is made possible through the unique properties of geotagged social media data, containing data on both social and spatial connections. These socio-geographical relations can help to understand a person’s social and spatial life, such as connections between friendship and distance (Scellato, Noulas, Lambiotte, & Mascolo, 2011), identifying individual activity spaces to reflect social issues (Hossain et al., 2016; Schönfelder & Axhausen, 2003) and understand human mobility patterns (Cho, Myers, & Leskovec, 2011; Jurdak et al., 2015). Social scientists have spent much effort to understand the aggregated network relation in connection to particular places - its social histories, development and cultural. For instance, social media has been used as a tool to document and observe public spaces in temporal continuity (Toscano, 2017), to connect people’s sentiment to characteristics of places (Kouloumpis, Wilson, & Moore, 2011), and to investigate the correlation between quality-of-life and the happiness level of people (Mitchell, Frank, Harris, Dodds, & Danforth, 2013).

However, one of the critical puzzles in these geographically-oriented research is knowing the user’s home location (Mahmud, Nichols, & Drews, 2014). Been able to infer users’ home locations gives an important clue of the user network relation in a geographical dimension to reveal further insights (Scellato et al., 2011). Home location enables fine-grained analysis not only in knowing numbers of participants engaged in an activity and distance people travel from to participate an activity but also identify types of places that activity takes place (e.g. workplace, commercial entity, public space, etc). For instance, Cho et al discovered strong periodic behavior that Twitter users have throughout the day alternating between home and work on the weekday; home and social-driven locations on weekends (Cho et al., 2011). It is based on these potentials that in this research, home location detection is an integral piece that bridges the gap between observing a mere population distribution or a meaningful insight into the social landscape of the city.

In the earlier research with social media data has primarily taken a descriptive perspective and focused on the density of socio-spatial relations in the city. Often, socio-geographical data points are visualized in an aggregated manner to indicate the tie strength, to show participations of particular activity (McGee et al., 2013; Prasetyo, Achananuparp, & Lim, 2016; Schönfelder & Axhausen, 2003), to use as poll for public opinion (Anstead & O'Loughlin, 2014) or identify meaningful places for the people based on the frequency of their tweets (Hossain et al., 2016; Mahmud et al., 2014; Yardi & Boyd, 2010). Nonetheless, city is a place of diversity in all dimension of the society and sociality happens between people of very different backgrounds in urban spaces (Humphreys, 2010). Especially to sense social hubs in the city - a space that serves as an important site of social interaction - the concept of diversity should take the front seat. Measuring 'diversity' is commonly used in fields of ecology study to understanding biodiversity but it is seldom used in architecture and urban planning field. It is a goal in this paper to attempt to quantifying the intangible quality of "diversity" as a critical element in social spaces in the city.

3. Research Methodology

In order to understand the relational socio-spatial network pattern embedded in the social media data, we use a methodology that draws from methods of home location detection and Simpson's Diversity Index algorithm, and use visualization and mapping to communicate our analysis as discussed in the following paragraphs.

3.1. TWITTER DATA PREPARATION

The case study is based on the geotagged tweets sent within Singapore from July 2012 to June 2015, yielding a total of 26 million tweets (Poorthuis & Zook, 2017). We remove the top 1% most active users as a pre-caution against bot-generated tweets. This leaves us with 24 million tweets in total. Geo-tagged tweets generally contain information about the user ID, coordinates from where the tweet was sent, timestamp and the text content. As the geographical coordinance is the most critical part of the dataset to our research, it is important to note that the accuracy of these longitude/latitude points depends on multiple factors such as privacy settings, user-entered geolocation and technology devices (Crampton et al., 2013; Poorthuis, 2017; Shelton et al., 2015). To minimize the inherent noise and challenges in the dataset, the data points are aggregated to a larger spatial unit. In this research, I use a hexagon grid of 300m by 300m. In other words, I have divided entire Singapore with a 300m by 300m hexagon grids.In addition to addressing the precision issues, aggregating data points also greatly reduces the complexity of the data set for both feasibility and efficiency to perform analysis (reduced 24 million points units to 8956 grid cells). The proposed methodology of sensing diversity is conducted in two stages; first, Iconduct home location detection to understand user' location as a reference to their social background and second, I take the user location as input for the subsequent diversity analysis as discussed in the following sections.

3.2. HOME LOCATION DETECTION

Prior research has mostly been using social network analysis to predict a social media user's home location, such as the place from which the user most frequently tweeted, or the most common last location of the day for the user's posts (Cho et al., 2011; Pontes et al., 2012; Scellato et al., 2011). Another alternative approach found in home location detection research is content-based (text mining) strategies using machine learning technique to detect keywords to infer user's location (Hossain et al., 2016; Mahmud, Nichols, & Drews, 2012). One significant shortcoming of such heuristics is the high inaccuracy rate for a large percentage of users and there is no consensus among researchers on which is the more comprehensive methodology (Mahmud et al., 2014). Lately, we are beginning to see research efforts on creating algorithms with more structured and consistent framework to address this issue. For example, the 'homelocator' package created by Chen and Poorthuis (2019) which adopts different approaches and allows flexibility in the algorithmic 'recipes' to accommodate different topic focus (Chen, 2019).

As such, in attempt to increase the accuracy of the detection algorithm, I am applying the 'homelocator' package in R with multiple variables and thresholds listed in Table 1 below. Each user's tweets are evaluated against the set thresholds of each variable. Only when the users' tweeting behavior satisfies all variables then a positive identification of a user's home location is successful. If there are more than one equal valued locations from the detection analysis, home locations are randomly assigned to the user from the finding.

Table 1. Table 1: Homelocation Detection Variables.

1	Min. tweets sent per user	10
2	Min. location sent per user	10
3	Min. tweets sent per specific location per user	10
4	Min. active hour per specific location per user	10
5	Active min. different days per specific location per user	10
6	Active min. consecutive days per specific location per usre	10
7	Removing bots	Top 10%

The result of this particular 'recipe', yields a total number of 22,597 positive home location identification of users across Singapore from a total of 849,926 Twitter users. The distribution of all the detected home location is mapped as shown in Fig. 1. As a validity check, I mapped Singapore's public housing locations based on the Singapore Land Authority data as well for comparison purposes. As is clear in Fig.1a and Fig.1b that the home location pattern resonates with the distribution of the high-density housing locations. These derived home locations of users are used as input data for the next analysis step of diversity measure.

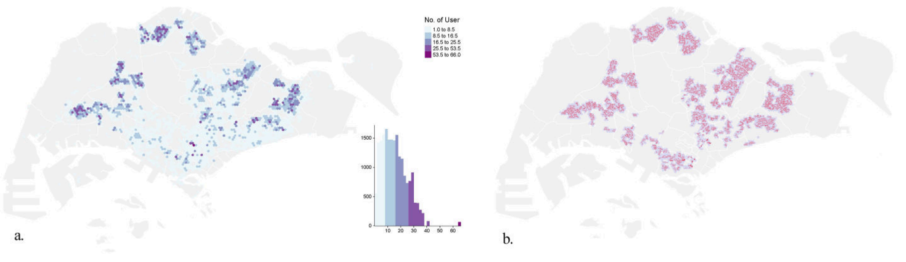

Figure 1. a: Distribution of Detected Home Locations in Singapore ; b: Distribution of High Density Public Housing Locations.

3.3. DIVERSITY ANALYSIS - SIMPSON'S DIVERSITY INDEX ALGORITHM

In this research, diversity is defined as in measuring the people visiting the same place based from their different home location districts. A place that attracts a greater number of people from different home districts is perceived as a more diverse place. As this is measuring how many different home districts of residents have a presence in a place, this conforms to the same logic behind Diversity Index algorithms, commonly used in biology or ecological research (Simpson, 1949) to calculate biodiversity of a certain habitat (Nunes, Silva, & Paiva, 2010). As such, Simpson's Diversity Index algorithm is used to calculate the diversity index for each of the grid cells within Singapore.

In preparation, I first ensure that each of the grid has a minimum of 100 tweets and 10 different visitors to minimise insufficient sampling which has resulted in 5596 grid cells. Secondly, I defined the home location zones into twenty-four different areas by distances and cardinal directions. These home locations zones are dynamic and generated based on distance (1km, 3km, 5km, 10km 20km and Far), as well as by 4 cardinal direction (North East, South East, North West and South West). The division of the buffering distance is to differentiate different catchment areas, where people's traveling distance can indicate different motivation (Spinney & Millward, 2013). For instance, visitors coming from within 1km could be the local residents who use a space in a daily manner. Singapore as a compact state country, visitors need to have a very strong incentives to travel up to 20km to visit a place. Further applying cardinal directions to differentiate the distant buffer zones can add additional layers of diversity, for example people coming from the East (Changi Airport) verses the people coming from the West (National Singapore University Students) could have very different profile.

$$D = 1 - \left(\frac{\sum n(n-1)}{N(N-1)} \right) \quad (1)$$

- n = the total number of home location zones of visitors
- D= diversity index
- N = the total number of visitors from each home location districts

In our context of urban sensing, the index can quantify the diversity of a space by taking into account the number of visitors and the number of different homelocation zones these visitors are from. The index value ranges between 0 and 1, and a greater the number of different home location zones and evenness of the visitor number from each zone results in increases of diversity. The calculation for each of the areal units of girds was computed by Vegan package (Oksanen et al., 2007) in R with Simpson Diversity Index attribute.

To illustrate, I apply the diversity measure on the grid cell at the center of Tampines Interchange using the above equation in the following manner (Fig.2): n determines the total number of home location districts presented in this grid cell, N is the total number of the users from each home location districts. The total number of visitors from each district is imputed to the equation listed above and yield a diversity index of 0.92118. As such, this particular grid cell is very diverse. The creation of the districts and calculation of the diversity index is dynamix for each grid cell within the city. The same algorithm will be applied to each grid to obtain the diversity index for all cells.

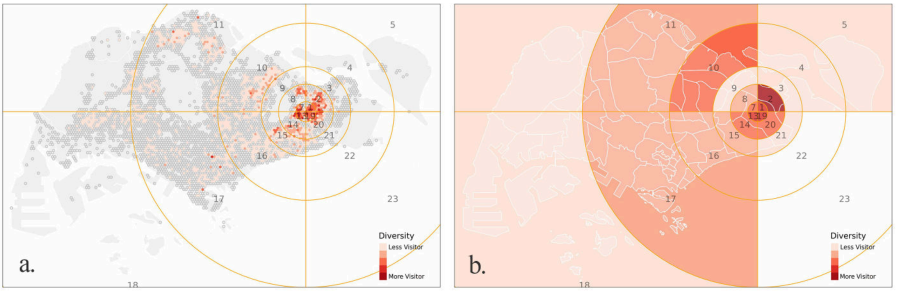

Figure 2. Home Location Distribution by a: by grid cells; b by districts.

4. Empirical analysis

As an illustration, I take the neighborhood of Tampines as our case study in this paper - one of the largest regional centers in Singapore, which includes a mix of mix land uses - for detailed analysis and contextualization. I visualized the results of diversity index within Tampines to their geographical location with natural breaks (fisher breaks) classification where the darker the color the more diverse the grid cell location is (Figure. 3a). The mapping has indicated a clear darker cluster of areas on the southern side of Tampines neighborhood where most of the commercial urban functions fall. For instance, places like Singapore Expo hosts events which attracts people from nationwide, Changi business park is home to many international companies which attracts workers from all over Singapore. Higher education institutes were also found with high diversity index as expected as they are not bound to geographical locations for admission, students are likely to come from all over Singapore. Contrastingly, a much lighter color of least diverse cluster around the middle section of the neighborhood where most of the residential programs are located. Residential blocks are private properties to many where people with no social connection to the residents will not have incentives to visit. Therefore, a residential area can have little diversity compare to other urban functions.

However, comparing this image with a more conventional view based on the density of geotagged tweets, where total tweets within each cell are aggregated and mapped, the results are indicating a very different scenario (Figure 3b). It is clear in Fig.3b below, the expected high diversity places (e.g. transportation hub, educational institution, business enterprise etc.) are still visible within the density analysis but many more are not. Density distribution of the dataset is reflecting the population density but not the diversity among them, for example, dense public housing area is indicating a higher density of user presence as expected but as discussed earlier housing complex is a very much localized place with less diversity of visitors. This preliminary comparison analysis has provided ground for us to be confident that the diversity index results are reflecting the urban condition rightfully.

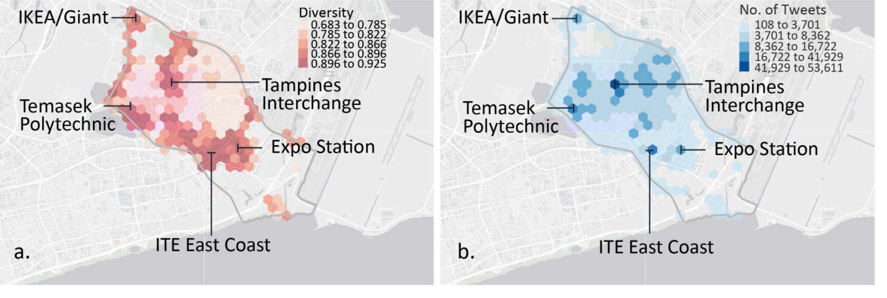

Figure 3. a: Diversity Index Visualization b: Density Value Visualization.

Based on this understanding, it is becoming viable to further investigate diversity index grounded with land use as a bottom-up strategy for where the social hubs are. Firstly, I draw the focus on the top two diversity index groups visualized by tmap package in R with classification by Jenks natural breaks method (Figure 4a), which resulted in 68 grid cells from a total of 220 grid cells of Tampines (Figure 4b) and contextualize with land use plan (Singapore's Land Authority Map) to eliminate places that are unlikely to be potential social hubs, for example, spaces which have specific or institutional urban functions, like schools, offices, business park, hospital, expo and roadway (Figure 4c). Secondly, I further investigate the rest of the high diversity spaces (21 grid cells) which can arguably be places that people gather for sociality for reasons other than work, study or social obligations (Carr, Stephen, Francis, Rivlin, & Stone, 1992; Oldenburg, 1999) and potentially be a place that caters to social interaction. Here I use the term 'social hub' rather than conventional terms such as public space, to refer to the broader sense of social spaces in the city, which includes all physical context that can serve social function as a place for sociality and recreation (Humphreys, 2010). As such, based on the proposed analysis method, it is clearly shown in Fig.4d that Tampines' social hubs are identified at Ikea, Tampines MRT and surrounding shopping complex, Expo MRT and Changi City Point (CCP), Tampines Eco-Green, Tampines Quarry Pond and Temples. The findings resonate well with the other research on public spaces, recognizing shopping malls and MRT station area as much a social place as a traditional public space - a park or a plaza is (Carmona, 2010 a, 2010 b). Additionally, the proposed diversity measure has proven to be a more comprehensive method compared to conventional methods of density measure by being able to detect places that are less expected like serene natural spots like Tampines Quarry Pond and informal places of temples. However, this is not a conclusive finding but rather a stepping stone to formulate further research topics on the city's public realm and explore the potential that geotagged data offers.

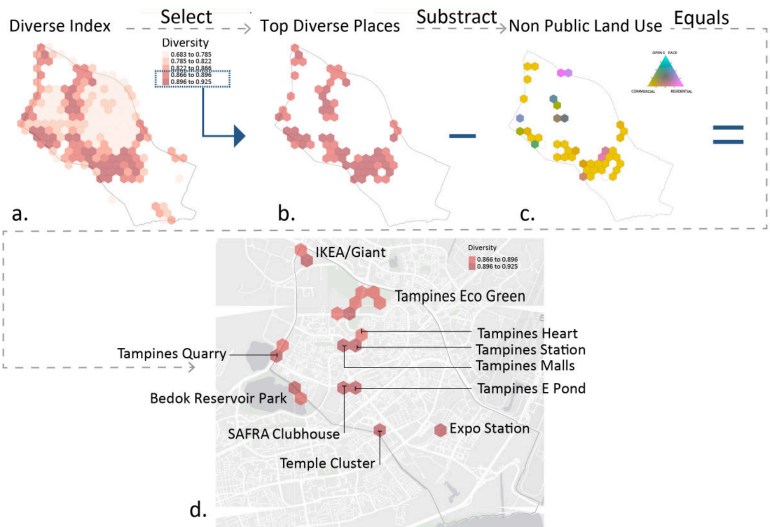

Figure 4. Diversity Analysis Methodology .

5. Conclusion and Future Research

It is not the goal of this research to find a 'type' of place to be named as "social hub" but rather to understand the social landscape of a city. Where and what are the places that have served as social sites regardless of their designated function. As I have shown here, by going beyond density and including diversity, the proposed quantitative method is able to leverage a bottom-up approach to attain a deeper understanding of the city's social landscape. Also by further disaggregating social spaces (detected or designated) into specific subgroups of their measured density (popularity) and diversity (inclusiveness), an even deeper understanding of the characteristics of social places can be attained. Such classifications can for example based on combinations of both density and diversity of the spaces measured and are used as a proxy for the top-down understanding of how social space is performing e.g., why are some of the popular social places not visited by a greater diversity of demographics and vice versa). In this way, we can provide architects and urban designers with a quick way of pinpointing underperforming areas or well-performing places to investigate for solutions and inform better planning for our future social places in our urban environment.

Although the present paper focuses on Singapore as a case study, the approach and methodology outlined here can be expanded to other cities as well. As such, this research expands the usefulness of social media as a practical tool to help understand urban processes by making the concept of diversity - a key consideration in many planning and design contexts - measurable and mappable.

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MODELING UAM SCENARIOS FOR URBAN DESIGN

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Abstract. Recent developments in unmanned aerial vehicles (UAVs), including drone delivery services and air taxis, are revolutionizing urban transport, leading to a new field of research referred to as Urban Air Mobility (UAM). While several contemporary efforts to computationally model future scenarios for UAM exist, in this paper we argue that these models tend to be narrowly conceived as air-space design and management tools and provide little information on ground-level impacts. This paper describes an ongoing effort to create UAM modelling tools useful specifically to urban designers as part of a push toward integration of urban airspace design with ground-level master-planning. Current functions permit designers to visualize drone-fleet origin-corridor-destination routes, generate a strategic model of UAM noise, and compare tradeoffs between UAM system efficiency and noise.

Keywords. Urban air mobility (UAM); urban design; data-driven design; simulation; parametric design.

1. Introduction

1.1. URBAN AIR MOBILITY (UAM)

In the future many thousands of UAVs (unmanned aerial vehicles, like drones and air taxis) will fly in the airspace above cities, not only making deliveries, but also carrying out many as-of-yet unimagined tasks. A new field of research on Urban Air Mobilities (UAM) is tackling questions of how this future airspace may function and how it will change our cities. While air taxis remain on the distant horizon, many technology companies are working today to make drone delivery commonplace, including Amazon and Google spin-off Wing Aviation (Curlander et al. 2017). Though today's drone deliveries mainly occur in rural or peri-urban areas of low population density, this is likely to change in the near future as UAV delivery companies pursue larger urban markets (Cervantes and Herrera 2019).

1.2. AIRSPACE DESIGN AND URBAN DESIGN

Current literature indicates that UAM traffic in urban areas is unlikely to follow direct, 'as the crow flies,' origin-destination routes. Jiang et al. write, for example,

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 71-80.

that a future UAM airspace would include, ‘elements of airspace design, corridors, dynamic geo-fencing,’ among other restrictions which would limit the paths UAVs could take through airspace (Jiang et al. 2017). The elevation at which different types of UAVs will operate is also an open regulatory question. In 2015 Amazon proposed a widely-cited two-tiered airspace design for UAVs with ‘low-speed localized traffic,’ operating up to an elevation of 61m and a ‘high-speed transit’ zone from 61 to 122m for, ‘highly automated vehicles operating beyond line of sight’ (Amazon Prime Air 2015). Airspace design will have an important impact both on the efficiency of any UAM system, as well as its impacts on ground-level activities.

General guidelines, however, are not enough to design airspace for UAM: detailed computational models and flight control tools are needed. Several UAM simulations and flight control tools are in the first stages of being developed and tested. AirMap in the United States is currently testing a UAS Traffic Management (UTM) Platform on that nation’s first 50-mile, ‘drone corridor,’ in upper New York State (New York State Governor’s Office 2019). In Singapore the NTU Air Traffic Management Research Institute is developing Traffic Management for Unmanned Aircraft Systems (Salleh et al. 2018). They have modeled urban route network scenarios for an urban town in Singapore with an emphasis on simulating system capacities over different urban terrains (Ibid).

While the examples cited above demonstrate that unmanned aircraft system traffic management (UTM) is developing rapidly, little effort has been focused on modelling the impacts of Urban Air Mobility for city planning, urban design and architecture. This oversight seems particularly concerning when we consider the potential ground-level impacts of large-scale UAM systems.

1.3. GROUND-LEVEL EFFECTS OF UAM

The primary effects of UAM on urban design will be through changes in mobility patterns. In the short term some ground-based delivery services will be replaced by UAM services. In the longer term, air-taxis like Volocopter may change the itineraries people take through the city. These primary effects are already partially anticipated and built into products being developed by Amazon Prime Air, Alphabet’s Project Wing, Uber Elevate, Matternet in Switzerland, Flytrex in Israel, and Volocopter in Germany. Urban designers and architects like Norman Foster, Jonathan Ledgard, Liam Young and Keith Kaseman have begun to anticipate these changes in their designs (Taub 2019).

The externalities, or unintended consequences, of scaled-up UAM, however, remain relatively under-studied. We know anecdotally that city residents may experience inconvenience from drone noise, privacy intrusion or drone crash (Jensen 2016, Garrett and Anderson 2018). However, there is a knowledge gap on how these potentially adverse secondary effects will evolve as UAM scales up, and in particular we are missing quantitative and spatial data for responding to these possible impacts as urban designers. Considering how the introduction of modern airports disrupted 20th century cities, it would seem prudent to anticipate the potential externalities of UAM in our future cities before problems occur (Ortner 2017). Urban designers and planners will need the capability to weigh in on where

UAM traffic should be concentrated over pre-existing areas of the city, and for new areas of the city to integrate airspace design with urban design.

1.4. A PRELIMINARY UAM MODELLING TOOL FOR URBAN DESIGN

To address the knowledge gap on the ground-level effects and externalities of UAM today's urban designers need tools to help them consider airspace design and ground-level design side-by-side and compare tradeoffs between the two. This integrated approach recognizes that we now live in a truly three-dimensional city, and that planning and design for our urban future requires an integration of airspace and ground-space planning. Future tools for urban design will need to support designers as they advocate for airspace designs which maximize benefits to the city below while minimizing negative externalities.

As a preliminary step, on the way to a more general UAM model, we developed a model to study a corridor-based urban drone delivery system and its noise impacts at ground level. This decision was based on a few key learnings from our literature review; namely that drone delivery in urban areas is likely in the near future, that drones in urban areas will not fly direct origin-destination routes but will likely be confined to geofenced areas or corridors, and finally that aggregate ground level impacts like noise are only anecdotally addressed in current literature.

In a methods section below we describe the key variables, outputs and functions of our model. In a subsequent results section, we describe how the tool was used in an academic urban design project for the city of Glasgow, allowing designers to anticipate the impacts of airspace design scenarios for a district masterplan. Finally, in a conclusions section we describe limitations of the current model and future plans to improve and expand it.

2. Methods

2.1. DEFINING KEY OUTPUTS: UAM EFFICIENCY METRICS VS. GROUND-LEVEL NOISE IMPACTS

Our goal in producing this tool was to assist urban designers to consider future UAM airspace scenarios as they develop masterplans. Specifically, we aimed to support understanding tradeoffs between the design of urban airspace and the design of ground-level urban masterplans. These tradeoffs could be understood in terms of airspace benefits vs. groundspace benefits but also in terms of airspace efficiency vs. unintended ground level consequences like noise. In a first step toward a more comprehensive UAM modeler for urban designers/planners we chose in this preliminary tool to consider trade-offs between UAM system efficiency and ground-level UAM noise distribution.

Efficiency of UAM systems is indicated by two metrics in our model; 1) total km travelled (for a given number of origin-destination-corridor itineraries); as well as 2) number of out of range destinations (for a given set of itineraries.) These two metrics provide a simple means of understanding the feasibility of an airspace scenario and of comparing efficiency between different airspace scenarios with identical origins-destinations. These two metrics and their use is further explained in section 2.2.

Ground level noise levels in our model are indicated by time-averaged noise pressure levels measured in decibels. These noise levels are simulated for a grid of sample points defined by the user. Explanation of the function for generating ground level noise values is detailed in section 2.3.

We anticipated that comparing UAM efficiency against a noise-level heat map would permit urban designers to discriminate between airspace/masterplan designs in search for variations that would maximize efficiency of airspace use and minimize noise-based disruption to sensitive urban areas. This is not presented as a comprehensive UAM model, but rather as a preliminary step toward supporting future integration of urban land-space planning and air-space design. Further discussion of how the key output metrics were used in an urban design test case are detailed in section 3.

2.2. KEY FUNCTIONS: VISUALIZING ORIGIN-CORRIDOR-DESTINATION SCENARIOS

The first key function of our drone airspace visualization tool allows designers to combine origin and destination data with possible corridors and compare resulting UAM airspace scenarios. In this first function we assume that regulations will require drones to begin their flights by ascending directly to a pre-determined corridor height, then proceeding along the shortest path to the drone corridor (figure 1). Beginning flight on a vertical vector minimizes nuisance to surrounding areas and would be a probable feature of future urban drone regulation according to contemporary literature (Ippolito et al. 2019).

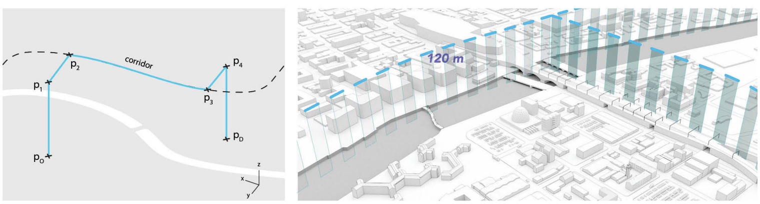


Figure 1. Drone routing sequence diagram (right), flight corridor elevations on site (left).

The corridor-based UAM flight-routing function used in our tool is derived from similar procedures identified during our literature review. It reflects, for example, a simplified version of the point-to-point package delivery use-case presented by NASA's Safe50 reference design study in 2019 (Ippolito et al. 2019).

The origin-corridor-destination function requires four inputs: (1) a list of origin points PO (i.e. droneports), (2) a list of destination points PD, (3) a list of corridors (as polylines), and (4) a corridor height value (figure 1). From a given destination PD the tool works backwards, first finding the closest corridor and then the closest origin point to that corridor. The sub-segment of the corridor lying between the closest points to origin and destination is then identified. A polyline is constructed linking origin (PO), a point at corridor height above the origin (P1), the corridor sub-segment (P2 - P3), a point at corridor-height above the destination (P4) and the destination point (PD) (figure 1).

We anticipate that delivery drones would need to return to their point of origin (the droneport) after delivery. To reflect this our function permits the initial origin-destination polyline to be linked to an additional return polyline which replicates (in reverse) the process described above. In figures 2 and 3 we have placed this return path below the origin-destination polyline to facilitate visualization.

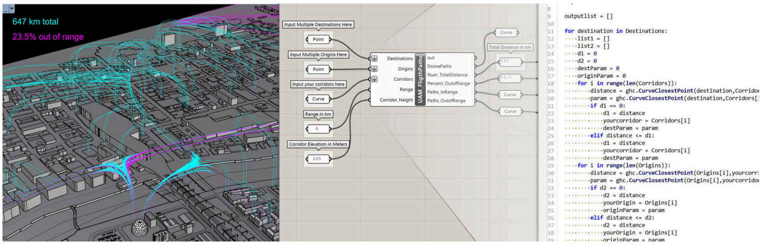


Figure 2. Screenshot of UAM flight path generator within Grasshopper for Rhino.

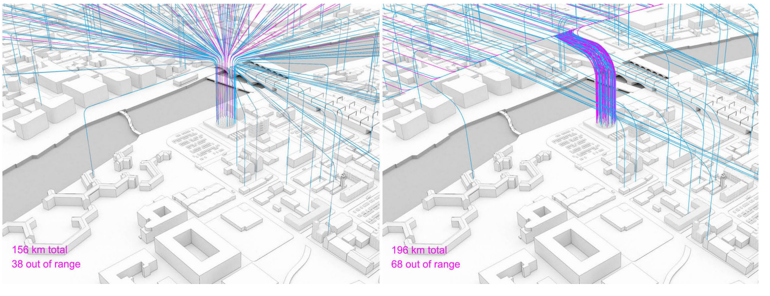


Figure 3. Corridor scenarios: direct routes (left), corridor above river (right).

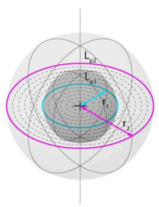
The tool facilitates the comparison of different origin-corridor-destination scenarios by offering a measure of the total distance flown by all drones in the scenario (figures 2,3). This offers a means of comparing efficiencies when testing different corridors (all other variables being held equal). As contemporary drones have significant range limits, we also include a function which sorts out routes that exceed a user-defined range limit. Routes that exceed the range limit are assigned a different color in the visualization, shown here as magenta (figures 2,3).

To visualize the real-time flights of drones (and to later produce a simulation of cumulative drone noise) we created an add-on script that animates drones ‘flying’ sequentially along their designated routes (figure 5). The drones are assigned an average speed by the user. This add-on script incorporates a timer to release the ‘drones’ at regular intervals and to mark their advancement along their routes. Upon returning from the destination to the droneport, the ‘drone’ is removed from the list of active drones. We next used this simulation of urban drone flight to create a simple UAM noise simulation.

2.3. KEY FUNCTIONS: ESTIMATING CUMULATIVE DRONE NOISE

Making strategic urban design decisions about the future of drone delivery means not only considering the efficiency of drone airspace, but also thinking about its impact on life on the ground. In a first step toward understanding drone delivery's impact on urban areas we used our drone delivery simulation described in 2.2 to create a cumulative drone delivery noise simulation.

This simulator works using a model of outdoor noise propagation known as Spherical Free Field Sound Propagation which calculates sound pressure level at a variable distance given a known pressure/distance reading (figure 4).



$$Lp_1 - Lp_2 = 20 \log r_2/r_1$$

where: Lp_1 = sound pressure level 1 (dB)
Lp_2 = sound pressure level 2 (dB)
r_1 = distance 1
r_2 = distance 2

Figure 4. Spherical free field sound propagation diagram and formula.

This equation provides the often-quoted rule of thumb that noise will decrease by 6dB with each doubling of distance from the source (Beranek 1954). This method of noise level calculation does not yet account for some key urban acoustic phenomena like reflections. We hope to account for these functions in the future and reserve further discussion for section 3 below.

To build a simulation from the Spherical Free Field Sound Propagation equation we first ask the user to input a drone noise level in decibels. These measurements are publicly available for some models of drones (Tinney 2018). A second input required from the user is a grid of sample points at which we will measure the cumulative noise level of the drones.

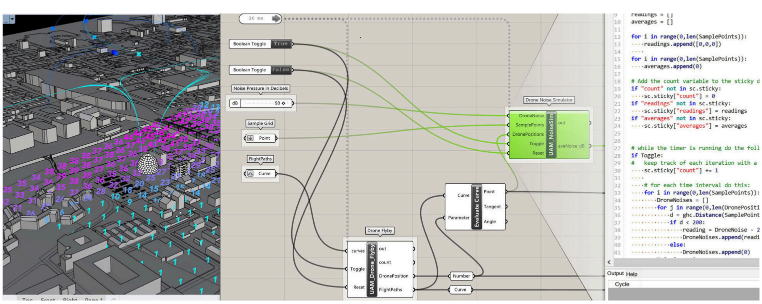


Figure 5. Screenshot of UAM noise simulator within Grasshopper for Rhino.

To simulate noise for a single drone we would calculate the noise level based on the distance of the drone from each point in the sample grid. To produce a time-averaged noise simulation we would then measure the noise level at each time state as the drone flies by, then sum these noise levels together using logarithmic summation and average them based on the number of time samples.

However, our simulation requires estimating the urban noise from many drones flying through the sky simultaneously. This requires measuring the noise level contribution from all flying drones to all points on the sample grid, then running the logarithmic sum of these noise levels. The cumulative noise of all the drones at each sample point is then time averaged following the same method described above.

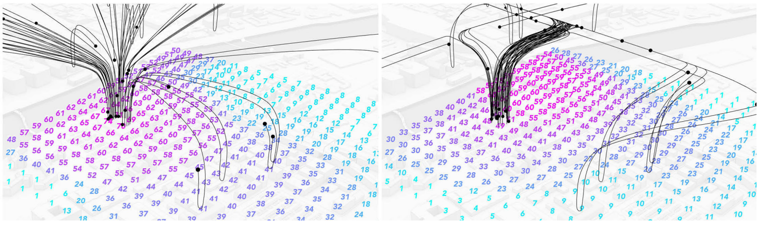


Figure 6. UAM noise simulation: direct routes (left), vs. a multi-corridor scenario (right).

To visualize the numeric estimate of the noise created by a fleet of drones flying over a flat area the tool has two outputs which are continuously written to each sample point: (1) time-averaged decibel level for each sample point, and (2) an RGB value based on a gradient from magenta to cyan. In figure 6 we have assigned the color magenta to values ≥ 70dB and the color cyan to values ≤ 20dB. The color gradient assigned to each sample point creates a 'heat map,' that gives users an immediate overview of where drone noise is concentrated for a given airspace scenario. An average of all the decibel levels simulated for each sample point is also returned to the user (figure 6).

Our tool shows, not unexpectedly, that concentrating UAM flights at single droneports or along corridors produces distinct noise 'hotspots' in the urban plan. In figure 6 we compare noise heatmaps for two contrasting airspace scenarios: in the image on the left, drones are allowed to fly directly to their destinations after reaching cruise elevation; on the right, drones follow an origin-corridor-destination path as described in 2.2, with a choice between a corridor above the river or above an adjacent elevated railway. While the multi-corridor scenario shown on the left produces a more distinct/concentrated noise hotspot, we can see however that it has a lower average decibel level. This lower average decibel level is due to the fact that the corridors have effectively pulled drone traffic to the periphery of the study area. The rectangular study area shown in figure 6 reflects an approximation of the masterplan area used in our design studies. As discussed in greater detail in the section 3, the presence of infrastructural sites on two sides of our site provided us with open space where drone traffic could be diverted, minimizing impacts to noise-sensitive areas.

The spatial evaluation of urban drone noise maps based on intuitive readings of heatmaps along with key airspace efficiency metrics supported a more precise discussion of future UAM scenarios in our design tests. In the next section we discuss the impact on design method and output of the tools we have presented thus far in the context of an academic urban design studio.

3. Results and Conclusions

3.1. RESULTS: DESIGN STUDIO FOR UAM ON POST-INDUSTRIAL SITE

We tested our UAM simulation tools in an urban design studio at EPFL that addressed more broadly the potential impact of the automated economy on a largely vacant post-industrial district in Glasgow. We asked our designers to develop a district master plan in parallel with an airspace design for drone delivery supported by the tools presented in this paper. We observed two distinct use-patterns associated with the tool.

A first use-pattern we would call, 'speculative,' or airspace-driven. In this use pattern, designers first attempted to design an efficient UAM corridor system, and then used this to organize their district plan, for example moving sensitive program away from noisier areas.

A second use-pattern we would call, 'assertive,' or groundspace-driven. In this use pattern the designer developed a general sense of the masterplan they felt would work best on the site, and then established 'quiet zones,' where they asserted that there should be minimal UAM noise impact. They then iteratively tested corridor options till they were able to achieve a result adequate to their intentions.

An example of a design that asserted desired quiet zones as a pre-condition for UAM airspace design is shown in figure 7. In this academic example the drone noise simulation has been merged with a district noise map obtained from an open-data source (SEPA 2016). While this design increases the total distance flown by drones in our model, it minimizes noise impacts to central areas where the designer hoped to introduce residential and educational programs. The design shown in figure 7 has positioned the drone port and drone traffic near a highway and rail corridor, where drone noise is masked by pre-existing traffic noise. This design used an add-on tool we developed to merge pre-existing municipal noise maps with our simulated UAM noise maps. This function is still in development and exceeds the scope of this paper.

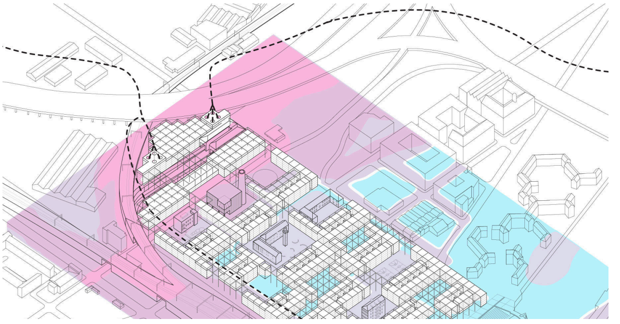


Figure 7. Design tests established ground-level quiet zones (cyan) using the UAM model.(student work: Jean-Baptiste Clochet, Nicola Mahon, EPFL Media x Design Lab).

We felt that the ability of the designers to take an assertive stance toward UAM, by pre-emptively establishing quiet zones and iterating their designs to achieve desired noise levels, was a validation of the potential of our preliminary UAM model. In the future we believe that an expanded version of our tool will help urban planners/designers in non-academic applications to come to the table with aviation authorities and private companies and argue for airspace designs that best anticipate the concerns of urban residents. This pre-emptive ability could facilitate the design of UAM airspace in a manner that minimizes community dissatisfaction before it occurs.

3.2. RESULTS: LIMITATIONS OF PRELIMINARY UAM MODEL AND ON-GOING WORK

Future UAM airspace, according to our literature review, will likely be volumetrically defined, with individual UAV checking in and out of zones as they move through urban airspace. The corridor-based model as described in section 2.2, thus presents a simplification of the way future airspace will likely work. While we feel that our corridor-based simulation is sufficient to preliminary urban design studies, and that it is has provided valuable input in our design explorations, we recognize that even for urban design applications a polygonal corridor model can be over-restrictive. In our on-going work we are moving toward a volumetric air-space model that would nonetheless still provide a simplified and global airspace overview useful to urban designers and planners.

The noise simulation we have presented in this paper also has limitations that we have recently explored in conversation with an acoustician. Spherical propagation provides a strategically sufficient model of UAV noise when the UAV is at cruising altitude and well-above elements of the built environment. An effort at benchmarking is currently underway. However, when UAV are in closer proximity to ground or architectural surfaces, reflection would significantly increase noise from certain vantage points.

As the study area for our master plan design study was low-rise and largely vacant, the impact of the 'urban canyon' noise effect was less important for our design studies. Looking forward, as we would hope to produce a tool with wider applicability, taking into account noise reflections would likely be a justified next step. Additionally, the ability to recalculate UAM noise levels based on the presence of proposed future buildings would be a valuable function for urban designers.

3.3. CONCLUSIONS

Future UAM airspace designs will be produced by many actors, from public institutions to private corporations, to citizen groups and designers. While no single actor should dominate the debate over UAM organization, we feel that designers of the urban realm should have an equal ability to advance their concerns relative to aviation industry and aviation authorities. A UAM model created specifically for urban designers would enable them to actively shape discussion over airspace design instead of a taking on more limited reactive role to proposals put forward by the aviation industry or aviation authorities.

The preliminary tool we have presented this paper lays out some first steps toward producing a UAM model for urban planners/designers and provides a road map for future efforts in this direction. Comparing tradeoffs between airspace efficiency and ground-level noise provides an important quantitative feedback on UAM design. As work continues on the tool, we hope to study ground-level privacy impacts of UAM airspace designs as well as mobility network impacts.

While we designed our UAM tool for urban design applications, it will also assist urban planners to reserve space for future UAM infrastructural needs, and aviation authorities to route growing UAM traffic over urban terrain. We hope the tool will support design of UAM systems that are complimentary to ground level activities without causing excessive nuisance.

Acknowledgements

The authors would like to thank EPFL Media x Design Lab students and staff who tested our tool.

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CULTURAL-SMART CITY: ESTABLISHING NEW DATA-INFORMED PRACTICES TO PLAN CULTURE IN CITIES

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Abstract. The idea of the Creative City has encouraged planners to develop cultural policies to support creative economies, city branding, urban identity and urban quality. On the other side, the concept of Smart City introduced the possibility to create, collect and analyse data to inform decisions on cities. The two city agendas overlap in different ways, creating a Smart cultural city nexus, that propose similar goals and mixed methodologies, like the possibility to inform planning processes with big data-based technologies. In line with this direction, we introduced conceptual and methodological tools: the first tool is the definition of Hybrid Art Spaces, the second tool is the Singapore Art Maps (SAM), which uses social media data to locate art venues in cities (Tomarchio et al. 2016); the third tool is the Social Media Art Model, which establishes a relationship between social media production and art venues features. While these tools have already shown interesting analytics outcomes (Tomarchio et al. 2016), it is important to validate their utility among practitioners and to set protocols of practices. This paper presents results from semi-structured interviews and a focus group, as a first step towards assessing the usefulness of our three tools for cultural planning practice.

Keywords. Social media; art; cultural planning; urban planning.

With the introduction of social media, the production and consumption of art are changing significantly. It has resulted in the emergence of Hybrid Art Spaces: social spaces existing both in physical space and on social media. The actual importance of the hybrid nature of art consumption is influencing the way art and culture are conceived, almost adapting art production to the aesthetic and format necessary for social media discussion and hype (Cascone, 2019; Woon, 2019). Anyone approaching the planning of art in cities ought to consider this shifting paradigm. Besides, social media produce user-generated data able to provide information about the urban environment and support for decision-making

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processes, in line to what is advocated by the idea of Smart City (Hashem et al. 2016; Lim, Kim, and Maglio 2018). The present paper positions itself at the convergence of Smart Cities and Creative Cities, an intersection that has emerged with the advent of social media and the resulting shifting modes of cultural production in creative economies (von Richthofen, Tomarchio, & Costa, 2019).

Studying social media related to art production and consumption, with a focus on planning, is potentially beneficial for different practitioners. This sector of interest is very wide and it encompasses many different studies and contributions from a variety of disciplines. Curatorial practices tried to frame how to interpret an audience's attitude towards picturing and sharing art in museums and art places (Stylianou-Lambert, 2016) or how to envision a shift in art production for museum institutions (Parry, 2010). The shifting of art production and consumption due to the introduction of social media has been analysed from many points of view. view. However, we have not encountered studies approaching this topic from a design perspective, which would be able to creatively use the definitions and tools for future case studies. In addition, there is a clear research gap when it comes to applying data analytics: a limited number of existing studies (Currid & Williams, 2010; Granpayehvaghei, Bonakdar, Zandiatashbar, & Hamidi, 2019) apply advanced data analytics on art-related user-generated data and include social media related indexes in cultural planning.

To address these gaps we introduced conceptual and methodological tools (Tomarchio et al. 2016) that include social media analysis to evaluate cultural planning strategies. More specifically, the tools we discuss are:

- The definition of Hybrid Art Spaces, which is a concept that integrates art venues and digital technologies;
- Singapore Art Maps (SAM), which uses social media data to locate art venues in cities (Tomarchio et al. 2016),
- Social Media Art Model, which establishes a relationship between social media production and art venues features (Tomarchio et al., 2020).

Those tools have already shown some promising analytical results. Nevertheless, the Smart city implementation is strictly connected with know-how development (Angelidou, 2015; Ben Letaifa, 2015); with this paper, we aim to address this need by introducing the tools to Singapore based practitioners. The research goals are to assess the perceived value of the tools, to determine their existing potentials and limits and to find current practices that could benefit from them. To pursue these goals, we organised a focus group and a series of interviews. The underlying question that drives all the interviews is: can we support cultural planning if we understand its relation with social media data?

The paper starts with a description of the methodology and some key aspects of cultural planning in Singapore. An overarching section describes the consensus on the validity of the research and then three separate paragraphs introduce the different tools. In each section, we shortly describe the tool and then we focus on the potentials, limits and future applications with reports from the conversations with practitioners.

1. Methodology

The aim of the research is to position three tools relative to the practices of different actors (cultural planners, urban planners, artists, art critics, and art managers). In this research we consider the term tool with a wide definition, which includes conceptual and operational tools (FUTURE CITIES LABORATORY, 2019). Tools support actions, like designing or thinking. The first tool is a concept, an original definition that we introduce and support through existing literature. The concept of Hybrid Art Spaces and its explanation can inspire and guide cultural practitioners in their activities. The second tool (Singapore Art Maps) is a methodological tool, to define metrics and indexes to quantify the social media activity in art venues and is also an analytical tool that users can navigate to explore art related social media data in Singapore. It is more open to different applications: we propose a way to collect, visualise and analyse social media data, but the interpretation of the data and application of the tool is open. The third tool (the social media art model) is a machine learning model (analytical tool) that correlates the media production in art venues with different attributes. The practitioners are mainly asked to comment on the results, which can inform their future work.

The methodology is based on two steps: a focus group with five people and four interviews. The people selected for both steps have been active in the context of cultural production in Singapore for the last five years, and they represent not only different disciplines but also different roles (institutional, independent, commercial). During the focus group, we asked different practitioners to do an individual presentation on the possibilities of the Smart Cultural city nexus and then through a guided discussion, focused on the points highlighted in this paper. The interviews, on the contrary, were semi-structured interviews, where the participants were shown the different tools and asked to comment on their value, possible future applications and limits and potentials. The outcomes are anonymised, but we highlighted the discipline domain to show a different perspective on similar topics. The age of the people currently interviewed ranges from 30 to 45 years old. The focus group was composed of an art manager (AM), two urban planning academics (UP), a journalist (J) and an art director (AD). So far, we have conducted the first four interviews, including an art manager (AM), two urban planners (UP) and an exhibition designer (ED). We recorded, transcribed and coded (Harding, 2015) both the interviews and the focus group. The following text proposes the recurring themes and confronts different opinions on similar topics.

2. Case study: Singapore and its context

The tools discussed in this research paper are currently applied in the context of Singapore. While the research refers to Singapore, many of the observed urban phenomena have a global scale. The dynamics between new media and art can likely be observed, perhaps at different speeds, in other cities around the world. Currently, the tools and the analytical resources have been tested and proven only in the context of Singapore and the outcomes of the interviews are strictly connected to Singapore specific art situation. Therefore a quick overview of the specificities of the art scene in Singapore, and its planning practices is beneficial.

The art scene in Singapore is still quite dependent on government support, with limited funding from private collectors and investors (Said, 2017). This dependency on government support makes it easier to observe the studied phenomena in isolation of other types of support, and hence easier to extract knowledge to inform planning and policy. The Singapore government created data resources on the website of National Art Council (NAC) that include lists of recipients of grants and the location of art spaces, such as facilities (studios, stages, spaces for rehearsal, galleries) offered to artists. Following the *renaissance city plan* and the *report on art and culture strategic review* (National Art Council 2008a, National Art Council 2008b, National Art Council 2008c), the government provided grant schemes, but also art spaces and art facilities (S$270 million worth of programmes). The art spaces and the art facilities are designated in conversation with the Urban Redevelopment Authority (URA), with a spatial agenda.

3. Perceived relevance of the research by practitioners

The overarching questions leading all the interviews and focus group was: can we support cultural planning if we understand its relation with social media data? There are two types of reactions to the above question: events curators and exhibition designers consider the relationship between art venues and social media as very relevant (*"I think it is beyond relevant. I think it is inevitable." (ED) and "It's mandatory, it's compulsory."* (AM). On the contrary, urban planners do not view social media as something that affects the way they think of art spaces. Social media rather represent side information that can be useful, together with another source of data, to frame and understand a place.

"*I think a lot of social media information can complement other things that we might get from places to put some kind of picture together of the full of places.*" (UP)

In the context of curators or art practitioners in Singapore, there is, among governmental clients, the introduction of specific requirements linked to the use of social media; the concept of 'Instagrammable' is a requirement that demands physical locations and works of art to instil in audiences the desire to make a picture though digital cameras and share it on social media. While the term is officially used in institutional tenders, the idea of Instagrammable is still very vague.

"*There has been this shift towards creating memorable experiences. In the daily vocabulary its Instagrammable. [...] And there has been a shift for example in the requirement of institutions client where more and more the word that comes is Instagrammable. It should be Instagrammable. Ten years ago, it wasn't [...] Any kind of cultural event should be Instagrammable because it can be shared. So, it's the aim of sharing to attract more people."* (ED) or *"They always ask for Instagramm-able moments*". (AM)

4. First tool: the concept of Hybrid Art Spaces

Hybrid Art Spaces are art venues existing both in physical space and on social media, resulting in various forms of hybrid consumption and production of art taking place in merged physical and non-physical social spaces. The term draws on the concept of Hybrid Space (de Souza e Silva, 2006) where space is intended primarily as social space (Lefebvre & Nicholson-Smith, 2011). Social space is constructed by situated social practices in the space; the innovation of hybrid (art) spaces is that (art-related) social practices can be situated in social media.

Different practitioners validate the definition, stressing specific aspects:

- the impression that production and consumption of art is shifting due to the introduction of social media, where sharing becomes a way to consume art: ”*artwork today is something to be shared and that's it because it is a way of consuming.*” (ED)
- the mutual interdependence between the physical world and the digital world, mainly happening through social practices that navigate between the two spheres: ”*there is always this idea of the online to offline to online again. You see something online, on Instagram, on Twitter, one Facebook and so on. It attracts you so you will go online to find that information. You can see the design hints: the graphic design, pictures. It excites you. You want to go there. You go there. You are there because you saw others taking pictures. You do the same. And then to show that you did the same, you share it*“ (ED); ”*people coming earlier, start taking photos that are mostly stories and videos (to be shared on Instagram) because then it attracts more people.*” (AM)

The term practitioners directly use to indicate that a physical space behaves as a Hybrid Art Space is Instagrammable. This term refers to the potentials of the physical spaces to attract pictures and shares and it became a client requirement in Singapore. How can we deconstruct the term Instagrammable, and explore what aesthetic, process, practice support the idea of Instagrammable in spaces and art? According to the different practitioners the nature of Instagrammable is to create an object (art, space, social interactions, practical items) that is:

- iconic and visually attractive: ”*when there is something iconic, when there is something that will draw attention. It can be light, it can be material, it can be an infinity effect. If it's not extravagant enough, if it's not strong enough or exhibition colours or exhibitions light, if it is too muted, they know that only certain kind of people will be taking pictures and that will not create the buzz.*” (ED)
- immersive for the audience: ”*Something that will make you looking good inside.*” (ED)
- encompassing different aspects: ”*So there has been this shift towards creating memorable experiences. In the daily vocabulary its Instagrammable. I use the word experiential because when we think of experiential we think of multimedia, big lights, big music, your body, the five senses.*” (ED).
- digitalised: ”*Digitalised as part of the experience [...] you must provide something that is also digitalised, in a way. AI experience. It has to be something that is bridging the digital and physical world.*” (AM)

The overall call for Instagrammability is a call for numbers, as the phenomena of picture taking and sharing are driving more and more people to art venues. Many practitioners question wether the requirement to produce Hybrid Art Spaces favours quantity over quality: ”*Now, it is becoming that nobody cares if it is intellectual or not as long people absorb it. So, there is content becoming more and more stupid just because it is easy to absorb because it is easy to see on a small screen and that is it. [...] We can have amazing artists, very spiritually, philosophically, aesthetically and artistically, historically strong but if they aren't Instagrammable then that's it. That's the most important thing.*” (ED)

5. Second tool: Singapore Art Maps

The second tool is the Singapore Art Maps (SAM), which is introduced in Tomarchio et al (2020). The SAM consists of a set of geographical data, derived from social media (Twitter) analysed with machine learning. This data is accessible in multiple forms of visualization:

- Singapore Views, a 3D visualisation developed by the Future Cities Laboratory (Fig 2);
- GIS based maps.

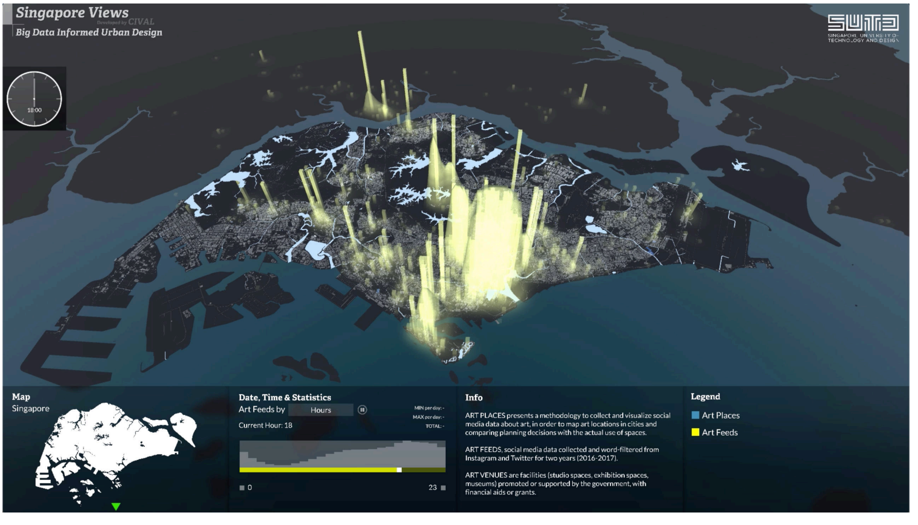

Figure 1. Singapore Views in a 3d environment to navigate across the social media data about art venues.

The tool comprises several sub-tools, to use in the different stages of the analysis. The overall process of SAM is:

- collection of Twitter data, with a crawler component in a Java environment to gather data from the Twitter API (Application Programming Interface). We collected a set of 8,035,207 tweets within Singapore covering a period of 615 days (from 25/04/2016 to 31/12/2017).

- Social Media Art Classifier: a machine learning feature able to depict art-related tweets in Singapore and its main topic.
- Topic Diversity and Sentiment analysis: machine learning features to determine the main topics of the art tweets (clustering analysis), and quantify the main sentiment of a tweet (sentiment analysis).
- Social media metrics: a combination of cultural planning data and social media data, resulting in the classification of different art venues in cities in three categories: Confirmation, Negation and Emergence. The Confirmations derive from planning practices in Singapore: they represent venues which benefit from grants and other forms of support. They meet a certain threshold of media production, derived from the general distribution of social media in Singapore. Negations are, on the contrary, planned locations, which do not meet the threshold. Emergences represent alternative art venues, locations not supported by planning policies, which still have a relevant media contribution.

The different practitioners comment on the tools and define a part of their activity or a general goal which would likely be supported by the use of the tools. One main criticism is the current lack of diversification both of the type of art production and the type of audiences. There are different urges to produce art, and while commercial art strives to attract wider audiences and therefore to be visible in maps, other productions are only limited to smaller audiences and minority communities that often do not wish to appear on social media. There is a subtle threshold between visibility and need for invisibility, where social media and social maps play an unknown role which might not be auspicious. ”*Some artists don't want to be called artists. Then those who want to be seen and called artists are interested in making art for everyone and selling.*” (UP)

Art practitioners and curators recognise SAM's potential to research alternative locations and venues, which is supported by the tool's Emergences. Singapore's art scene lacks a variety of venues, besides official ones, and the tool can offer alternatives. ”*For much of the past 15 years these sites, especially independent artists' initiatives, diminish in the wake of large-scale institutionalisations, including the development of the National Gallery, the Art Stage Fair, the Art Science Museum and Gillman Barracks.*” (AM)

”*I think it is very useful. Not necessarily for big institutions but for art planners, art event companies that are looking for other attendants. But what is important is to ensure that it is reachable. If it is not reachable, and you are targeting families, they will not come because it is too complicated. If it is to target for the young people, they are pretty mobile, they can easily move then that is okay.*” (ED)

Other activities to be supported by the tools would be Museum Planning (ED), which is the planning activity to support the foundation of a new museum, including establishing the museum vision, in reference to existing ones. Other practitioners (AM) consider the tools useful to calculate cultural events impact, to gather further support from stakeholders and investors.

Urban planners acknowledge the potentials of the tools for cultural assets mapping, but they question the sustainability of the emergences, meaning the art venues that show interesting media contribution and that currently do not benefit from planning support.” *When you see emergences, is it concentrations that last* *over time? Or are they quite transient? Is a location slowly becoming a centre of life?* ” (UP).

6. Third tool: the Social Media Art Model

Finally, the interviewers judged the construction of a machine learning model which is able to understand what features mainly influence the social media outcome in art venues. The machine learning model correlates features of art tweets in particular art locations to their art-related social media production, labelled as Negation and Confirmation (Fig 2). The aim of this model is to understand the relative importance of different features in the generation of art-related social media communication (Confirmation or Negation).

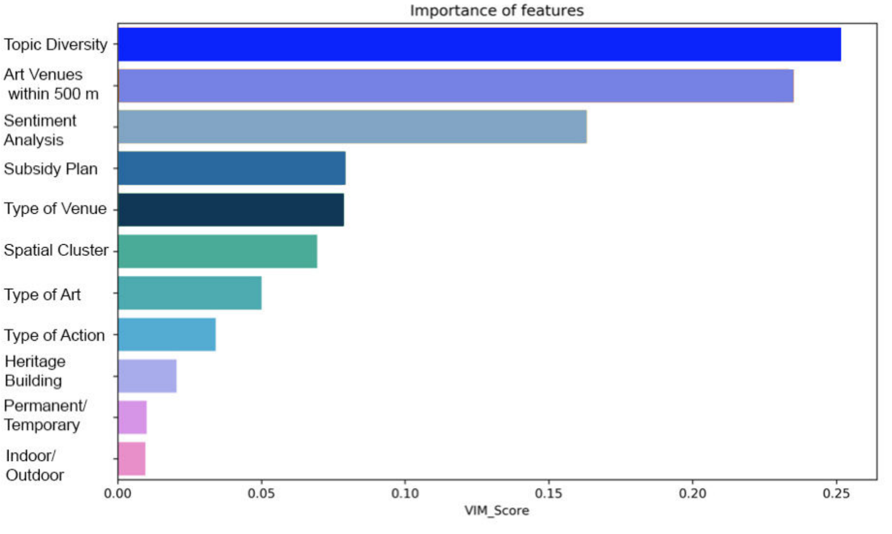

Figure 2. Importance of art venues features correlated with social media production. .

The interviewers commented on how to integrate the model or to make it better based on their experiences. The first criticism is the lack of festivals and events as separate art venues. Festivals and events are becoming the main asset in Singapore’s cultural scene, and while they usually take place in locations generally used as museums or galleries, festivals transform those venues, making them accessible during a different time of the day, proving food or not, etcetera. In the current model, there is no specific focus on festivals and events. ”*it is suddenly to transform an art venue that is known, the National Gallery, the National Museum, Singapore Museum into a destination for a special event. And people go because it goes with an empirical system. You have food, you have retail, the streets are closed so there is this idea of suddenly you own the space as a community.*“ (ED); ”*But once in a while, they have these festivals or something that suddenly becomes a big draw for people. Whether there are food and beverage nearby, at least in the Singapore context, would influence media production.*” (UP)

Other comments suggest data to further integrate into the model, including rent prices (ED), visibility from the road (UP) or accessibility of the location (UP). Moreover, some practitioners express the need for an audience division, where the model is subdivided in multiple models targeting specifically tourists, locals, or art enthusiastic audiences. While such profiling using social media data is possible and has been done in many studies (Blanford, Huang, Savelyev, & MacEachren, 2015; Fisher, 2010), it implies gathering and evaluating people's social media profiles, which is not considered a desirable outcome for the current research.

7. Conclusion and current limits

With the current study, we aimed to position three tools within the broad context of cultural planning practice in order to explore their limits and potentials. The interviews validated that different cultural planning-related fields are interested in this topic of research and the tools developed to study it. Their feedback was very valuable in mapping potential applications of these tools. The general feedback on the value of the research was very positive and it points out the direction of future work, like museum planning and events impact calculation. The general definition of Hybrid Art Spaces is well accepted and it encompasses the idea of 'Instagrammable", which is widely used by institutional and commercial clients. The idea of Instagrammable encompasses visual identity, with multimedia and digital experiences. Currently, the interviews and the focus group include practitioners aged between 30 and 40 years old; future iterations of the research would benefit from the inclusion of younger practitioners, as there is a generational gap of the use and approach to social media (Venter, 2017).

Acknowledgments

This research was supported by the Goethe Institute Singapore that contributed to the organization of the focus group. This research was conducted at the Future Cities Laboratory, Singapore-ETH Centre, which was established collaboratively between ETH Zurich and Singapore's National Research Foundation (FI 370074011). This research also benefits from funding from the Singapore University of Technology and Design (SUTD).

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SPECTRAL CLUSTERING FOR URBAN NETWORKS

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Abstract. As planetary urbanization accelerates, the significance of developing better methods for analyzing and making sense of complex urban networks also increases. The complexity and heterogeneity of contemporary urban space poses a challenge to conventional descriptive tools. In recent years, the emergence of urban network analysis and the widespread availability of GIS data has brought network analysis methods into the discussion of urban form. This paper describes a method for computationally identifying clusters within urban and other spatial networks using spectral analysis techniques. While spectral clustering has been employed in some limited urban studies, on large spatialized datasets (particularly in identifying land use from orthoimages), it has not yet been thoroughly studied in relation to the space of the urban network itself. We present the construction of a weighted graph Laplacian matrix representation of the network and the processing of the network by eigen decomposition and subsequent clustering of eigenvalues in 4d-space.In this implementation, the algorithm computes a cross-comparison for different numbers of clusters and recommends the best option based on either the 'elbow method,' or by "eigen gap" criteria. The results of the clustering operation are immediately visualized on the original map and can also be validated numerically according to a selection of cluster metrics. Cohesion and separation values are calculated simultaneously for all nodes. After presenting these, the paper also expands on the 'silhouette' value, which is a composite measure that seems especially suited to urban network clustering.This research is undertaken with the aim of informing the design process and so the visualization of results within the active 3d model is essential. Within the paper, we illustrate the process as applied to formal grids and also historic, vernacular urban fabric; first on small, extract urban fragments and then over an entire city networks to indicate the scalability.

Keywords. Urban morphology; network analysis; spectral clustering; computation.

1. Introduction and Background

Spectral clustering is a well-established practice in a number of fields based in computational analysis such as network theory and mesh or image processing (Chung 1996; Zhang, Van Kaick, and Dyer 2010; Shi and Malik 2000). However,

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 91-100.

it is so far little explored in the domain of urban analysis. Spectral clustering makes use of the eigenvectors of the Laplacian matrix of a graph or network to remap the graph before partitioning (Ng, Jordan, and Weiss 2001; von Luxburg 2007). Compared to other methods, spectral clustering performs well at finding clusters that are defined more by their topological connectivity than by convex groupings which suggests that it could be a useful approach for urban networks.

The widespread availability of precise geodata through GIS software or other sources has encouraged an increase in computational approaches to the study of urban morphology. The most prominent set of such practices goes under the name of 'Space Syntax' and is primarily oriented toward "deep structures" of spatial patterns specifically in the "cognitive dimension of architectural and urban space" (Hillier and Hanson 1997; Marcus, Westin, and Liebst 2013). To some degree, Space Syntax has become an umbrella term for an increasingly diverse set of operations, however it can be more consistently defined by a representational model that utilizes the dual graph where "precedence is given to linear features such as streets in contrast to fixed points which approximate locations" (Batty 2004). This paper avoids such models and instead uses the prime graph. This graph is more similar in structure and form to the common models in graph theory and is also readily available from cities' public GIS databases (often labelled as a 'street centerline' file) or sources such as openstreetmaps. An example of work on urban networks using the prime graph is the Urban Network Analysis toolkit from City Form Lab which has advanced a number of metrics based on geodesic analysis (Sevtsuk and Mekonnen 2012).

Within urban studies, spectral analysis has been used to determine points of centrality in an urban network using the eigenvectors as an alternative to geodesic centrality (Nourian et al. 2016; Boulmakoul et al. 2017). In another case, spectral analysis was used to compare global cities, but this work did not depend on geographical urban networks or spatial data, but rather a high-dimensional data set that described features of the various cities (Hanna 2009).

2. Methods

The work of this paper was realized in Grasshopper for Rhino 6. The matrix decomposition made use of the MathNet.Numerics library and the remainder of the code was written in custom ghPython modules.

2.1. 1.1 CREATING THE GRAPH LAPLACIAN MATRIX

The initial step is to create the Laplacian matrix: this is classically defined in the unweighted case as the difference of a diagonal matrix D that denotes the degree of each node i for D_{ij} and the adjacency matrix A that indicates a connection between nodes i and j with a 1 at the element A_{ij}.

$$L = D - A \tag{1}$$

$$D(i,j) = \begin{cases} \text{degree of node } i & \text{if} \quad i = j \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$A(i,j) = \begin{cases} 1 & \text{if } \ i \ \text{ and } \ j \text{ are adjacent} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

When combined, the graph Laplacian will be a symmetric matrix with rows and columns that sum to zero because the number of links adjacent to the node is, by definition, equal to the degree of the node. In the case of a weighted network, the adjacency matrix is a replaced by a similarity matrix that resembles the adjacency matrix but with a range of values in place of the binary 0/1 choice. The diagonal entries of the weighted Laplacian will then equal the negative of the sum of the linked weights such that the rows and columns of the matrix L continue to sum to zero.

$$L = D - A \tag{4}$$

$$D(i,j) = \begin{cases} \sum_j A_{ij} & \text{if } \ i = j \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$A(i,j) = \begin{cases} weight & \text{if } \ i \ \text{ and } \ j \text{ are adjacent} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

In the case of urban networks where links are not purely abstract but indicate real, spatial connections, it is sensible to use a weighting function based on distance-or a similar proxy such as travel time-to indicate nearness (though one could also consider other data such as existence of programmatic amenities such as in (Agryzkov et al. 2019)). In this study, we have used a Gaussian function:

$$w = .25 + 1.5e^{-\frac{l^2}{2\sigma^2}} \tag{7}$$

where l is the length of the connecting segment in the network, the mean (μ) is fixed at 0 and thus does not appear, and the standard deviation (σ) is assigned following the lengths of segments within the network. Though the lengths are unlikely to themselves follow a normal distribution, a normal distribution would include 95.4% of its values within two standard deviations from the mean. Following this, we have identified the value at the 95.4th percentile in a sorted list of network lengths and used half of that length as the default value for σ. Figure 1 illustrates the outcome of this function for a sample network based on the plan of the Roman city of Timgad.

After the weighting has been computed as a list of arrays, the graph Laplacian matrix is created using MathNet.Numerics' LinearAlgebra.CreateMatrix.DenseOfRowArrays<T> command.

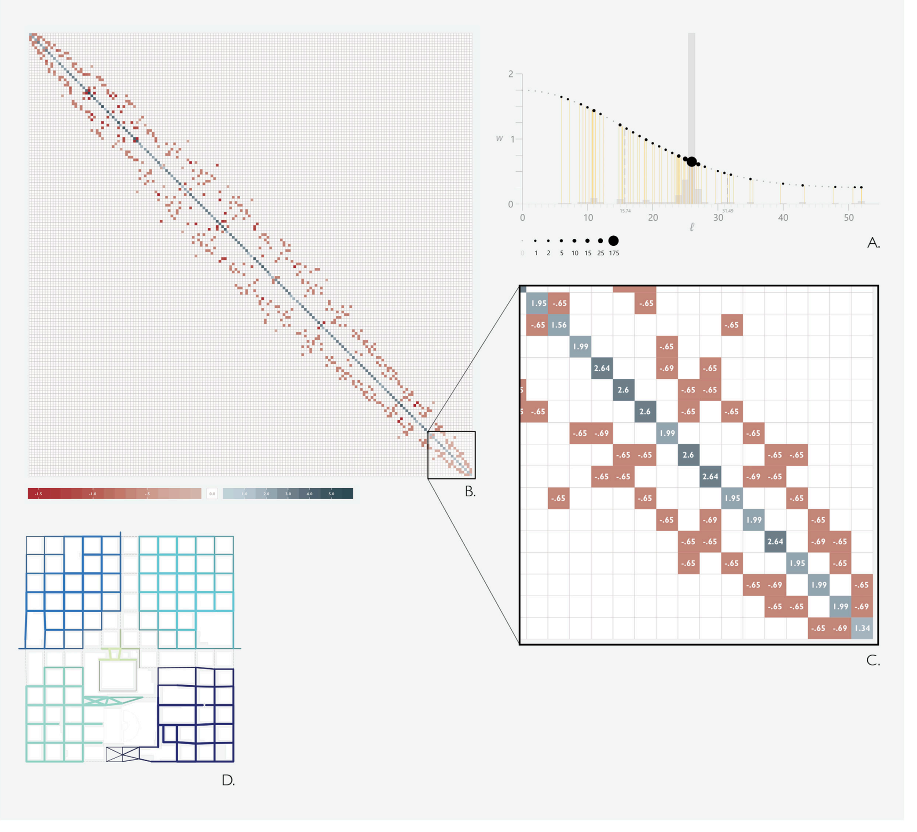

Figure 1. A) Graph of the weight as a function of segment length. The actual lengths of the sample are plotted along the x-axis in orange over a histogram of their distribution. The distribution is also indicated by the size of the dot in the graph. The standard deviation σ and 2σ are also indicated with vertical dashed lines at 15.74 and 31.49, respectively. B) The graph Laplacian matrix of the Timgad sample which has 166 nodes. Although the order that nodes are indexed is not significant, for the purposes of this illustration they have been sorted by their geometric location from bottom-left to top-right. C) A highlight of the bottom corner of the graph Laplacian matrix allowing the values to be read and to confirm that the rows and columns sum to zero. D) The sample network of Roman Timgad with the resulting clusters overlaid (redrawn by author after Frederik Pöll).

2.2. PLOTTING EIGENVECTORS AND CLUSTERING

After the graph Laplacian has been composed, we compute the eigenvalue decomposition again using the MathNet.Numerics library. This returns the full set of eigenvalues sorted from lowest to highest and the associated eigenvectors. Each eigenvector will have as many components as the number of rows or columns in the graph Laplacian, which is to say: as many as there are nodes in the network. Spectral clustering pairs the components of each eigenvector with the respective node and constructs a new coordinate set. For a connected graph, the first eigenvector will entirely comprise components of a constant value and so it can be disregarded. The next eigenvector is known as the Fiedler vector and the component values can be used to quickly partition a graph into two clusters based on whether a nodes' component is greater or less than zero. For a greater number of clusters, more eigenvectors are used. In these examples we used the Fiedler vector and the 3 following eigenvectors to construct four-dimensional points (in the visualization in Figure 2 only three dimensions are plotted). Increasing the dimensionality tends to give more consistent and stable results than using three-dimensional values evidenced by less jumping in the boundaries of cluster divisions when the number of clusters was changed.

Once the points generated from the eigenvectors have been plotted, they can be clustered by any standard, convex clustering algorithm. In the literature a k-means clustering is frequently used, however k-means clustering can be highly subject to randomness in the selection of initial centroid points. In place of this we have implemented a version of the k-means++ algorithm, which assigns the first center from one of the plotted points at random but assigns a probability to all the remaining points that is proportional to the squared distance of the points from any already selected center (increasing the likelihood of well-spaced centroids) before choosing the remaining centers (Arthur and Vassilvitskii 2007). From there, the algorithm proceeds as in k-means: determining the catchment of each center and relocating to the centroid of that point set. To account for the potential influence of randomness remaining in the selection, the clustering algorithm is run a number of times with different random seed values and the result with the lowest residual sum of squares selected.

As shown in the middle column of Figure 2, plotting the eigenvector-derived points in three dimensions transforms the original layout but the topology remains intact and recognizable. Square, gridded networks that are connected by a fairly even distribution of connections tend to produce the saddle-shaped hyperbolic paraboloids illustrated here. Absent other prominent disruptions such plots seem to tend to five clusters: one at each corner and a fifth in the center.

The examples in Figure 2 illustrate how different urban network features manifest in the spectral clustering. Between the first and second examples we can see both the overall similarity and the perturbations that differentiate the two. In both, densely interconnected links exert a pull on the cluster centroid: for example the positioning of the central cluster rightwards toward the close double line of Park Avenue, or, in the second example, the inclusion of more blocks around the Broadway and 5th Avenue intersection. Conversely, long and uninterrupted links are not tightly connected and are frequent locations for partitions between clusters: the long block between 5th and 6th Avenues in the first example is a clear break. These examples illustrate how spectral clustering can provide a useful interpretative tool, especially for neutral networks-like grids-that do not immediately display an obvious clustering logic. In the third fragment in Figure 2, we see yet another example of the technique's potential where the pattern changes dramatically and the clustering identifies how the colliding grid orientations cause produce clusters that automatically distinguish between thee grids.

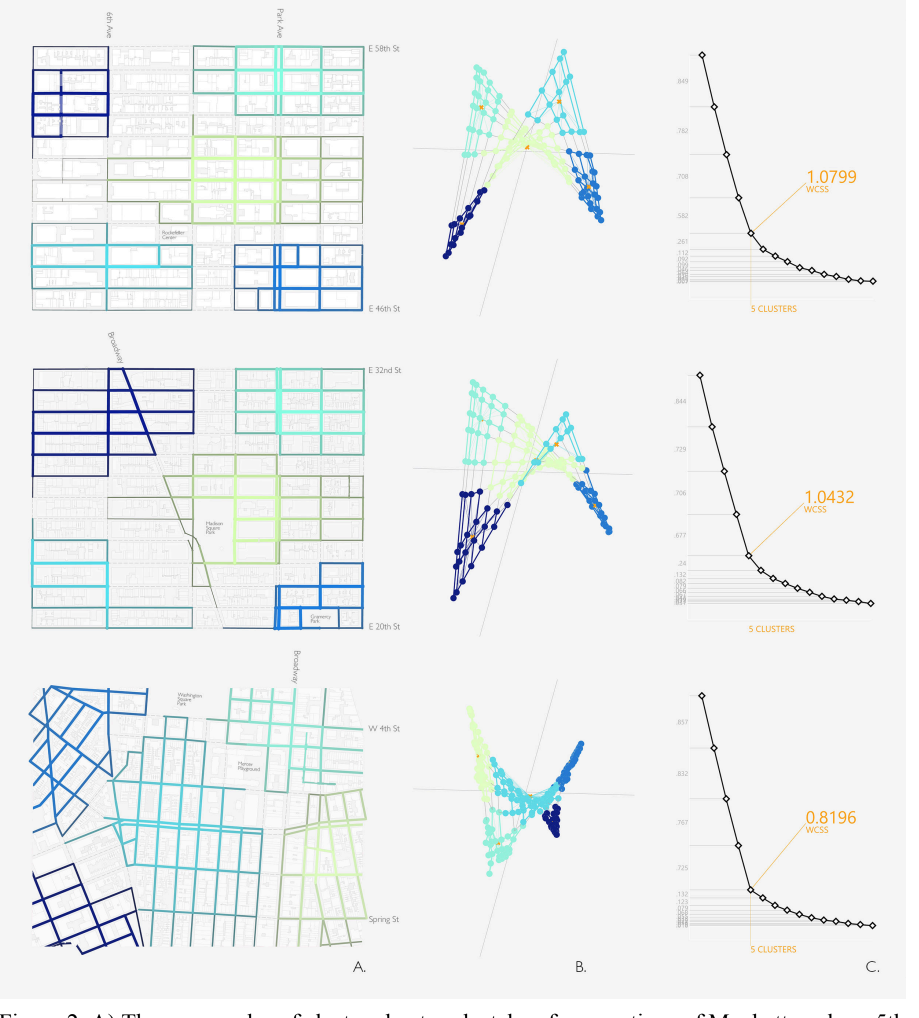

Figure 2. A) Three examples of clustered networks taken from sections of Manhattan along 5th avenue. Geodata sourced from NYC Open Data. B) Three-dimensional plots of the eigenvectors derived from each network with the k-centroids marked with an orange '×'. The topological connections have also been drawn in to assist with visual identification. C) Graph of the 'within cluster sum of squares' values for different cluster numbers illustrating how the 'elbow method' determines the recommended number of clusters to evaluate.

2.3. DETERMINING THE NUMBER OF CLUSTERS

Absent a ground-truth definition of actual clusters, it is difficult to assess the validity of a clustering solution and, in particular, the decision of how many clusters to partition the network into. One of the most common-and most straightforward-is the so-called 'elbow method.' This method records the within cluster sum of squared distances (WCSS) between plotted eigenpoints and their cluster centroid. As the cluster count increases, the WCSS value will decrease monotonically. However, at some point the improvements show diminishing returns that can be observed as a bend or 'elbow' in the graph of the WCSS values. For the preceding examples, the third column of Figure 2 shows these graphs and highlights the point where the elbow occurs. This point is identified by comparing the difference between iterations; when the current difference is dramatically lower than the previous one (here we use <50% as a threshold), the elbow can be identified, and the number of clusters assigned.

An alternate method that is equally straightforward to compute is the 'eigen gap' method, which uses the list of eigenvalues-still sorted in ascending order-and compares the difference between consecutive values. The ordinal of the value that has the largest gap between itself and its predecessor provides the suggested number of clusters. This method typically indicates a larger number of clusters than the elbow method and so may be useful for overall larger networks. Figure 3 utilizes this method. Both techniques are described in (von Luxburg 2007).

3. Results

3.1. ANALYSIS BY COHESION, SEPARATION, AND SILHOUETTE

In addition to overall metrics, once the clusters have been defined, we can also analyze how well-formed the clusters are, or how well-situated within a cluster any given node is. Since there are no *de facto* groupings in urban networks it is particularly useful to be able to not only assign points in the network to discrete cluster categories but also to assign to each point a fitness value along a range that indicates the confidence of the clustering.

We can define the 'cohesion' of a cluster as the average squared distance between a point in the cluster and all other points in the same cluster. This calculation can be simplified by noting that the cluster centroid is the average of all the cluster points and so the same measurements used to form the clusters and calculate the WCSS value also provide the cluster's cohesion value. Furthermore, each node can be assigned a cohesion index that is simply the squared distance from the eigenpoint to the cluster centroid. In the previous examples (Figure 1 and 2), although individual nodes were not annotated, the color and lineweight of links was determined by averaging the cohesion indices of the two connected nodes with brighter and bolder lines denoting greater cohesion (in this metric a lower value indicates higher cohesion).

A related, and complementary, measure is the separation value, which measures the average squared distance between each point and all the points of the closest neighboring cluster. Again we can use the neighbor cluster's centroid to reduce the number of calculations required. In our python implementation of the k-means++ algorithm, the nearest cluster is calculated using a list comprehension to find the squared distance to all centroids and then selecting the first value from a sorted list of the results. This means that finding the separation value does not require any additional computation it only requires the algorithm to also remember the second value. Separation indices are useful because cohesion values can sometimes give a false sense of how much a node belongs to a cluster: points on the periphery will usually have a low cohesion value because they are not near to the center, but they are even farther from any other cluster so their separation value is high; contrarywise, some very central points may not belong to their cluster so distinctly if they are located in an area where two clusters press closely against one another. These conditions can be found in the networks of Figure 2.

This ambiguity indicates the value of a composite metric that combines the influence of both cohesion and separation. Rousseeuw proposed a measurement called the 'silhouette' of the cluster that was composed by subtracting the cohesion value from the separation value and dividing by the larger of the two values. (Rousseeuw 1987). This measurement was shown to be an effective means of validating clusters (Arbelaitz et al. 2013). It also has the benefit for comparative studies and graphic representation of normalizing the range of values within $(-1, 1)$, whereas cohesion and separation will vary based on the size of the network.

Since we have used k-means++ clustering, it is a given that the separation value will be larger than the cohesion value, which reduces the formula for Rousseeuw's silhouette value to:

$$s(i) = \frac{C(i) - S(i)}{S(i)} where: \begin{array}{c} C(i) = \sqrt{Cohesion} \\ S(i) = \sqrt{Separation} \end{array} \tag{8}$$

and the range to positive values (0,1). For the visualization in Figure 3, we have chosen to use the Euclidean distances rather than squared distances mentioned earlier; this is indicated in the equation above. Figure 3 depicts the spectral clustering analysis performed on the combined pedestrian and vaporetto network of Venice. This network comprises 11343 nodes and 12486 links, illustrating the scalability of the method to entire cities. The plot of silhouette values at the left show the quality of composition within each cluster across the network. The western islands of the Giudecca are the most tightly clustered (6th column) with a few scattered outliers due to the boat routes coming into Sacca Fisola. Also having a high silhouette value is the Giardini (3rd column) in the east, cut off as it is by the Arsenale.

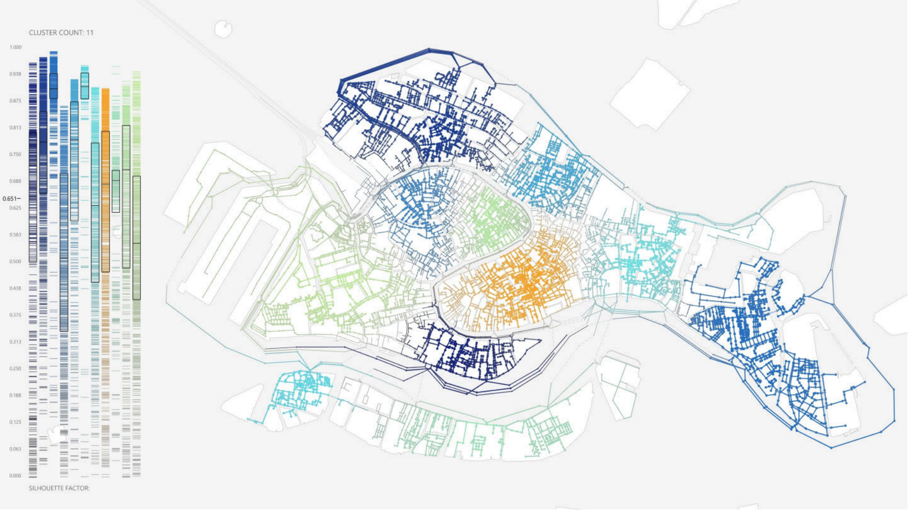

Figure 3. Clustering of the pedestrian network of Venice. The silhouette value for the entire network is plotted at left, grouped by cluster to show the relative fitness of cluster formations. The box plots indicate quartile divisions. These values are mapped onto the network through lineweight and color that matches the plot visualization. Geodata sourced from Piano di Assetto del Territorio of the Comune di Venezia, supplemented from openstreetmap. .

4. Conclusions and Further Work

The method described is successful in producing useful clusterings in spatial networks and has uses for both analysis as well as in support of design. In Figure 3, many details of the cluster partitioning illustrate how well this method can correspond with experiential ideas of neighborhood (in particular, the strong grouping at Piazza San Marco but which quickly ends at the back of the Doge's Palace; the indeterminate placelessness of the station Santa Lucia; the division of Dorsoduro in two). Additionally, the visualization of clustering fitness indices at every point in the network is useful to indicate a degree of certainty in the cluster assignment while also relating better to the concept of urban networks as continuous networks that transition gradually rather than as truly discrete, island-like clusters. We imagine this could be explored further by superimposing the results of multiple analyses using different cluster counts to highlight which edges are frequently boundaries compared to those that shift toward different centroids.

Compared to earlier work on the topic (Patt 2018) the use of 4d eigenpoints and automatic comparison across different random seeds produces more reliable and repeatable results. In future work we would like to more thoroughly evaluate the impact of uneven segmenting: in many GIS files the division of paths into segments is irregular (for example, curved paths are denoted by many more nodes than a straight path of the same length) and we hypothesize that an additional processing before clustering can reduce the sensitivity to uneven densities of nodes that this clustering technique exhibits.

Finally, it is clear that the clustering algorithm can be a useful tool in urban design to assess traits of an existing network morphology, e.g. to identify prominent centers or locations for increased connectivity. The same should be true at the architectural scale, and we intend to test conditions for handling the various modes of connection (stairs, lifts, open corridors versus doorways) so that this spectral clustering technique can also be used in the design of buildings or campus plans.

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FROM MACRO TO MICRO

An integrated algorithmic approach towards sustainable cities

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Abstract. As urbanization rapidly increases towards concerning levels, new methodologies and approaches are required to shape future cities. This research combines passive design approaches with building performance simulation in the same algorithmic description, to highlight the bidirectional impact of the building and the urban context in which it is inserted. To that end, the proposed workflow employs an algorithmic design tool along with validated analysis engines, to assess incident solar radiation and comfort metrics. We apply this methodology in a case study, exploring alternative building geometries to mitigate the consequences of uninformed design decisions in the environment. Results show that the application of passive design strategies can be done within early design stages, allowing a continuous workflow from project to construction while minimizing time and labour requirements regarding building efficiency.

Keywords. Algorithmic design; Building analysis; Passive design; Urban comfort.

1. Introduction

Buildings are responsible for 60-80% of the energy consumption and 75% of the carbon emissions at a global level (United Nations 2019). With 68% of the world's population predicted to live in urban areas by 2050 (UN DESA 2019), an excessive and unplanned increase in urban density can significantly impact cities' comfort levels, as well as their overall energy demand. Buildings are increasingly expected to fulfil a series of environmental and efficiency requirements, and the concern over the ecological footprint of new urban areas reflects a ubiquitous need for new decision-making strategies regarding project conception and design.

The evaluation of building energy efficiency is typically postponed to a later design stage, where the building form is already definite. This happens because (1) in early design stages there is considerable uncertainty in simulation inputs and, thus, large parameter ranges need to be used (Samuelson et al. 2016), and

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 101-110.

(2) architects and engineers tend to approach the design process in discrepant manners, emphasizing either design exploration or the optimization of building systems (Yang and Yan 2016).

Parametric design approaches can provide new form-finding and communication methodologies for urban planning and architecture, promoting design understanding and learning outcomes from the user's perspective (Schnabel 2008). These approaches can potentially expand the design exploration space, allowing for the generation of multiple design outcomes that respond to specific objectives and needs. When combined with building performance simulation (BPS), parametric design approaches establish a bridge between urban design and environmental requirements, allowing the evaluation of the impact of the physical properties of buildings, urban density, and the use of renewable energy sources in the project's site (Tereci and Kesten 2014).

1.1. RELATED WORK

Considering the diversity of parametric design approaches and their disciplinary connections, informed decision-making processes in urban design involve the contemplation of trade-offs. Delmas et al. (2018) implements the concept of integrated design through a platform that incorporates accurate physics with parametric modelling for data exchange, design exploration, and performance-driven optimisation. The usability and appropriateness of this platform are investigated through a workshop, highlighting the need to improve the fluidity of modelling within different phases, along with the transparency of assumptions and calculations. Following this line, the design workflow developed by De Luca (2019) comprises several integrated algorithms to generate building cluster variations and perform daylight analysis, as well as wind and urban comfort simulations. Fink and Koenig (2019), alternatively, focus on the analysis of designs in different disciplines such as climate, usage, and spatial quality, emphasizing the need for automated processes and the development of a strategy for interdisciplinary data exchange.

Integrating multi-software approaches denotes a comprehension of the required balance between investments and achievements, as the project process is divided into a series of smaller tasks - ranging from the creation of an initial shape to the making of a 3D model and, subsequently, one or more analytic models. The back-and-forth communication between different programs and software experts is not direct: in most of the cases, the analysis tools require a simplified version of the original 3D model that needs to be created manually, turning the task of performance evaluation into a process that is more susceptible to user mistakes which cause delays in the project's timeline (Leitão et al. 2017).

1.2. OBJECTIVES

There are two key perspectives to be considered in urban design: (1) the impact of the building in the urban context, and (2) the impact of the urban context in the building. Changing quantitative variables regarding geometry, building systems, and site morphology contributes to the adaptation of a project to different climatic and urban contexts. The presented research develops an integrated approach for urban design, combining algorithmic design (AD) and BPS. The goal is to reduce the time required by the separate tasks, as well as to avoid information losses caused by moving the building model between different tools.

Section 2 defines the workflow of the presented work. This methodology is applied to a case study, described in Section 3. Section 4 discusses the results of the proposed study, outlining the final remarks and future work in Section 5.

2. Workflow

To achieve an integrated urban design approach, we present an AD strategy that merges the design and analysis modelling into a single task. We use a new AD tool, Khepri, to automate the generation of equivalent models in several CAD, BIM, and analysis tools, as well as game engines. An abstraction layer is used to translate the operations for geometric modelling into the corresponding operations of each specific tool, commonly known as *backends*. Although based on a textual programming language, Julia, Khepri has a smooth learning curve so that architects can develop large-scale projects in a short time span (Leitão et al. 2019; Sammer et al. 2019).

Our AD approach is illustrated in Figure 1. Along with the building design component, it comprises radiation analysis to assess the impact of a building on the adjacent urban fabric, and comfort analysis of buildings within different urban contexts. OpenStreeMap (OSM) and weather data are retrieved through Khepri from a previously selected location site. The building geometry is described parametrically, along with the required operations for each *backend*. The user can directly visualise the 3D model or, instead, run simulations and visualise the attained results in a chosen platform. This workflow is applied to a case study, to ponder upon the performance of a building design when compared to other design variations.

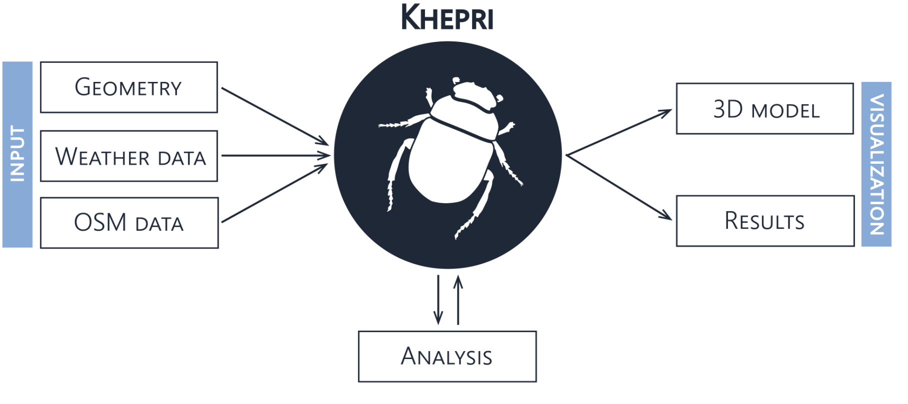


Figure 1. Proposed workflow.

3. Case Study

To evaluate the applicability of the proposed workflow, a case study is modelled and analysed to observe the interrelation between a building and its surroundings. The building design is inspired by Rafael Viñoly's 20 Fenchurch Street in London, often called the *Walkie Talkie*. Since its construction, the concave shape of the Southern façade raised multiple concerns regarding the creation of a lens effect, concentrating sunlight towards Eastcheap Street and, consequently, severely increasing temperature and glare levels in the area. Viñoly argued that a lack of tools to accurately analyse the problem in a design stage was responsible for this fault (Wainwright, 2013). The presented work uses this case study to show that incorporating AD and BPS into the design workflow can significantly help to identify issues before the building's construction, ultimately preventing additional costs to the project.

3.1. DESIGN STAGE

The first step of our workflow encompasses the generation of building geometry through an algorithmic description. The modelled elements have specified design constraints, which can be manipulated throughout the design process. In this case, we explore passive building design variables such as building height, glazing ratio, and the shape of the building envelope, namely its concavity/convexity. Afterwards, the user selects the location of the urban environment to be tested alongside the building, as well as the tool in which the model will be generated (Figure 2). The possibility of using various *backends* allows the user to take advantage of the multiple capabilities of each tool, transitioning effortlessly from one to another without having to import or reproduce the model from scratch.

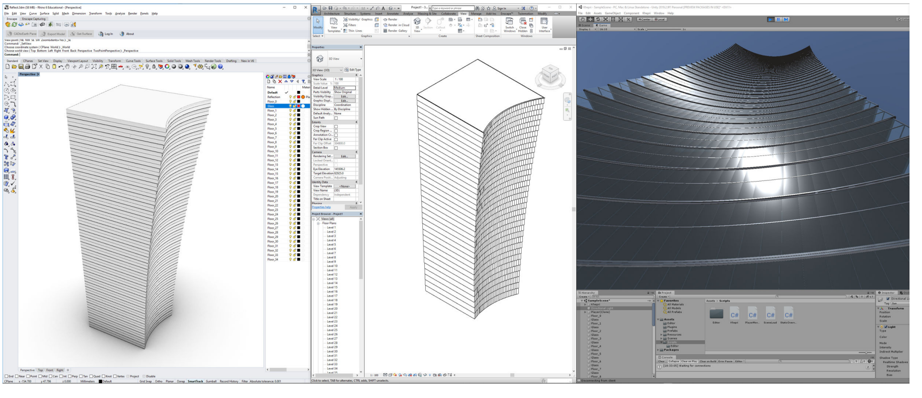


Figure 2. Visualization of the algorithmic model in different Khepri backends. From left to right: Rhinoceros 3D; Revit; Unity.

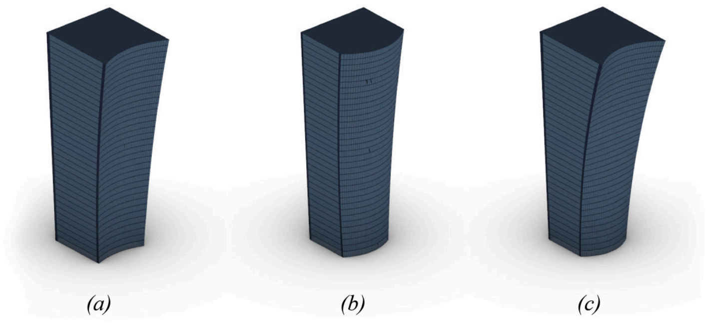
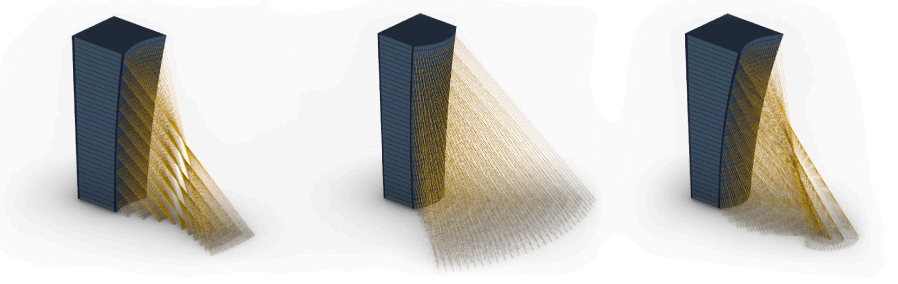


Figure 3. Design variations for the case study geometry: (a) original design, with a concave façade; (b) convex façade; (c) concave and convex façade.

The urban context is incorporated into the algorithmic definition using the previously retrieved and converted OSM data. Two contrasting environments are modelled, to understand how different urban fabrics can impact the same building. For this work, apart from London, we integrate our building into the city of New York. The built environment of Lower Manhattan, shown in Figure 4b, has an average building height that can, hypothetically, accommodate a structure as the *Walkie Talkie* more adequately. Therefore, it is predicted that the incident solar radiation in our case study is significantly smaller in this location than in the building's original site, hence enhancing the comfort level in interior spaces.

Figure 4. Urban models for the cities of (a) London and (b) New York.

Before transitioning to the analysis stage, we can already discern the effects of each design variation in terms of the reflection of sun rays. By observing the light reflection at the centre of each glazed surface, it is possible to foresee the areas of impact in the surrounding environment (Figure 5). As seen in (a), there is a high concentration of sun rays at the ground level and along with the building height, contrasting with (b) which shows the higher radiation dispersion of the three. As a compromise between the two scenarios, the inflection point in (c) where the façade turns from convex to concave may be revised, so that its reflection does not focus on any building or public space in the urban fabric.



(a) *(b)* *(c)*

Figure 5. Preliminary feedback for the reflection of sun rays in the three building variations.

3.2. ANALYSIS STAGE

Two distinct simulations are contemplated in the analysis stage. Firstly, a grid-based daylight simulation is performed, where the impact of the case study, as well as its geometrical variations, on the nearby buildings and public space is evaluated through a radiation map. Secondly, we observe the influence of the urban fabric in the interior comfort of our case study, comparing its performance in the two selected sites. To perform the required analysis, we use validated simulation tools, namely Radiance (McNeil and Lee 2012) and EnergyPlus (Witte et al. 2001).

3.2.1. Radiation Analysis

Prior to running the simulation, the building materials need to be defined. For this case study, we use a plastic material with a 30% reflectance for the façade and context, and a mirror material for the glazing to replicate the highly reflective glass panes of the *Walkie Talkie*. An analysis grid is positioned in the ground geometry and surrounding environment, with three meters between each analysis node. The simulation runs from August to September, between 11 AM and 1 PM, in the urban fabric of London, using the correspondent weather file for this location.

We test the cumulative incident solar radiation per area caused by the three geometric variations shown in Figure 2. The purpose of these analyses is to grasp if the issues concerning the original construction of the *Walkie Talkie* could have been avoided. Changing the façade concavity to convexity along the building height should show better results than the original, highlighting the importance of including BPS in early design developments.

3.2.2. Comfort Analysis

In this stage, we change from a day-long to a year-long analysis period to contemplate the cumulative effect of the urban fabric in our building. Weather variables (e.g., outdoor dry bulb temperature, and wind speed) and building performance variables (e.g., mean radiant and operative temperatures) are joined to compose an adaptive comfort chart based on the ANSI/ASHRAE Standard 55. The percentage of comfort hours for each floor is calculated for the locations shown in Figure 4, and their performance is compared for two contrasting climates. Afterwards, we assess the impact of the urban fabric on a smaller scale to observe the relation between the outdoor and indoor temperatures on an average floor.

4. Results and Discussion

The radiation analysis results are illustrated in Figure 6, comprising the incident radiation in both the public space and in the building envelopes that surround our case study. We compare the performance of the design variations with a scenario in which no building is inserted, which showed a significant distinction regarding the impact of a building with this height and glazing in a low-height urban fabric such as the one of London. The maximum values for the cumulative incident radiation reach 39, 87, 45, and 56 kWh/m2 for (a), (b), (c) and (d), respectively.

The first design option, with a fully concave façade, was intended to roughly reproduce the effects caused by the *Walkie Talkie* building in Eastcheap Street. A higher density of incident radiation is clearly identified in the adjacent public space and buildings, which will negatively affect their indoor operative temperature and energy needs due to the increased heat transfer. This effect is reduced to nearly half when the tested geometry has a fully convex façade, as the output of the second design option is approximate to scenario (a). The third design option portrays a more flexible compromise, as the convex shape at the building ground level diffuses the radiation in the immediate surroundings. However, as the top portion of the façade is still concave, it is evident that the effects caused by the glazed parabola will occur out of the simulated bounds. By increasing the analysed site area, it would be possible to discern the area that might be affected by this phenomenon.

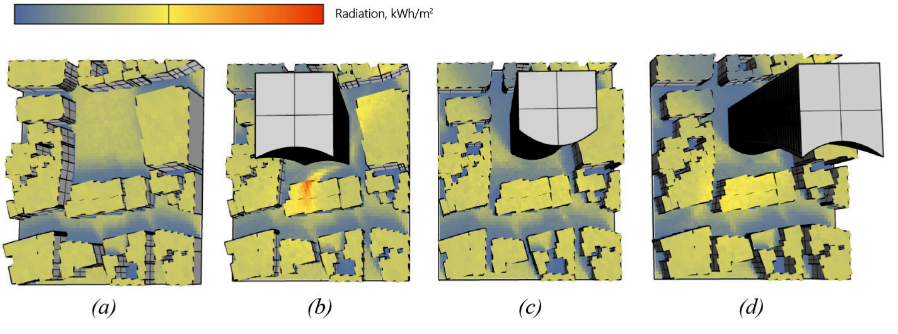


Figure 6. Incident radiation per area for the empty site and the three building variations.

The comfort simulation output provides an overview of how different urban fabrics and climates can affect the same building. The annual percentage of comfort ranges between 64 and 70% in a warm climate (Figure 7) and between 49 and 61% in a cold climate (Figure 8). Results show that the overall indoor comfort levels are lower in the urban fabric of London than in the one of New York, from the 8th floor until the top floor. Considering the average building height of the two sites, it is logical that the case study performs at a higher level in the latter, given the increased amount of shading produced by the surrounding buildings.

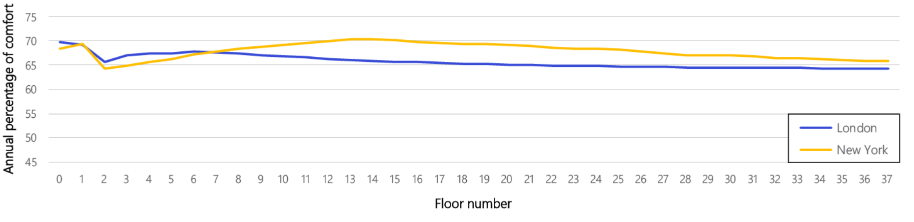


Figure 7. Annual percentage of comfort for a warm climate.

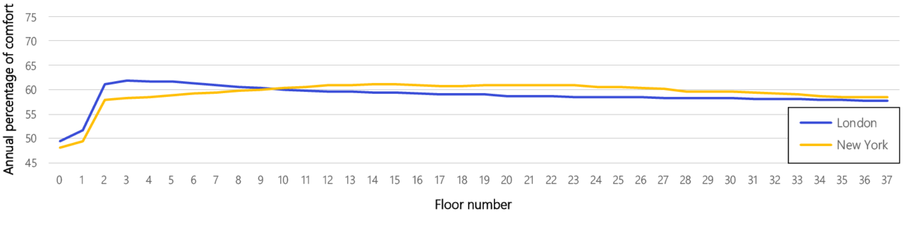


Figure 8. Annual percentage of comfort for a cold climate.

Figure 9 shows the adaptive comfort chart for an average floor, comprising an agglomeration of the hours in which an occupant would feel comfortable in the interior space. For the sake of simplification, this simulation uses only the weather file of the cold climate. New York shows at least 500 hours where occupants are slightly cold, with indoor temperatures of 16 to 18ºC contrasting with an 8ºC outdoor temperature. Moreover, this location shows a reduced thermal amplitude when compared to the same floor inserted into London's context, particularly when temperatures are higher. In this specific case, we see a variation of only 3% between the comfort hours of both locations. However, on some floors, this variation can reach up to 10%. Ultimately, this form of output is valuable to discern how climate and urban fabric affects the building shape, allowing the user to adjust the project in a passive way (e.g., building height, glazing ratio, number of floors) to ensure maximum comfort levels for occupants.

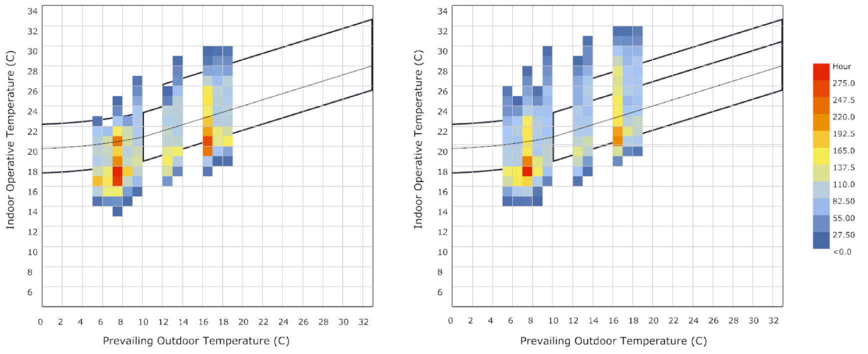


Figure 9. Adaptive comfort chart for an average floor. Left: New York; Right: London.

Although BPS is a relevant component of this workflow, it is important to consider that these analyses are to be applied in early design stages. Hence, the selected material properties, as well as the project orientation and scale, can be a source of uncertainty for the radiation analysis output. However, we can discern design heuristics from this case study, quickly identifying high impact parameters in the shape's algorithmic description, which can affect incident radiation and consequent decrease in urban space indoor comfort levels. This work does not consider parameters such as metabolic rates, occupancy levels and light density, which are often only considered in later design stages when the requirements regarding building systems are stricter.

5. Conclusions and Future Work

This work merges AD and BPS into an integrated approach for architectural and urban design to facilitate the application of passive design strategies. Using AD, the implementation of design changes is significantly less time-consuming than the manual adjustment of a model (Leitão et al. 2013), while at the same time allowing for several levels of information regarding BPS inputs, creating a continuous process with an incremental level of detail as we move along design stages. Although the presented AD tool, Khepri, is used specifically for radiation and comfort analysis in this research, it encompasses several other kinds of building simulation and visualization methods.

Considering the building that inspired our case study, one can argue the urgency of incorporating this workflow into project conception. Applied in early stages, it helps the architect to predict and prevent severe damage and discomfort in the surrounding context of the modelled building, while maintaining the creative freedom to explore design variations.

One limitation of the presented workflow is that it does not yet involve optimization processes based on iteration, where analysis results are used to improve building and urban design. We are currently working on incorporating this feature. Moreover, future developments in our methodology aim to include an analysis component based on computational fluid dynamics, which will allow further extension of the analysis scope to wind tunnel and air flow simulations.

Acknowledgements

This work was supported by national funds through Fundação para a Ciência e a Tecnologia (FCT) with references UIDB/50021/2020 and PTDC/ART-DAQ/31061/2017.

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A FRAMEWORK FOR A COMPREHENSIVE CONCEPTUALIZATION OF URBAN CONSTRUCTS

SpatialNet and SpatialFeaturesNet for computer-aided creative urban design

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Abstract. Analogy is thought to be foundational for designing and for design creativity. Nonetheless, practicing analogical reasoning needs a knowledge-base. The paper proposes a framework for constructing a knowledge-base of urban constructs that builds on an ontology of urbanism. The framework is composed of two modules that are responsible for representing either the concepts or the features of any urban constructs' materialization. The concepts are represented as a knowledge graph (KG) named SpatialNet, while the physical features are represented by a deep neural network (DNN) called SpatialFeaturesNet. For structuring SpatialNet, as a KG that comprehensively conceptualizes spatial qualities, deep learning applied to natural language processing (NLP) is employed. The comprehensive concepts of SpatialNet are firstly discovered using semantic analyses of nine English lingual corpora and then structured using the urban ontology. The goal of the framework is to map the spatial features to the plethora of their matching concepts. The granularity ànd the coherence of the proposed framework is expected to sustain or substitute other known analogical, knowledge-based, inspirational design approaches such as case-based reasoning (CBR) and its analogical application on architectural design (CBD).

Keywords. Domain-specific knowledge graph of urban qualities; Deep neural network for structuring KG; Natural language processing and comprehensive understanding of urban constructs; Urban cognition and design creativity; Case-based reasoning (CBR) and case-based design (CBD).

1. Introduction

Creativity is the effort of searching for novelty that proves to be useful (BRINCK, 1997; Funke, 2009). And as such, creativity is not limited to art, but it is part of any aspect of life. Searching for novelty and usefulness requires a Knowledge-base that conceptualizes the physical signs (BODEN, 1997). Associating the materialized spatial symbols with their meanings is called symbol grounding, alternatively known as symbol conceptualization. Symbol grounding

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 111-120.

and conceptualization has been proved to be a prerequisite for creativity (Ventura, 2015). By grounding physical symbols, the world of meanings and semantics will be accessible to computation, and hence, structuring autonomous creative architectural agents that can assist in a design process is viable.

The paper proposes a framework for conceptualizing urban constructs that builds on an ontology of urbanism (Ezzat, 2019; Ezzat, 2018). The ontology establishes three perspectives; named rational, visual, and emotional; for a comprehensive conceptualization of urban constructs. The framework is composed of a deep neural network (DNN) named SpatialFeaturesNet, and a knowledge graph (KG) called SpatialNet. The framework accepts the inputs of variations of the digital representations of any urban construct; e.g., non-topological 2d images and sketches, voxels, point clouds, or topological meshes; and predicts the concepts that are fuzzily associated with the examined urban constructs. The process of predicting the concepts of any examined urban constructs can be summarized as the following:

- Firstly, the digital representations of the examined urban constructs are preprocessed then fed in the SpatialFeaturesNet DNN as inputs. The role of SpatialFeaturesNet is to predict the spatial features; e.g., the various features of space, walls, openings, structural typologies, shapes, textures, colors, or activities; associated with the examined urban construct.
- Secondly, The predicted features are then queried from the SpatialNet KG. The query yields the concepts that are fuzzily associated with the spatial features.

For SpatialFeaturesNet and SpatialNet to function as prescribed, they need first to be structured. The paper presents in detail the structuring of both of them using deep learning. Deep learning requires both a training dataset and a model whose parameters are optimized against the training dataset. The structuring of SpatialFeaturesNet and SpatialNet is conducted as the following:

- SpatilafeaturesNet: the DNN model is composed of several independent convolutional kernels. Each of these kernel-pooling filters accepts different forms of 2D/3D digital representations. These different kernel-pooling NNs will be max-pooled into a latent space. The latent space is mapped using a fully connected NN into the spatial features. By doing so, a representation like a sketch, a mesh, etc. will be mapped to their potential spatial features.
- SpatialNet: although SpatialNet is a KG, a DNN is needed for completing its structuring, which is known in natural language processing (NLTP) as KG completion. Two models for the DNN can achieve this goal. One of which is similar to (Bordes, Weston, Collobert, & Bengio, 2011), while the other is specific to the underlying ontology and is conceptually similar to state of the art convolutional neural network (CNN) presented in (Rotsztejn, Hollenstein, & Zhang, 2018). The training dataset is segments of the KG, and the trained DNN should predict the completed KG based on this scarcely labeled data. Techniques specific to the underlying ontology are presented for enhancing generalization over the risk of overfitting to the scarce training dataset.

SPatialFeaturesNet is an application of computer vision, while SpatialNet is an application of natural language processing. The proposed framework is materialized as a Grasshopper solution (GhS). The GhS contains components for either training the DNNs or for presenting the predictions of the trained DNNs.

The SpatialFeaturesNet DNN and the SpatialNet KG compose the knowledge base needed for any artificial architectural agent to aid in a design process. Contemporary theories praise the notion that creativity can be achieved by any of the three approaches of exploration, transformation, or combination (BRINCK, 1997; Funke, 2009). Consequently, a theoretical discussion concerning the foundational role of the proposed framework, as a knowledge base of the agent, in any of these three approaches will be discussed in the coming section.

1.1. RELATED WORK

Analogy is a leading field in artificial intelligence (AI) for simulating cognition, reasoning, and creativity (GOEL & CRAW, 2006). By the mid-nineteen-nineties, several frameworks for computational aided architectural design employed an analogical AI technique known as case-based reasoning (CBR), which was consequently applied on design as case-based design (CBD) (Heylighen & Neuckermans, 2001). The goal of applying CBR on design is to search for analogous or similar cases of any given preliminary design. By doing so, the designer, at an early ideation phase of the design, can be presented with similar previous cases, which is thought to be a valuable source of inspiration during the ideation phase.

In principle, the main similarity between the proposed framework and CBD is that both of them rest on analogical reasoning for aiding design during the early ideation phases. For doing so, both of them acquire the structuring of a knowledge-base, upon which the analogical reasoning can be conducted. The knowledge-base of both of them are comparable based on the following grounds:

Most of the CBD frameworks maintain knowledge-bases that couple spatial connectivity graphs (SCGs) and corresponding searchable keywords. They function as record keepers and memory retrieval of similar designs, and consequently, They share the following characters (see Figure 1) (Heylighen & Neuckermans, 2001; Richter & Donath, 2006):

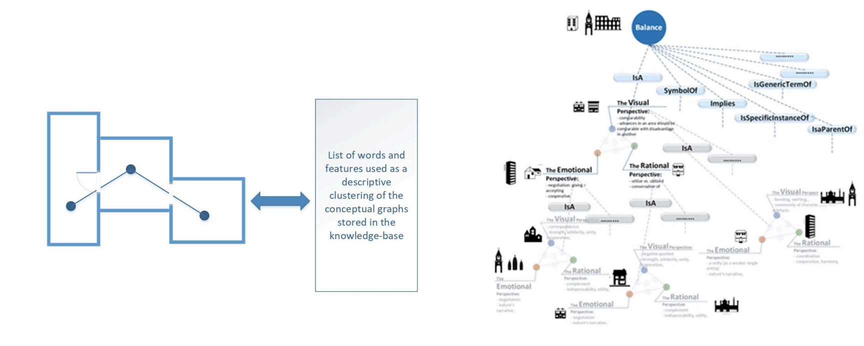
- These CBD knowledge-bases are either query-able based on matching the graphs/sub-graphs of the spatial connectivity or by the words to find similar previous designs.
- Some implementations use sketches of architects for searching for the corresponding spatial connectivity graphs (Weber et al. 2010). The proposed SpatialFeaturesNet extends the idea of using sketches for searching for similar designs into more sophisticated various digital representations.

On the other hand, the CBD criticized drawbacks have been rectified by the proposed framework as the following:

- CBD failed to employ big-data for discovering the SCGs or the related keywords and rested on experts' labeled ontologies. Its knowledge-base is manually labeled based on the non-standardized preferences of its experts, mainly due to the lack of proper backing theorization. On the contrary, the proposed framework automates the structuring of SpatialNet based on the minimal labeled conception that builds on an accessible ontology, and it utilizes nine lingual corpora to achieve this (see section 2).

The two approaches differently augment design and creativity as the following:

- CBD is a source for inspiration for designers by keeping the records of what is believed to be similar cases, it is not meant to contribute to creativity beyond these inspirational gestures, nor is it thought to be viable for augmenting an automated design process. Additionally, explainability and justifiability need specially devised procedures (Ayzenshtadt, Espinoza-Stapelfeld , Langenhan, & Althoff, 2018).
- Contrary to that, the proposed framework replaces the SCGs by the dynamic and more sophisticated SpatialFeaturesNet DNN. The keywords in CBD is replaced by SpatialNet, which is a comprehensive KG that has the causality relations (Causes and CausedBy) and the symbolic relation (SymbolOf). SpatialNet's concepts are derived from the semantics of the human spoken language. The designer can explore the various interpretations of the plethora of concepts; e.g., welcoming, repulsive, enclosed, tranquil; as interpreted by the three perspectives of the underlying ontology and their combinations. The SymbolOf relation facilitates the co-existence between the spatial features and the materialized symbols; e.g., space, structural typology, walls, slabs, openings, etc.; and the SpatialNet's conceptual interpretations. This implies the inherent explainability of the proposed framework and its viability for playing an influential role in design and design creativity, as has been defined in the previous section.



1 2

Figure 1. A comparison between the CBD approach (1) and the proposed framework (2), which is illustrated by the exemplary word of "Balance" and its conceptualizing exemplary semantic net. The same approach applies to the whole dictionary for constructing SpatialNet as a comprehensive semantic network.

Further related works may include several experiments from two knowledge domains that seek the automation of acquiring detailed knowledge using a minimal contribution of expert agents. One of these domains belongs to the theory of mind, while the other belongs to natural language processing (NLP) using deep learning. The paper employs NLP for structuring SpatialNet. In the following sections, the DNN models for structuring SpatialNet or SpatialFeaturesNet are detailed in sections 2.0 and 3.0, respectively. Then, in the discussion in section 4.0, the methods for annotating the training datasets are introduced. The paper concludes by future developments, in section 5.0.

2. SpatialNet

Information is meaningful in structured formats. Structuring information requires tools like knowledge graphs (KGs). In KGs, abstract or concrete entities are linked by relations, subject (head-h)-predicate (relation-r)-object (tail-t), for forming the triple of (h,r,t). Consequently, knowledge graphs are sets of the (h,r,t) triples, and structuring any KGi requires calculating the probability of any # (h_j,r_l, t_j)inKG_i # . Equation (1) is for calculating the probability of (t) given (h,r).

$$KG \mapsto P(t|h,r) \quad (1)$$

KGs are used for structuring either general-purpose knowledge bases; such as Freebase, Yago, DBpedia, and Google's KG; or domain-specific knowledge bases like Gene Ontology. Nonetheless, KGs need ontologies to be meaningfully structured.

The paper introduces a domain-specific KG named SpatialNet that conceptualizes the spatial qualities. SpatialNet builds on an ontology of urbanism (Ezzat, 2019; Ezzat, 2018). The ontology states that urbanism can be comprehensively comprehended by three perspectives named emotional, rational, and visual. The ontology is grounded on a thorough analysis of the entire urban constructs, movements, and theories. This ontology entails that for each (h,t), three variations are belonging to each of the three perspectives. This means that SpatialNet is structured by extending Equation (1) to be (see Figure 1):

$$KG_{SpatialNet} \mapsto P(t|h,r,perspective) \quad (2)$$

A main contribution of the ontology is that these three perspectives are not only relativistic views of urbanism, but they are also contrasting with each other. By "contrasting", we mean that there are mutual dependencies between the three perspectives; the three perspectives have to be comprehended in parallel. Therefore, given any set of words, allocating which of these words belonging to which perspective can be clearly established. That set of words is the context of any (h,r) (see Equation 2). Consequently, the paper's proposed computational model for structuring SpatialNet will be based on Equation (3).

$$D\mathbb{N}\mathrm{mod}el_{SpatialNet} \mapsto P(t|h,r,perspective,con \quad (3)$$

Deep learning has evolved as a robust tool for handling high-dimensional and parallelized computation, which is leveraged by the recent advances in GPUs. The paper proposes a DNN for structuring SpatialNet. In the following section, the model of the DNN will be presented, while in section (4), a discussion of the aiding tools for labeling the training dataset will be illustrated.

2.1. THE COMPUTATIONAL MODEL

Our proposed DNN model is tailored to the underlying ontology. We assigned a single annotator, an architect, for populating the dataset needed for training the DNN. It was observed that intuition about the three perspectives is a prerequisite for the annotator to structure triples of SpatialNet that match Equation (2). The annotator's intuition is merely three sets of keywords that briefly describe each perspective. Based on that intuition, when the annotator is presented with any set of words, the context of (h,r), the doubts about structuring the triples shortly vanish. The context is merely the words that are in close relation with (h,r), and consequently, the context can be computationally deduced. Training the DNN is a mimicry of the annotator's learning process.

The mission of the DNN is to recognize the features of the context and then to learn how to map the recognized features to the binary classification of each of the words in the context. The paper proposes three different DNN models for each perspective. The output of the three models will be concatenated to produce the DNN's overall predictions. The following three models will have the word embeddings of the context as input for (see Figure 2):

1. Convolutional/pooling kernels (CNN) followed by fully connected layers that output the softmax binary classification for perspective_1.
2. This model is similar to the aforementioned model (1), except the fully connected layer will be replaced by a bidirectional long-short-term memory model (BLSTM) that directly output the softmax binary classification for perspective_2
3. A BLSTM model that directly output the softmax binary classification for perspective_3.

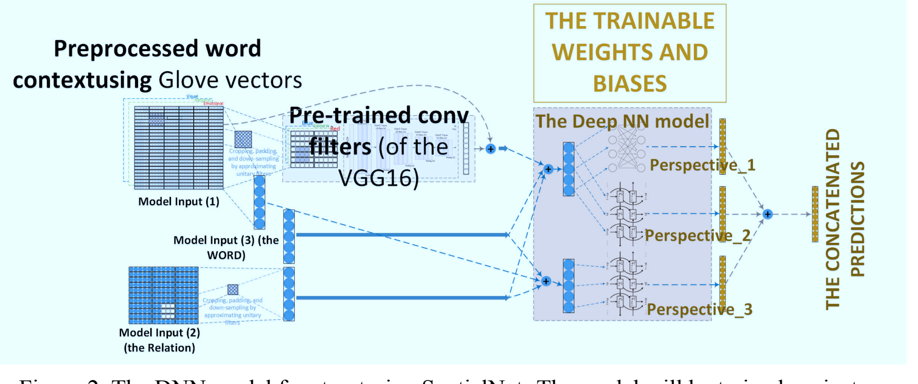


Figure 2. The DNN model for structuring SpatialNet. The model will be trained against an extended version of the ontology, which is presented as a KG, and the word embedding of the trained concepts.

Therefore, there is a different DNN model for each of the three perspectives. As a matter of fact, using either CNN or LSTM has achieved remarkable results in classifying or extracting relations from textual sentences. Nonetheless, Using Hybrid models in DNNs have achieved state-of-the-art results (Rotsztejn, Hollenstein, & Zhang, 2018; Zheng, Hao, Lu, Bao, & Xu, 2017; Zheng, et al., 2016). Those above proposed first and the third models are similar to the record winner model of Rotsztejn, Hollenstein, & Zhang, (2018), including the hyperparameters of the model as well. The differences are that our CNN is based on the Google's pre-trained VGG16 convolutional kernels, which achieved exceptional results in image recognition in 2015, rather than training new kernels. Additionally, the context of our model is specially devised for training the DNN, rather than the case with the contemporary knowledge extraction and KG structuring that are trained by sentential word sequences.

2.2. TRAINING THE MODEL

The labeled data is scarce, and overfitting the DNN over such scarce data is a serious challenge for the DNN's training and its predictability. Additional to the aforementioned word contextualization approach, the paper adopts the following policies for enhancing the generalization of the DNN:

- Dropouts, 0.5 for most of the layers (Srivastava, Hinton , Krizhevsky, Sutskever, & Salakhutdinov, 2014).
- Batch normalization, before the activation of each layer (Ioffe & Szegedy, 2015).
- L2 Regularization (Ng, 2004).

Stochastic gradient descent (SGD) will be utilized to optimize the model's parameters. The DNN and the annotator will get involved in a mutual learning process. The main goal is that the neural network's predictions should enhance over time to the point that the neural network takes over the whole task of classification.

2.3. EXPERIMENTAL SETUP

We had to prepare two computational tools to train the DNN.

1. The first tool (see Figure 2&3): a graphical user interface, coded in .NET, that has the backing of an embedded database, using SQLite database. The goal of this tool is to aid the annotator during the generation of the labeled dataset and then to save the labeled data in the database. .NET wrappers of the APIs of WordNet and ConceptNet are used for generating the context. Accord.net is used for the k-means, genetic algorithm (GA), principal component analysis (PCA), and statistical measurements.
2. The second tool (see Figure 2): Keras, with the backend of TensorFlow, is used to model and train the DNN. We used visual studio community edition as the IDE.

After the DNN graph is modeled in Keras, the graph is trained and scored using TensorFlowSharp inside the first .NET tool. The early-phase code of the two tools is dumbed in https://github.com/SpatialNet-Final/SpatialNet-v0.0.

3. SpatialFeaturesNet

The role of SpatialFeaturesNet is to predict the features of any urban construct's digital representations. Currently, three digital representations are selected, which are non-topological 2D images (as a sketch of a designer), point cloud (as 3D scanned constructs), and topological meshes. The metric properties of these three digital representations are encoded as a tensor using three different convolutional deep neural networks (CNN), CNNs have achieved notable results in 3d shape matching similar to that of the remarkable achievements of image recognition. That tensor will be then fed in a simple, fully connected deep neural network (FCNN) (see Figure 3). The FCNN is trained by a dataset to classify the encoded tensor of any physical model against all features defined by the underlying ontology. Consequently, the original 3d model's features will be recognized by SpatialFeaturesNet.

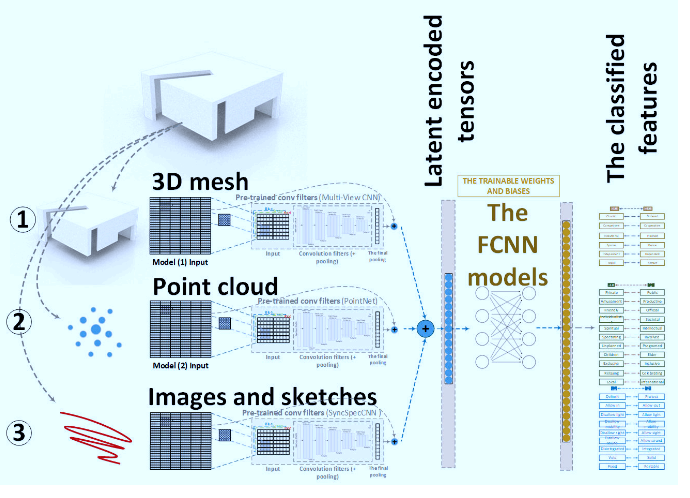


Figure 3. The proposed DNN model for SpatialFeaturesNet that maps three digital representations of CNN models into their spatial features. .

This approach is currently realizable due to the knowledge transfer by the paper's reutilization of three different pretrained CNN models. The three CNN models are the Multi-View CNN, PointNet, and SyncSpecCNN; (Su, Maji, Kalogerakis, & Learned-Miller, 2015 ; Qi, Su, Mo, & Guibas, 2017; Yi, Su, Guo, & Guibas, 2017). The retrained convolutional kernels of the three DNNs encode a latent tensor that will then be decoded by the FCNN for classifying the tensor according to the list of the defined features.

4. Discussion

So far, the DNN models for learning the SpatialNet's concepts or the SpatialFeaturesNet's features are presented. Nonetheless, training these models requires reach datasets. For doing so, the paper introduces a grasshopper solution (GhS) for labeling the 3d models by the corresponding spatial features (see Figure 4). Each 3D Gh model is rendered into eight different images from different angles, to match the specification of the Multi-View CNN, or represented by point cloud for the PointNet CNN (using plugins like Volvox or Tarsier, which are available from www.food4rhino.com), or represented as a mesh for the SyncSpecCNN CNN. Additionally, the parameters of any Gh model are randomly altered, a technique known as data augmentation, to enrich the training dataset with possible genetic variations of the same model.

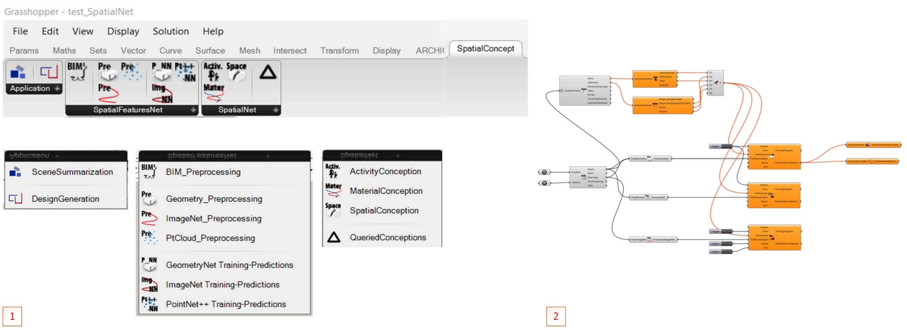


Figure 4. The GhS for populating or querying the digital representations of urban constructs.

5. Conclusion

The paper presents a framework for structuring a coherent knowledge-base that is inherently explainable and justifiable due to the underlying ontology. Such knowledge-base is the foundation for upper layers of episodic memory, memories experienced from previous designs, and analytical analogical reasoning; the two of which are prevalent fields in cognitive architectures or AI, respectively. For future development:

- The proposed framework is believed to resolve most of the weaknesses of other analogical design inspiration approaches like CBD. Nonetheless, developments in CBD may suggest the future extensions of the proposed SpatialFeatureNet's signs to be supplemented with other CNNs for extracting the features of the spatial connectivity graphs and BIM elements.
- One of the main goals of the project is to embed the different spatial representations; images, point clouds, meshes, connectivity graphs, BIM elemental relations, and the concepts of SpatialNet; in a common shared geometric space. Implementing this goal would facilitate applying higher layers, such as learned episodic memories.
- The proposed framework is theoretically founded on an examined ontology. Nonetheless, although the proposed framework can yield an independent comprehensive conception that is map-able to any other comprehensive conceptions, there is an urgent need to assess the relatedness between the computationally learned comprehensive conception and those of the designers and users. Consequently, there is a futuristic preparation for an online graphical user interface that measures the correlation between the computationally learned relatedness between the spatial signs and concepts and that of the designers and the users.

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REDUCING ENERGY CONSUMPTION THROUGH CYBER-PHYSICAL ADAPTIVE SPACES AND OCCUPANTS' BIOSIGNALS

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Abstract. The field of architecture has long embraced adaptive approaches to address issues of sustainability and efficiency. Building energy consumption accounts for about 40% of the total energy consumption in the U.S. This energy is mainly used for lighting, heating, cooling, and ventilation. Researches show that 30% of that energy is wasted. One of the main reasons for such high energy waste in the commercial (and even private) sectors is a generic assumption about the occupants‘ preferences. To fill this gap, the objective of this project is to optimize building energy retrofits by creating smart environments that autonomously respond to the occupants' comfort level using affective computing and adaptive systems. This adaptive approach will help optimizing energy consumption without sacrificing occupants‘ comfort through passive cooling and heating strategy, responding to occupants' preferences detected from their biological and neurological data. Progress towards achieving this goal will make building energy costs more affordable to the benefit of families and businesses and reduce energy waste.

Keywords. Human-Computer Interaction; Optimizing Energy Consumption; Sustainability + High Performance Built Environment; Adaptive and Interactive Architecture; Cyber-Physical Spaces, Affective Computing, Occupants' Comfort and Well-Being.

1. Introduction and Objectives

We spend more than 87 percent of our lives inside buildings. Studies show that the built environment affects our behavior, thoughts, emotions, and well-being and has both direct and indirect effects on mental health (Cooper et al. 2011, Eavns 2003). Sarah Williams Goldhagen argues in her book, Welcome to Your World: How the Built Environment Shapes Our Lives, that the built environment has a profound impact on people's lives. She believes that “There's no such thing as a ”neutral“ environment and your built environment is either helping you, or it's hurting you.” (Pedersen 2017). The field of architecture has long embraced adaptive approaches to address issues of sustainability and efficiency. The increasing practicality of the Internet of Things (IoT), artificial intelligence (AI), innovation in materials

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 121-130.

science, algorithmic design capabilities, advanced analysis of human factors, and the integration of new tools in communication push our physical environment to be on the verge of becoming an extension of the Internet (Atzori 2010). The Internet of Things and related computation technology merge seamlessly with the goals of adaptive architectural systems, providing tools to enhance the environmental quality of buildings and promote more flexible, human-centered designs.

Building energy consumption accounts for about 40% of the total energy consumption in the U.S (Department of Energy 2015). This energy is mainly used for lighting, heating, cooling, and ventilation. Researchers estimate commercial buildings account for 20% of all the energy used in the U.S., while 30% of that energy is wasted. One of the main reasons for such high energy waste in the commercial (and even private) sectors is a generic assumption about the occupants' preferences (Agarwal et al. 2010). Current energy efficiency retrofits focus on maximizing thermal performance regardless of occupants' preferences. To fill this gap, this proposal focuses on developing a tangible relationship between users' preferences, comfort zone, and energy consumption through adaptive spaces and interactive systems of control. The objective of this project is to optimize building energy retrofits by creating smart environments that autonomously respond to the occupants' comfort level using artificial intelligence, affective computing, and adaptive systems. (Affective Computing or artificial emotional intelligence aims at improving interactions between people and computers by recognizing, interpreting, processing, and even simulating human emotions). This novel responsive approach will help us to improve the energy productivity and efficiency of housing without sacrificing the occupant's comfort. Progress towards achieving this goal will make building energy costs more affordable to the benefit of families and businesses and is a sustainable approach.

BAS (building automation systems) are a healthy step in reducing the amount of energy a building uses by keeping track of occupant's whereabouts and automatically adjusting temperatures, lighting, and other core systems when the building is not in use. Despite the frequent existence of Artificial Intelligence in our daily life, architectural spaces remain mostly unchanged, because of a separation between architecture as an object, on the one hand, and the needed AI "brainpower" with the proper interface, on the other (Alhadidi 2017). This project aims to add up AI to the traditional BAS system to improve the energy productivity and efficiency of housing without sacrificing occupant comfort.

The main goal of this project is to develop three smart housing retrofit systems (SHELL, SPACE, & CORE) (Figure 1) to address the following research questions: 1. What is the measurable impact of the proposed smart environment on reducing energy consumption and sustainability? 2. How can such a smart environment retrofits measurably improve the well-being of occupants by autonomously responding to their comfort needs?

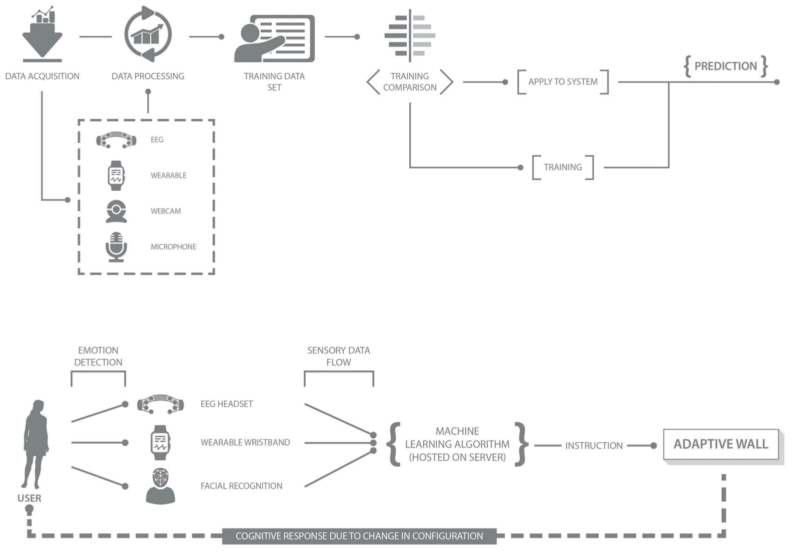

Figure 1. Flowcharts show the process of human-computer interaction in these smart spaces.

This paper focuses on a smart shell. This adaptive retrofit solution is intended to respond to occupants' preferences decoded from biological and neurological signals to fulfill their desire for light/heat/ventilation/view. Changes in the shell enclosure are the direct result of the users' biological, mental, and environmental needs. Examples of these responses include changing the size, location, and shape of a window, and openings to provide natural air and light to optimize energy consumption through passive approaches or moderating the occupant feeling by changing the light and atmosphere of the built environment. Such adaptive and in-situ modifications and autonomous responses to the user's comfort have significant potential to reduce energy consumption through passive heating and cooling systems while offering higher quality environments for the occupants, as opposed to existing solutions that, especially in public housing, make generic assumptions about the occupants' preferences. They can also provide localized comfort settings for different individuals in shared housing conditions (i.e., dormitories shared apartments) and office spaces.

User's well-being, thermal comfort, and energy efficiency are not new ideas; however, linking them to responsive smart environments and measuring them from biosignals is an innovative area of exploration. This type of Human-Computer Interaction approach is unique within the field of architecture and there is no substitute for that currently. The target level of performance in this project is to increase energy performance by 50% of current median EUI from space heating and cooling, water heating, and ventilation for offices, single/multi-family, and loft retrofit projects.In addition to energy efficiency, this project has significant applications in the medical field via assisting people with disabilities and elderlies, ultimately empowering individuals with physical challenges to regain control over their environments. This aids in meeting the growing demands of the aging population and at-home health care. These types of spaces that can recognize behavioral patterns and support human decision-making can also be used in hospitals and nursing homes. They can make caregiving institutions and people aware of the feelings of people with PTSD and Autism.

2. Methodology

This paper presents a prototype of a smart shell that can be controlled by occupants' biological and neurological signals and change according to environmental data, users' needs, comfort, and preferences. This shell is a sensor-enabled phase changing exterior envelope panel and window shading system to optimize solar protection and gain for single-family and multifamily residential retrofit conditions based on occupants and environmental data. It is a flexible and reconfigurable shell that can undertake different configurations through active shapes and kinetic components (Figure 2). To achieve the goal of this project, we have to take a multi-faceted approach. To achieve the goal of this project, we pursue the following objectives:

1. Measure and analyze bio and environmental signals.
2. Translate signals into actionable changes in an adaptive structure.

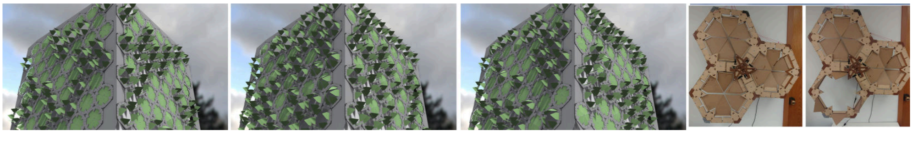

Figure 2. A smart shell that can be controlled by occupants' biological and neurological signals and change according to environmental data, users' needs, comfort, and preferences.

We emphasize energy use optimization and, additionally, sustainability, by investigating the use of time-of-use shifting using thermostatically controlled loads (TCL), residential renewables (such as solar photovoltaics), lighting coordination and timing, and shift in day-to-day habits. In our preliminary work on display at Washington State University, we have demonstrated how a prototype wall can respond to an occupant's biological and neurological data by reconfiguring itself. This system was implemented based on a TCP/IP-based client-server network to allow the independent implementation of various emotion recognition software and hardware tools (Figure 3)

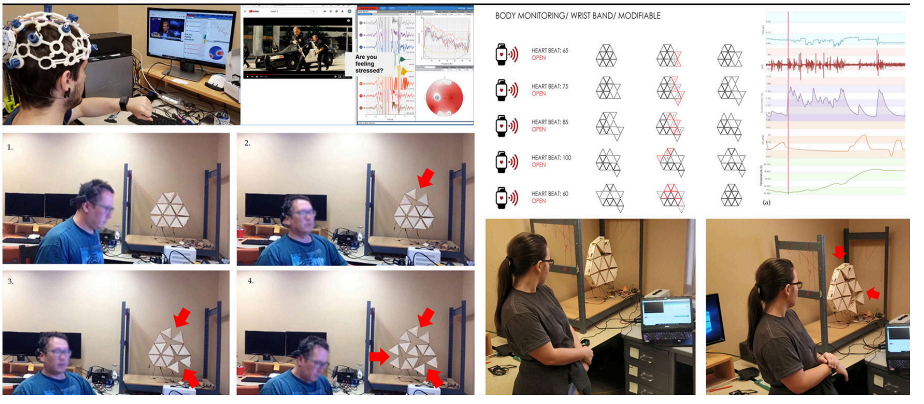

Figure 3. Left: Neurological data collection with EEG. Emotional interaction via neurological data and wall reconfiguration based on the neurological signals. As shown in the neutral status the wall is completely closed (1), and by changes in the moods and body temperature it changes its opening. Right: Biological data collection via wristband. Emotional interaction via biological data and wall reconfiguration based on changes in biological data.

2.1. MEASURE AND ANALYZE BIOLOGICAL AND NEUROLOGICAL SIGNALS

In this project, we used technology to measure biometric data to define emotions, comfort, and preferences and actively reconfigure the physical space. While regions within the brain's limbic system are primarily responsible for emotions, different emotions give rise to subsequent measurable changes in physiological signals such as skin conductance and electroencephalography (EEG), which can then be analyzed for emotion recognition. (Janig 2003). When correlated with the sympathetic autonomic nervous activation system, emotions could be extracted from neurological signals.

In our model, using affective computing, biological and neurological signals such as heartbeat, perspiration, brain voltage, and skin conductance, sweat secretion, and body temperature are being measured to identify the precise emotions and actively reconfigure the shell. The project is to equip users and the environment with smart embedded devices (such as Empatica E4 smartwatch and Emotive EPOC +14 Channel EEG Headset) that can collect users' real-time behavioral data, mental and physical, within the realm of IoT. Empatica's E4 wristband was used to collect heart pulses and skin conductors revealing the inner perception of outer reality. Collected data with the wristband can be streamed through Bluetooth, and this stream can be viewed live on the E4 real-time app. In particular, data for galvanic skin response, blood volume pulse, and skin temperature appear to contain patterns correlated with emotions. The changes in biological measurements are indicative of factors such as excitement, arousal, or stress.

To translate biosignals to an emotional status, we use fuzzy logic and machine learning techniques, e.g., deep neural networks, Random Forest, and Decision

Tree, to create emotion recognition algorithms. Interactive ground-truth data collection solutions are used for training these algorithms. Through comparing the accuracy of different machine learning algorithms, the results show that applying Decision Tree on sensor data from wearable wristbands yielded promising preliminary results (86% accuracy) in recognizing six basic human emotions and mental states. The data for training machine learning models are being collected both in-the-lab and in longitudinal fashion through normal daily living activities.

2.2. TRANSLATE BIOSIGNALS INTO ACTIONABLE CHANGES IN AN ADAPTIVE SHELL

The collected biological data is analyzed by our machine learning algorithm to extract features such as feelings, comfort, and desire for light/heat/ventilation/view, which in turn causes the shell to respond to predicted emotional state. For example, by changing the occupant's heart rate, body temperature, and sweat secretion from biological data, the shell will open up autonomously to moderate the temperature of space through the passive cooling system. (Figure 4)

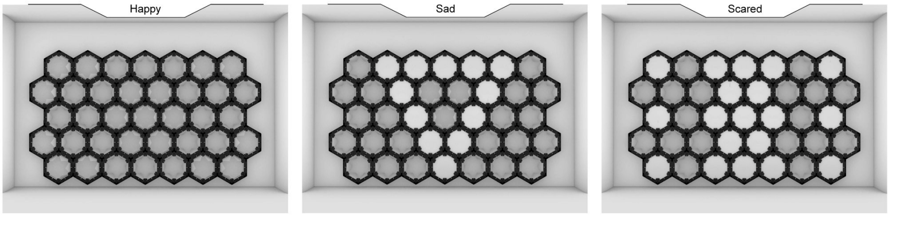

Figure 4. Smart shell responding to predicted emotional state, biological and environmental data.

The shell implements kinetic components to perform certain reconfigurations, such as seamlessly opening or closing upon command. This shell can change its shape, size, and open up its surface to a view, to control the light and natural ventilation, or to enhance the occupant's condition. In doing so, algorithmic and generative logic process the data to perform predefined operations, calculate the results, perform simulations, evaluate the design strategies, and subsequently generate an optimized output. Here the built environment is treated as a learning machine capable of feedback cycles, receiving data, and implementing change as needed. To achieve an adaptive shell that can respond to the user's emotions, we took below phases:

2.2.1. Identify Maximum Flexibility in Adaptive shell

In this phase, we designed an adaptive shell that can change according to the occupant's needs. Maintaining stability while allowing flexibility is a major challenge in adaptive structures. To identify the balance between flexibility and stability, we used simulation tools such as Grasshopper, Kangaroo Physics 2, Ivy plugin, and Python to design, simulate, and test a series of active components, deployable structures, and transformable modules for different configurations. We computationally analyzed the shell's structure to detect weaknesses and optimize its form by applying different combinations of stress distributions, torques, bending patterns, natural forces, hinge forces, and plasticity. (Figure 5)

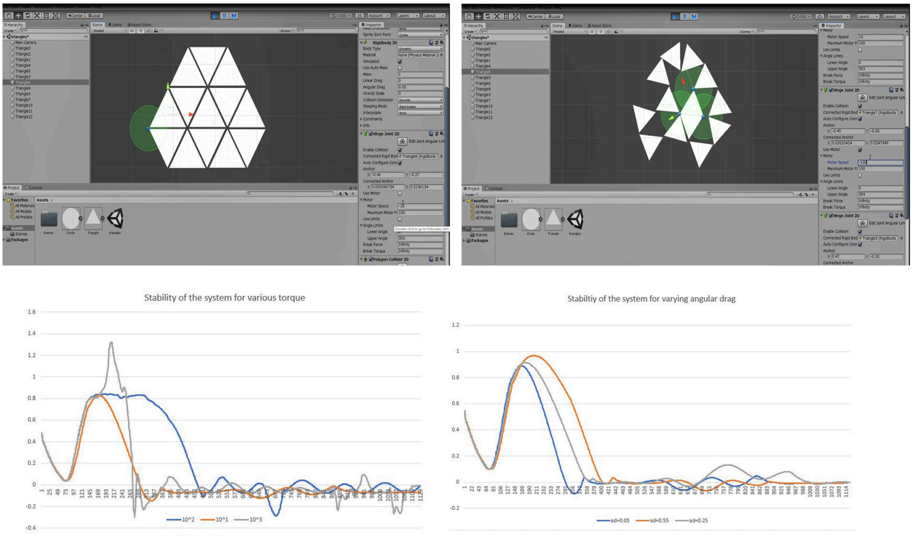

Figure 5. Simulation of the shell's structure to detect weaknesses. Tables represent the stability of the adaptive triangular wall for various torque (left) and for varying angular drag (right).

2.2.2. Identify Proper Actuating System and Materials

To identify the proper actuating system, we tested an prototyped a series of actuating mechanisms such as programmable materials, conductive materials, soft robotics, and mechanical actuating systems. The adaptive mechanism of the shell is designed to perform optimally and consists of a series of 3D printed gears and joints that are moved only with one servo (Figure 6).

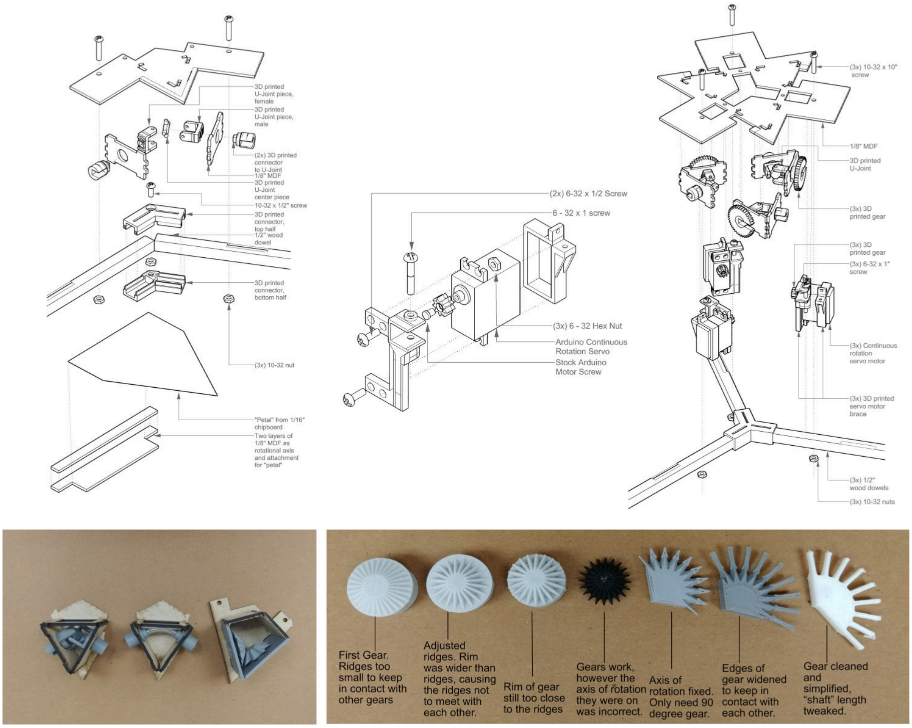

Figure 6. Rapid prototyping of alternatives to gearbox and exploded axon of actuating mechanism.

2.2.3. Correlate Emotions with Shelter Changes

This shell responses autonomously to the occupant's biological data in real-time. By using a smart wristband, the physiological data such as body temperature and heart rate are collected, and the smart shell adjusts its openings based on the collected data. The shell should automatically offer additional openings to increase the natural light and ventilation to moderate the occupant's physical and emotional status and optimize energy consumption. The state-space methods approach, in combination with machine learning techniques, can detect changes in biomarkers. Then we mapped a relationship between an occupant's comfort, optimal energy usage, and the optimal configuration of the structure around them. A change in the latest stored state triggered a change in the shell. We used Raspberry Pi devices to poll the biological data and control the actuators. (Figure 7)

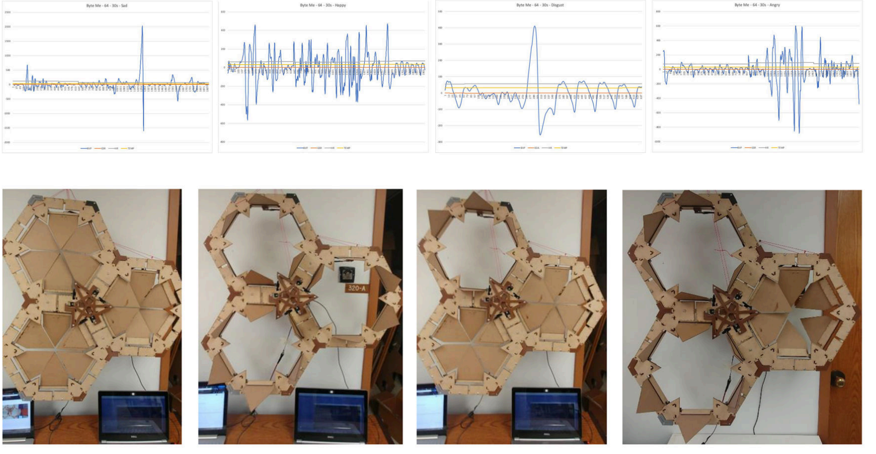

Figure 7. Prototype of the smart shell communicating with the biological data. Changes in the panels are the direct result of changes in the biological and environmental data.

3. Future Development

In addition to reevaluation and improvement of what has been done in the prototype setting, this project needs to be tested in full-scale and in real-world settings. Further development will focus on 1) SMART SPACE (This is an interior technology integrated furr out solar radiant heated, data-enabled, and finish flexible lining panel that is custom fit for single-family and multi-family residential retrofit conditions); and 2) SMART CORE (This is a thermally regulating interior wet core that is AI-enabled to track user and occupant behavior and respond accordingly is intended for warehouses to loft apartment retrofit projects in urban areas). We will develop smart spaces that can learn from users and change the environment based on the users' behavioral patterns. This machine learning analysis and evaluation of successful interactions would make the system gain experience to optimize its prioritized tasks such as user healing, user comfort, energy optimization and adaptive structural stability. Our future development can take advantage of machine learning techniques to endow spaces with the personality and character of the user.

4. Conclusion

This paper seeks to address the role of AI, IoT, human-computer interaction, and adaptive spaces in improving the mental health and well-being of the occupants while optimizing energy consumption. By focusing on affective computing, this research presents an alternative method by which to transcend the limitations of our spaces with AI. This research pushes the boundaries of what can be achieved to improve the human affective experience within space while practicing sustainability. The life-like behavioral spaces influence personal health and optimize energy consumption through passive heating and cooling systems.

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Design Cognition /Digital Conservation & Heritage / Anthropocene

STYLISTIC REPRODUCTIONS OF MONDRIAN'S COMPOSITION WITH RED, YELLOW, AND BLUE

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Abstract. Shape grammars are employed for analyzing and delineating the formal structure of Mondrian's painting. The proportionality (dynamic equilibrium or commensurability) embedded in the structure of the artifact is optimized with Genetic Algorithms. The optimization process introduced in this paper allows a user's intervention to provide a guided search for finding stylistic reproductions of the original. Two types of the stylistic reproductions are conducted: 1) generating formal descendants of the original, and 2) tuning the original structure. The implementation of the reproductions is described also.

Keywords. Mondrian; Style; Shape Grammar; Proportionality; Genetic Algorithms.

1. Introduction

The motivation for generating stylistic reproductions conducted in this paper comes from the design of a building façade delineating proportional patterns embedded in Mondrian's "Composition with Red, Yellow, and Blue." His painting is known to be the artifact of delivering "living rhythm," which is the essence of dynamic equilibrium created from proportions. In his "Plastic Art and Pure Plastic Art," Mondrian explains that the development of the dynamic equilibrium guides the development of the laws that consist of the relationships of position and dimension of the constructive elements in the painting.

Shape Grammars have been applied for the analysis and synthesis of various artefacts including buildings, artworks, industrial products, and historical contents. The set of shape rules with the basic elements and their transformational relationships represent the morphological structure of the given artefact in shape grammars (Cenani and Cagdas, 2007; Knight, 1980). Furthermore, shape grammars have been employed for understanding design styles and languages (Koning and Eizenberg, 1981; Li, 2004; McCormack et al, 2004). Shape Grammars represent style and explain the purpose of style characterization 1) with the clarification of the underlying commonality embed in a given artefact; (2) with providing a prototype or a yardstick for the style; (3) as a compositional machinery for new instances of the style (Stiny and Mitchell, 1978); and (4) with its descriptive power to reveal intrinsic simplicity or regularities in designs (Park, 2008). With maintaining an embedded style, shape grammars allow a designer

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to generate infinite variations of an artefact by changing parametric values of the morphological structure of the artefact.

Based upon proportionality (March,1998; Park, 2017) embedded in the painting, a computational application for generating stylistic reproductions of Mondrian's "Composition with Red, Yellow, and Blue" is introduced in this paper. Proportionality is a commensurability (dynamic equilibrium) providing proportional balance among three different terms. With the analysis of the morphological structure of Mondrian's painting, the series of shape rules, schema, and the labeled parameters are defined to delineate the re-productions of the original. The rules and parameters become input variables, constraints, and objective functions of the set of mathematical models. The models are developed for the optimization of the proportionality embedded in the formal structure of the painting. Genetic Algorithms are employed for this guided optimization in order to generate the stylistic reproductions with maximizing the proportionality (kelly et al, 2010). The proposed application including its input, output system, and user-interface is implemented within MATLAB, a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks.

2. Design Schema and Variables

Mondrian's "Composition Red, Yellow, and Blue" painted in 1930 with oil on canvas has 45 cm x 45cm dimensions. It has been exhibited in Kunsthaus, Zurich.

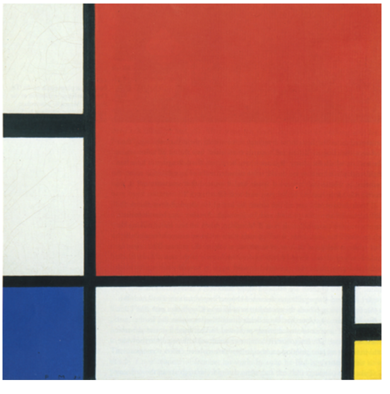


Figure 1. A scanned image of "Composition with Red, Yellow, and Blue" (Blot-kamp, 1994).

The geometric model of the scanned raster image is constructed in a vector graphic within AutoCAD. The position of lines, constructive elements or basic elements, is in rectangular form. The dimension of the lines is defined with a scale of 45 cm. The dimensions of 36-line segments are identified as essential design components of the painting. The design schema of the painting is illustrated in Figure 2. The decomposition of the original structure with the schema becomes the basis of defining the geometric relationship in order to perform the parametric variations of the original.

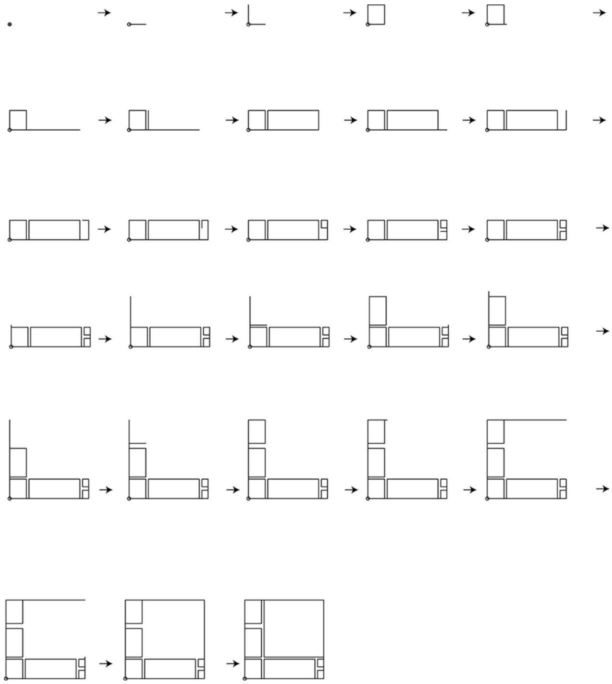


Figure 2. Design schema of the formal structure .

With the schema, the 36 line segments are defined as design variables to have various parametric values as $x_i, i = 1, \ldots, 36$. The reconstructed geometric representation of the painting is illustrated with the dimensions in Figure 3.

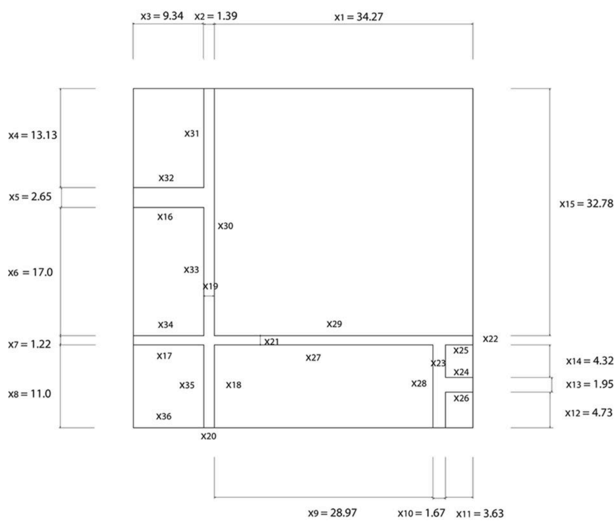


Figure 3. The geometric representation of 36 variables & original dimensions.

3. Objective Functions and Criteria: Proportionality

The relationships between the parts and the whole are treated in mathematics as commensurability. Commensurability among three ordered terms and their differences is established when they have equality among their proportional relationships. When the commensurability is achieved among them, we achieve a proportional equilibrium among the parts and the whole. There are 11 ways of representing three ordered numbers and their differences with the equalities of the ratios among them, which were developed by ancient Greek mathematicians (Heath, 1921; D'ooge, 1926; March, 1998). The 11 ways of representing the equalities of the ratios among the three ordered numbers and their differences are defined as "Proportionality" (March, 1998, Park, 2017).

The goal of the optimization is to maximize proportionality (dynamic equilibrium) value, the essence of Mondrian's style, embedded in the painting. The proportionality value from the combination of 36 variables is employed as a fitness criterion for the optimization of the artifact. The objective function of the proportionality synthesis on the painting is to minimize $f_r = V_r$ (remainder value) of the dimensions from the 36 design variables (n = 36) with the computation of proportionality. By minimizing f_r subject to the values of the input variables, the maximization of the proportionality value V_p of the design variables is achieved. The computation of the objective functions starts with the dimensions of the input variables. The dimensions of the 36 design variables are generated from the dimensions of the input variables. Results for all triplet combinations for the 36 variables are aggregated statistically and a final value, the proportionality value V_p, is computed as a percent of the number of triplets observing any form of proportionality relative to the total number of the triplet combinations. The computation of individual proportionality value P_k, proportionality value V_p, and remainder value V_r are illustrated as below.

k proportionality number (1˜11)

n number of the dimensions of design variables

x_i i^{th} parametric value (dimension) of design variable, $i = 1, \ldots, n$

L the list of triplet combinations from x_n

A_k an algorithm computing number of triplet combinations within P_k

$L_k = A_k(x_n)$ the number of triplets by algorithm A_k to x_n in P_k

$T_k = |L_k|$ the number of triplets in the list L_k

T the total number of triplets combinations from n

The total number $T = C(n, 3) = \dfrac{n!}{(3!(n-3)!)}$

Individual proportionality values $P_k = \dfrac{100 \cdot T_k}{T}$

Proportionality value $V_p = \sum_{k=1}^{K} P_k$

Remainder value $V_r = 100 - V_p$

4. Constraints

From the computation of the objective functions, the dimensions of the 36 design variables are generated for a given range of the input variables. If the morphological structure established by the dimensions violates any given constraints, then the set of the dimensions computed from the input range is not passed on to the optimization process by penalty functions. There are five basic constraints necessary for maintaining the essence of the design of Mondrian's painting: Overlap, Adjacency, Rectangular shape, Boundary configuration, and Positive value of V_p. The visual representations of the cases that violate the basic constraints are given below.

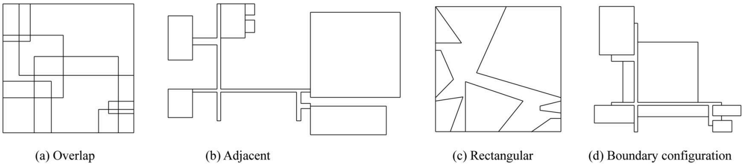


Figure 4. Design Constraints.

5. User Interface: Receptors and Effectors

The receptor and effector are the user-interface to perform a guided search for a formal structure of Mondrian's "Composition with Red, Yellow, and Blue" with an optimal proportionality value. The receptor includes design definition, genetic algorithm setting, input variables, and reset & execute. The effector includes output (plot of the optimization process and morphological transformations). There are three stages of an optimization process on the user-interface: 1) initial stage, 2) evaluation stage, and 3) representation stage. At the initial stage, the application provides the original parametric values of Mondrian's painting and its morphological structure as in Figure 5.

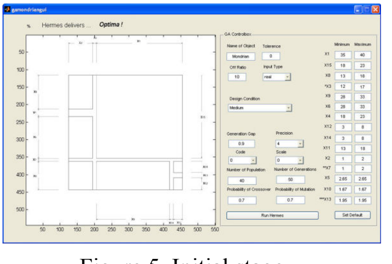


Figure 5. Initial stage .

According to a user's input, the optimization proceeds with minimizing the remainder value V_r for each generation. The trace of this evolution is recorded at the end of the evaluation stage. The visual representation of the output is made at the representation stage.

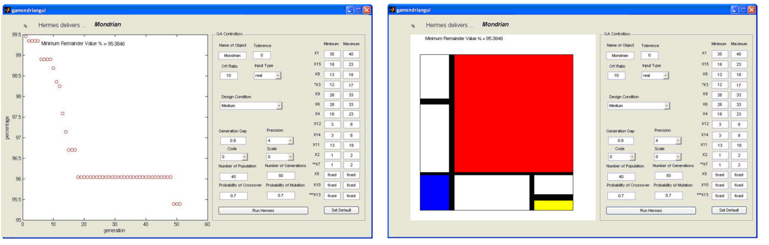


Figure 6. a) Evaluation stage b) Representation stage .

6. Output

The output from the design optimization conducted with proportionality synthesis on the painting of Mondrian has four different output formats: 1) a text file that shows remainder value V_r, and the best set of dimensions of design variables at each generation; 2) a visual representation based upon the optimized dimension in two different formats (line drawing and color-filled drawing); 3) a screen capture of the input settings and its evolutionary optimization process on a user-interface of a computer-based proportionality synthesis application; and 4) an animation made of the series of visual representations of the best design for every generation.

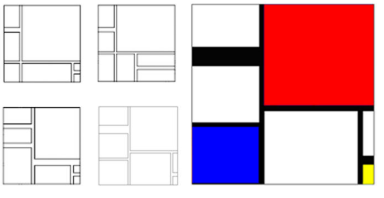


Figure 7. Output samples (a)Line (b)Color -filled.

7. Stylistic Reproductions

The various morphological transformations with maximizing the proportionality values (V_p) embedded in the formal structure of the original painting have been generated. The first approach is to generate the stylistic reproductions of the original painting, as its morphological descendants, by performing a guided optimization. The ranges of the dimensions of input variables are defined according to a user's concept within the receptors of the synthesis component in MATLAB. Accordingly, the animation of the alternatives is reviewed to adjust the optimum with narrowing down the ranges of the input dimensions. With continuing the procedures, four stylistic reproductions of the original were generated in the consideration of the proportionality value of the design and a user's design concept. For the comparison of the stylistic reproductions to Mondrian's other paintings, Figure 9 shows similar Mondrian's paintings at different times.

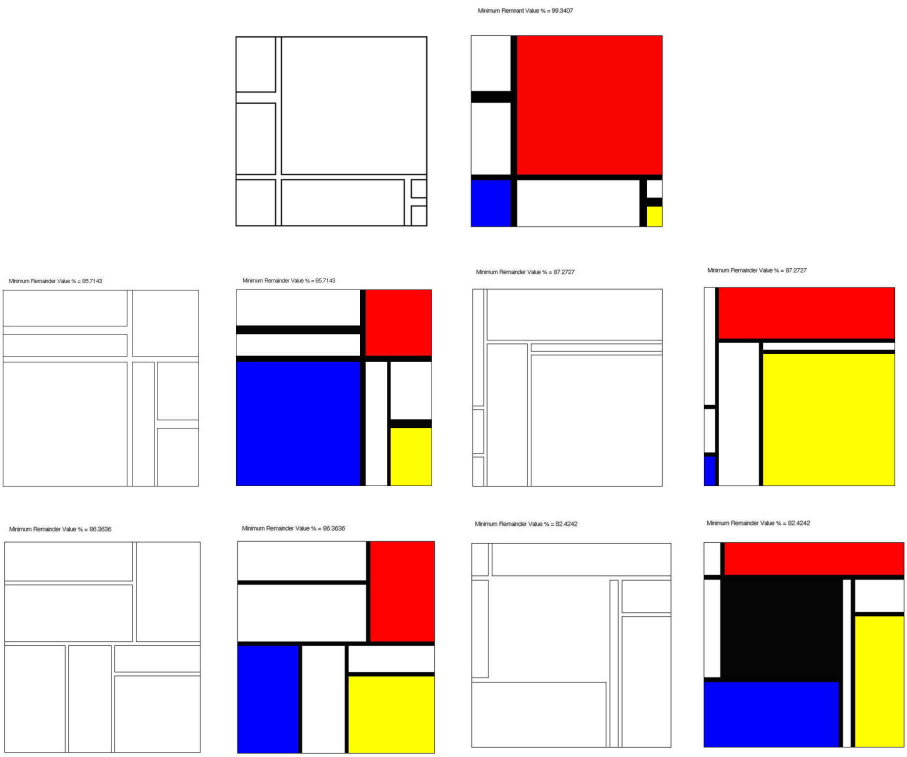
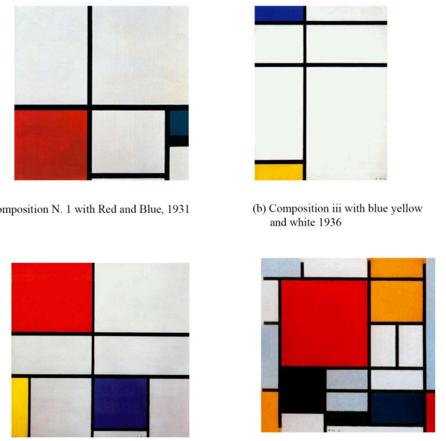


Figure 8. Four stylistic reproductions of the original.

Table 1. Numerical comparisons (R: Red, B:Blue, Y:Yellow, K: Black).

	Original Composition	**Composition BRY**	**Composition YRB**	**Composition YBR**	**Composition KBRY**
x_1	34.27	24	48	18	44
x_{15}	32.78	24	14	36	8
x_8	11	45	8	22	16
x_3	9.34	45	3	36	4
x_9	28.97	8	11	12	2
x_6	17	8	12	16	24
x_4	13.13	13	32	11	8
x_{12}	4.73	22	36	18	4
x_{14}	4.32	22	2	4	28
x_{11}	3.63	15	36	24	4
x_2	1.39	2	1	1	12
x_7	1.22	2	1	1	1
x_5	2.65	3	1	1	1
x_{10}	1.67	1	1	1	1
x_{13}	1.95	3	1	1	1
V_p (%)	0.7	14.3	12.7	13.6	17.6
V_r	99.3	85.7	87.3	82.4	82.4



(a) Composition N. 1 with Red and Blue, 1931

(b) Composition iii with blue yellow and white 1936

(c) Composition C (No.III) with Red, Yellow and Blue, 1935

(d) Composition with Large Red Plane, Yellow, Black, Gray and Blue, 1921

Figure 9. Other Mondrian paintings created in 1931, 1936, 1935, and 1921 .

The other approach is to tune the structure of the original painting with maximizing proportionality value. Through the tuning, the proportional value went up to 18.2% even with 0% tolerance.

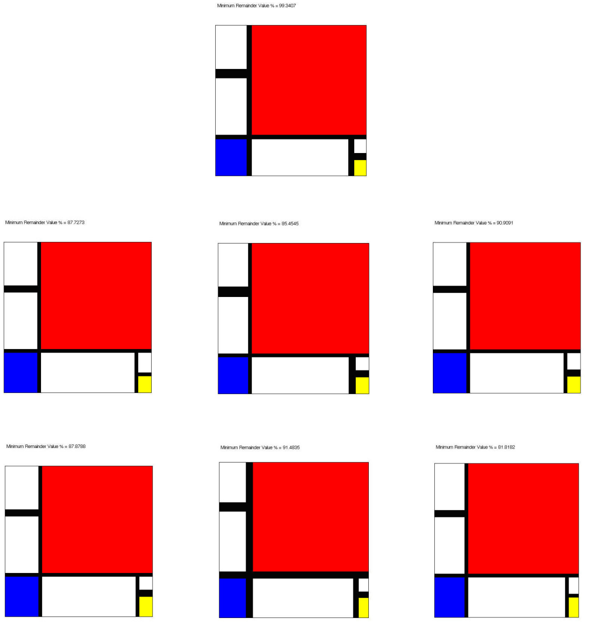


Figure 10. Tuning of the original.

8. Discussion

In this paper, the stylistic reproductions of Mondrian's "Composition with Red, Yellow, and Blue" were generated by optimizing proportional balance as a living rhythm or dynamic equilibrium embedded in the morphological structure of the painting. The design schema of the original painting became the instrument for 1) defining the geometric relationships of the basic elements in the original and 2) performing its parametric variations. With Genetic Algorithms (GAs), a guided search through a user's intervention within the interface of the proposed application is applied for the optimization (Kelly et al, 2010).

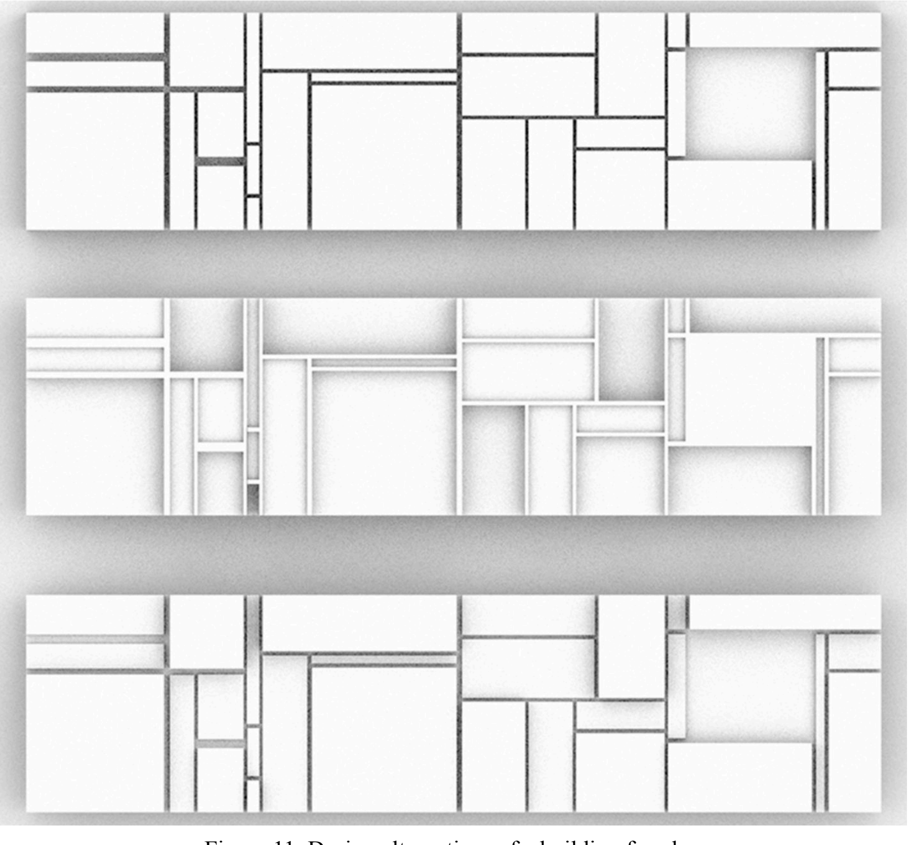


Figure 11. Design alternatives of a building facade.

As the outcomes, two types of the stylistic reproductions were presented. The morphological descendants of the original exhibited their own characters with maintaining a higher level of proportional balance than the one of the original. At the same time, they showed their stylistic resemblance to Mondrian's paintings in the contemporary years of Mondrian's "Composition with Red, Yellow, and Blue." The descendants have been applied for the motif of a façade design as shown in Figure 11. The facade design is introduced as an architectural application and came from differentiating the heights of rectangular partitions of the descendants (Schnier and Gero, 1998). The proposed approach of the stylistic reproductions will be further developed in the design of a building layout (Michalek et al, 2002).

With the other type of reproductions, the higher quality of the proportional balance of the painting was tuned and restored. The proportionality values of the tuned paintings went up to $V_p = 18.2$ with 0% tolerance is higher than the one of the original painting, $V_p = 12.5$ even with 2.9% tolerance that is the range of Just Noticeable Difference (Fechner, 1966) in Vision. It may lead to a new definition of the original painting of Mondrian: "what is the original?"

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VILLA GIRASOLE

A Filter for Movement in Building Cognition

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Abstract. This paper outlines a framework for building cognition that emphasises the role of architectural movement.The framework is relevant for a new type of building that is digitally augmented and autonomous, and that relates to occupants in novel ways. Based on an embodied view of cognition, the framework might serve a complementary approach to integrating building cognition in the overall building design. The significance of architectural movement in this context is unpacked and evaluated in this paper using the Villa Girasole, a historic work of kinetic architecture near Verona in Italy. The villa serves as a filter to investigate movement through three key concepts of the framework: acting out, coupling, and exteriorisation. The paper proposes that architectural movement might enable an interdependency between building, occupant, and environment that is critical for establishing a form of highly specific building cognition.

Keywords. Kinetic; Enactive; Building Cognition; Villa Girasole.

1. Introduction

For designers of the built environment, it may only seem natural that we have entered the geological time of the human. Since 2007 more than half of all people in the world live in cities; and even though cities take up just three per cent of the land on Earth, they are responsible for 60 per cent of the use of resources and 70 per cent of the world's carbon emissions (United Nations 2019). Many cities and their inhabitants face challenges such as inequality, pollution, inadequate housing, and restricted access to public transport or public space. At the same time, cities disproportionally contribute to global GDP and provide a critical mass for business, culture, and social development. The impact of human construction on Earth is thus significant, but the effect of the built environment on human behaviour has also been profound.

The innate ability to change our environment to benefit from it, is not limited to humans however: many animals construct their habitats. On a more fundamental level, animals deliberately change their environment to function. Some species of fish, for example, have been shown to create vortices in their submarine surroundings to enhance their agility (Triantafyllou and Triantafyllou 1995).

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 143-152.

Animals change their environment, and simultaneously it changes them. Some argue that the ability to cause a stir is required to perceive the world and to make sense of it. This ability is, therefore, a fundamental part of the mechanics of cognition (Gibson 1979, Varela et al. 1992, Pfeifer and Scheier 2001, Noë 2004).

Figure 1. The Villa Girasole in Marcellise, Italy. Linthout, L 2015, photograph, http://www.linthout.it/girasole-esterni.html.

Now so many of us live in urban conditions, this habitat has become the new normal. It is to be expected that most of our interactions with the world take place in the built environment. The buildings we interact with, operate with increasing levels of autonomy, a growing capacity for kinetic adaptation, and sometimes exhibit traits of artificial cognition. Buildings have become, and progressively will be, a special kind of machines that operate like robots (Green 2016, Davidson 2017, Daas and Wit 2018). This notion of the building as robot positions the building as an agent that has an active relation with its environment and with its occupants. And it highlights the need for a wide investigation of building cognition, which is not solely algorithm-driven. Like in robotics, such an investigation might embrace an embodied approach towards cognition that implies a mutual relation between buildings, their environment, and their occupants; a convergence of ideas from the philosophy of mind, robotics, and kinetic architecture. Adopting the name of a branch of philosophy, we might refer to such building cognition and its embodiment as *enactive architecture* (Mulder 2018).

This paper outlines a framework for building cognition that emphasises the role of movement in enacting cognition. The significance of architectural movement in this context will be unpacked and evaluated using the *Villa Girasole*, a historic work of kinetic architecture near Verona in Italy (figure 1). Designed and built well before the computational era, the villa serves as a filter to investigate movement that enables coupling between building, environment, and occupant. The paper argues for the relevance of this coupling in establishing a form of highly specific building cognition. Such specificity would provide a complementary approach to the more generic contemporary strategy of employing general-purpose algorithms to drive artificial forms of cognition in buildings.

The ambition is that for a new class of buildings like robots a more specific and holistically designed approach to cognition will be employed. Not to replace algorithms, but to develop algorithms and their embodiment concurrently in a manner that is inclusive of a building's environment and occupants. If cognitive features not merely exist as a digital abstraction, but also as physical building components, structure, and organisation, the design of building cognition might take place in a tradition of integrated building design. This might ultimately help overcome a deficiency in adaptive buildings where the restricted capacity of each sub-system is a potential limitation for future use. As mediators of the digital and the physical, the computational designers of the built environment might be the first to acknowledge and to grasp this approach.

2. Methodology

When algorithms, devices, or buildings are designated *intelligent*, there may be different thinking models supporting the notion of intelligence. The organised science around artificial intelligence has more or less started in the 1950s. An influential movement at the time was a multi-disciplinary research programme in psychology, philosophy, neuroscience, computer science, linguistics and anthropology called *cognitive science* (although this term only came into use in the 1970s). The premise was that the human mind is an information processor that manipulates abstract, symbolic structures, similar to how computers operate. One of the persistent ideas of this movement is the idea that intelligence is computational, and thus that computers are ideally suited to simulate or assume intelligence (Pfeifer and Scheier 2001, Russell and Norvig 2010). While this idea has brought significant progress to the development of artificial intelligence, it also has several fundamental problems. Philosophers of mind and roboticists alike have for example argued that intelligence can not be purely computational because of how intelligence is physically embodied and related to the world. Some emphasise the relevance of movement and interaction as the basis for cognition. Notably, the work of robotics engineer Rodney Brooks (1991) has led to what we might call the *enactive* approach to cognition, supported by the work of philosophers such as Francesco Varela (Varela et al. 1992) and Alva Noë (2004).

As part of a research project that investigates architectural movement in terms of enactive cognition, a framework was established around three key terms: (1) acting out, (2) coupling, and (3) exteriorisation (Mulder 2018). These terms are meant to apply to the building and its occupants separately, but also to their hybrid form.

Acting out refers to the co-evolved ability for sensing and movement in organisms. Without movement, there is no perception. Because movement is highly specific to each type of organism, this leads to specificity in the perception and understanding of the world.

Coupling is derived from the work of Maturana and Varela (1980) and points at a bi-directional and critical relation between agent and environment as a condition for cognition. This relation is expressed in figure 2(a).

Exteriorisation relates to the idea that some cognitive functionality may lie outside of the agent's body. Memory is an example where objects, drawings, or text may serve to store information and thoughts outside of oneself. Specifically, exteriorisation may also refer to how a building can mediate a coupling that exists between occupant and environment.

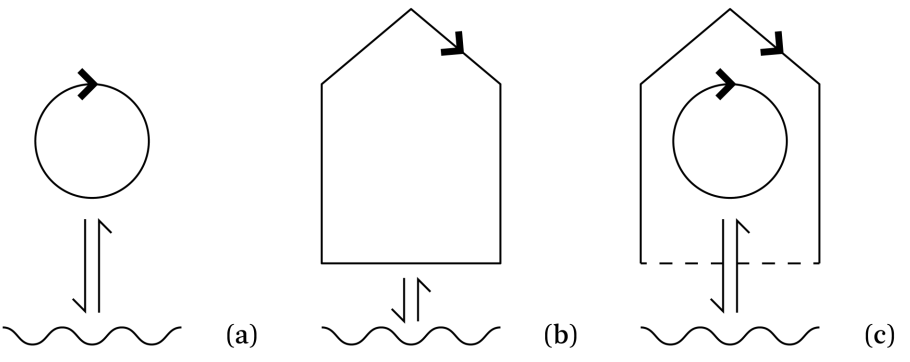

Figure 2. Coupling between organism and environment (a), coupling between building and environment (b), and mediated coupling between occupant and environment (c).

In this paper, a case is discussed of a building that features architectural movement. In section 3, a description of the building is given that contextualises and clarifies its capacity for architectural movement. This description is based on writings, photographs, drawings, video, and the accounts of an occupant. In section 4, the building is analysed through the three aspects of the framework. First, acting out: how does the particular ability for movement shape the building's sensitivity for its environment? Second, coupling: how do the movements of the villa affect the relationship between the building and the environment? And third, exteriorisation: how does the building affect how occupants understand the world?

The building discussed is the *Villa Girasole* in Northern Italy. The reason for analysing this building is that it features intentional architectural movement: movement that was deliberately designed to operate beyond the utilitarian functionality of for example opening a door or a window. It was important also that the project had been actually built, to understand the villa in use and its practical intricacies. By focussing on the movements of the villa, the project acts as a filter for this investigation. Other buildings that could have been featured in this paper are for example OMA's Maison à Bordeaux (1998), or Blur Building (2002) by Diller and Scofidio.

3. Villa Girasole

'*Ho deciso di fare il giro completo*', I have decided to make the complete turn, Angelo Invernizzi told his surveyor at the end of November in 1933 (Galfetti et al. 2014, p. 26). Over some years in the 1920s, Invernizzi had in steps acquired an area of land on the slopes just north of the village of Marcellise near Verona in Italy. His ambition was to erect a holiday home for his family, he was married with two children, where they could spend the summers and where they could receive guests. Invernizzi might have been developing ideas for the villa over some time, but the first known drawings date from 1929. And construction started in the summer of 1931. It would continue over the following summers and be completed in 1935 (Randl 2008).

For reasons not known with certainty, perhaps perceived health benefits or a sheer interest in novelty, Invernizzi had designed a house that would turn. Tracking the sun, it would take the house 9 hours and 20 minutes to make a full rotation. The Sunflower, he called it, *Il Girasole*.

Invernizzi was trained as a civil engineer and had worked for the Italian state railways before starting his own construction business in Genoa. On the design for the villa, he worked closely with his friend, the architect Ettore Fagiuoli, and the mechanical engineer Romolo Carapacchi. The resulting building became aesthetically, but also quite literally, a machine to live in; the influence of Le Corbusier's 1923 manifesto likely to be a factor, even though some of the specificity and complexity of the *Girasole* was arguably running against the ideas Le Corbusier was promoting.

The villa can be described as two distinct parts: a monumental static plinth and a modern mobile superstructure. The cylindrical plinth is dug into a slope on the terrain, exposing the main entrance of the villa at its base and a covered walkway with colonnade running above. The plinth was clean and formal when built and is almost baroque in its ivy-overgrown contemporary condition. On top, a circular platform is laid-out as a dial, with a series of green patches that are separated by nine radial and two circular paths.

Parted by about 1.5 m installation space, which is host to the building's particular machinery, the mobile structure rises almost as a separate entity, overlooking the valley. Clad in aluminium sheets, seemingly fastened with rivets, and with open balustrades, the similarity to aircraft, trains and vessels from the time would be deliberate. Lightweight, yes, but to make clear also that this was not an ordinary house.

The mobile villa contains two wings at a 90-degree angle. At the intersection of the wings a round tower, resembling a lighthouse almost doubles the height of the block. Internally, the tower also extends downwards, to the lowest part of the foundation, literally forming the pivot of the rotation. The two wings have a similar layout on two floors. The living quarters are situated on the ground floor, the sleeping rooms on the first. All quarters face the courtyard that is wedged between the wings and that moves along with the rest of the villa. The vertical distance between the main entrance and the top of the tower is about 42 m. Part of the height can be navigated by an elevator positioned inside the tower. A spiral staircase provides an alternative route.

The structural frame of the mobile villa is made of reinforced concrete, cast in situ. It is constructed as a moment frame, consisting of columns, beams, floors with downstand beams and helical slabs inside the tower. Six columns around the circumference of the tower run from the foundation to the top of the tower, connected by several horizontal rings. A steel transfer structure at the bottom of the tower in the basement leads vertical loads to a large custom thrust bearing. This bearing allows for rotation around a vertical axis whilst resisting vertical forces. Accessing this bearing is possible via a hatch in the floor at entrance level.

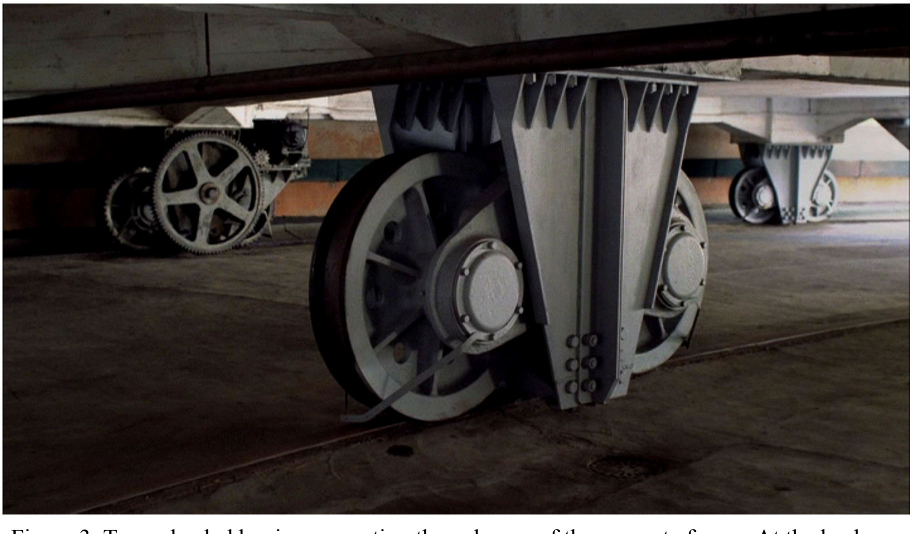

Figure 3. Two-wheeled bogies supporting the columns of the concrete frame. At the back, on the left side, a motorised bogie is visible. Still from Schaub and Meili, Girasole: A House Near Verona (9:35).

Each wing of the villa has a further six columns, three in each of the long faces, creating more or less equally sized bays. To keep the total weight of the mobile structure low, walls between the concrete columns have been erected with Eraclit infill panels, which are made with wood chips. The twelve columns are each supported by a two-wheeled bogie with wheel diameters of 700 mm (figure

3). The twelve bogies run on three concentric circular tracks, four on each track. The courtyard is supported by a further three bogies, each with one wheel; two are running on the outer rail, and one on the middle rail. A network of downstand beams under the courtyard floor provides some redistribution of the loads.

Level with the top of the plinth, a ring of 20 thrust wheels was installed around the circumference of the tower to guide the rotation. The wheels are mounted to the rotating structure and run on a steel rail installed on the static plinth. Two of the two-wheeled bogies are motorised and set the house in motion. These bogies are placed on the outer rail, adjacent to the courtyard. A large reduction through several cogs and a low speed of rotation make that relatively modest electric motors were used of 1.1 kW each. The building was controlled through an interface with three buttons: forwards (*avanti*), backwards (*indietro*) and stop (*arresto*). The interface was located on ground floor of the mobile villa, in the wall behind a little glass door. Electricity in the house for the motors, and for the domestic functions, was fed through a large slip ring installed on the fixed plinth around the tower, with a power collector on the rotating part of the building.

We might consider the movement of the villa in three ways: the capacity for movement, the result of movement after it took place, and the actual motion.

First, the capacity for movement becomes evident when looking at the building from the outside. The building is clad in a lightweight material and features a spindle in the form of a tower. Worn circular tracks suggest past usage, and wheels indicate a degree of freedom. The cogs and motors on two of the bogies reveal the driving force behind the movement. Even inside the building movement is suggested in the spiralling staircase and the emblematic mosaics on the floor. In a documentary about the villa (Schaub and Meili 2010) Lidia, Invernizzi's daughter, suggests that for her father the promise of movement was of key importance: 'I think he was content to know that his house had something which no other possessed'.

Second, the result of movement is the changing orientation of the villa. This would have been the most enduring effect of the building's motion, because 'few were the days when papa would decide to make the house turn', says Lidia Invernizzi (Schaub and Meili 2010). When the villa was turned with the courtyard towards the hill, it gave direct access to the orchard. And it would block some of the scorching summer sun. The villa became more intimate, with the courtyard concealed between the building and the landscape. Turned the other way, the villa would face the valley and expose a different character-more imposing and more open.

Third, the actual movement was slow and only just perceptible. 'Lifting my eyes from my book, each time I would see a new vista carved from the landscape. There were always new views and in a different light, although we had not perceived any movement', remembers Lidia Invernizzi (Schaub and Meili 2010). The villa has also been referred to as the *house without shadows* (Frascari 1990, Lewis et al. 2007). This description might be more poetic than technically correct, however. Even if the villa was tracking the sun, movement of the sun relative to the house would be vertical, still resulting in a particular movement of shadows. But with a full revolution in nine hours and 20 minutes, the villa would move at about

2.5 times the apparent speed of the sun, disregarding variations in the velocity of the sun's azimuth angle during a day.

4. Enactive Architecture

The specific way of acting out of the villa was a rotary movement that was cautious and hardly perceptible. It was said that only the kids would see it, and those who were interested in the mechanism (Schaub and Meili 2010). The cogs of the gear on the two motorised bogies would be visibly turning, but the edge of the building, at about 20 m from the centre, where movement would be most significant, would only move at a speed of about four millimetres each second. This was exactly how the villa was designed, as Invernizzi had intended. He had specified the machinery including the size of the wheels, the ratio of the gears, and the power of the motors, to make the building rotate at this particular velocity. And the custom thrust bearing in the basement, the circular layout of the rails, and the horizontal guide rollers are there to facilitate the building's rotary movement around the central axis of the tower. When it moves, the villa enacts this designed intention for movement; it becomes what it was set out to be: a revolving building. And even if the building is not moving at a particular moment, it is still clear that the building has the capacity to do so. The promise of movement is emanated from the sight of machinery, the circular layout of the garden, the decorations of the interior. It is only a matter of pressing a button for the movement to be actualised.

This acting out couples the building to its environment. When the building revolves, it enters in a particular relation with its surroundings. This is expressed in figure 2(b). Where we might say that static buildings are subjected to such relations, kinetic buildings actively engage in them. Even though the building does not by itself decide to rotate, movement is an intrinsic capacity of the villa. The villa's movements are manifested both in it taking on different orientations and in its rotary movement itself. Different orientations with time affect how observers from outside regard the house and sightlines change relative to other buildings. Windflow around the house is also affected by its orientation. Wind-facing and lee faces switch sides relative to the dominant wind direction with more subtle changes occurring in the downward vortex street. The local climate around and in the house is perhaps most affected by the particular variation of exposure to sunlight. Whether the villa rotates during the day or takes on a specific orientation, the pattern of irradiation is linked to the villa's ability to rotate rather than just the path of the sun. Rotation might result in more constant levels of light and more persistent heat gains in certain areas of the villa. And changes in orientation might result in more optimally shaded conditions on hot days and open conditions on other days.

The building's coupling to its environment provides a form of exteriorisation to its occupants. The movements of *Il Girasole* might have been felt or heard by its occupants. A buzz of the motors, some friction between moving elements, or a shudder as the wheels navigated rails on an uneven foundation. But most of the experience of movement would have been indirect. Where occupants of static buildings develop a sense of time based on the directionality of daylight entering a space, this sense of time would not be reliable in the *Villa Girasole*. Rather, time might be related to the changing view of the landscape, seen through a window (figure 4), or from the courtyard or the roof terrace. Sunlight that hit the building would warm it and it would light spaces, but moving along with the sun would make the effects persistent. We could say that the capacity for rotation makes the building sensitive for sunlight in a particular way. Being exposed to these effects, the sensitivity transfers to the occupants. The building's movements would expand their own; their enactive perception of the environment is modulated by the building, expressed in figure 2(c). There is also the possibility that the movement is stopped by pressing a button, leaving a memory in the orientation of the building. A memory that fades when the house moves on.

Figure 4. View from a window in the villa. Still from Schaub and Meili, Girasole: A House Near Verona (3:32).

5. Discussion

We have seen in the *Villa Girasole* a specific capacity for architectural movement. Angelo Invernizzi designed a villa where everything supports the building's capacity to revolve around a central point: the building's concrete frame, its lightweight facade, the central tower, the mechanical gear. The villa's movements allow it to engage in a coupling with the environment. How wind and sun affect the building is influenced by the building's movements and at the same time the building influences the visual character of the slope on which it is perched and the local climate around the house. The villa's rotation then brings to occupants an altered sense of time, based on outlook, rather than on directionality of light. And the particular sensitivity of the villa for solar radiation might expand the occupants' sense of light and temperature, affecting directly the understanding of their environment, and making it, in a sense, more building-like.

The significance of the presented framework for computational designers might lie in widening the perspective in design approaches for a new class of buildings as robots that operate highly autonomously. Rather than designing systems that might cover the full range of expected scenarios, systems and occupants could be capacitated to extend each other's reach. This may reduce the requirements of individual building systems, or more radically, it may lead to buildings that are able to deal with fundamental change beyond the scope of the underlying model. This work is not a critique of existing approaches of digital augmentation, that might serve to design and construct buildings that help alleviate some of the concerns about our collective future on this planet. However, if there is an ambition to design cognition that touches on the core of a building, and that capacitates future buildings for coping with outlier conditions of use and environmental load, we might need a broader approach that the framework of enactive architecture could help provide.

Acknowledgements

The author would like to thank the reviewers for their thoughtful and constructive feedback.

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LEARNING FROM USERS AND THEIR INTERACTION WITH A DUAL-INTERFACE SHAPE-GRAMMAR IMPLEMENTATION

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Abstract. We present a shape grammar implementation with two new characteristics. One is that it is visual and directly manipulable: users draw the shapes and rules in a modeling application. The other characteristic is advanced technical capabilities, such as non-visual attributes and higher-order elements like surfaces. It consists of three components running in Rhinoceros3d. We also report on workshops that introduced the implementation.

Keywords. Shape grammars; interaction; implementation.

1. Introduction

The shape grammar formalism was developed some 40 years ago (Stiny and Gips 1972, Stiny 1980), and the first implementation followed quickly (Krishnamurti 1982). Most subsequent implementations have attended to only the most basic technical capabilities of shape grammars: labeled points and straight lines in 2D space. Notable exceptions include the one by Chau et al. (2004), which implemented these elements in 3D space, and Grasl and Economou (2018), which implemented parametric grammars.

Numerous technical capabilities remained to be implemented: surfaces in 3D space, attributes, and descriptions, to name a few. And in addition to the technical issues, there is also the question of user interface, which has received attention only from Tapia (1999) and Grasl and Economou (2018).

We have been working on an implementation that addresses both advanced technical capabilities and the user interface. We expect that we will be able to develop it into a tool that is both powerful and congenial for visually oriented users like designers.

It consists of three components running in the Rhinoceros3d environment: a back end and two front-end interfaces. The back end handles shape calculations and subshape recognition, and works with both interfaces. One front end offers direct manipulation of points, lines, shapes, and rules; it aims to capture the visual immediacy of shape grammars. The other interface offers advanced technical capabilities, including surfaces and curved lines in 3D space, attributes, and descriptions; it aims to provide more of the technical power of shape grammars.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 153-162.

All are written in Python; the 'technical' interface is implemented as a Grasshopper plug-in. These components have been reported previously (Dy and Stouffs 2018, Li 2018).

In this paper, we briefly present the three components as well as a series of workshops we ran to disseminate the results, informally test the implementation and learn from users interacting with either interface. We then discuss our findings and suggest a way forward.

2. The implementation

The shape grammar implementation we present here consists of three components running in the Rhino modelling environment: a back end and two front-end interfaces. We briefly describe the components and their capabilities, starting with the back end. we refer elsewhere for more extensive explanations (Dy and Stouffs 2018, Li 2018).

2.1. THE BACK END

The back end consists of a code library and API developed in the Python programming language, termed the SortalGI shape grammar interpreter. The SortalGI library has been developed with flexibility in mind, not imposing any specific representation, but providing a series of representational building blocks, supporting both geometrical and non-geometrical data types, and allowing these data types to be combined into larger representations, using both object-attribute and disjunctive compositional relationships (Stouffs 2018a). For example, supporting, among others, points, line segments, plane segments and labels, points and labels can be combined into labeled points under an object-attribute relationships, while labeled points, line segments and labeled plane segments can be combined under a disjunctive relationship, allowing any of the components to be present independently of one another. Currently, the SortalGI library includes representational building blocks for points, line and plane segments, circular and elliptical arcs, quadratic Bezier curves, labels, weights, colors, enumerative values, and (parametric) descriptions, in both 2D and 3D.

In addition, each representational building block and, by virtue of the (formal) compositional relationships, each composite representation includes a mechanism to support emergence, that is, the ability to recognize a specific shape within a larger combination of unstructured geometrical elements. In fact, the SortalGI library distinguishes two alternative matching mechanisms for spatial elements. The first one supports visual emergence under transformations of translation, rotation, reflection and uniform scaling. These similarity transformations allow a square or any other figure to be recognized irrespective of location, orientation and size. Scaling is uniform and, thus, a rectangle will match any rectangle with the same proportion between length and width. Shape grammars relying on shape recognition based on similarity transformations are often termed non-parametric shape grammars.

The second matching mechanism supports associative emergence under topological constraints and associations of perpendicularity and parallelism.

Adopting a graph-based representation, this matching mechanism allows any arbitrary *n*-sided polygon to be recognized as such. In addition, if the polygon to be matched contains any parallel or perpendicular edges, these will also be considered as constraints. As such, a rectangle will match any rectangle irrespective of its proportion between length and width. There are few shape grammars, if any, in the literature that rely on associative emergence. Most are identified to require an explicit parametric matching mechanism, although there exist no general shape grammar implementation supporting any explicit parametric matching mechanism. Instead, other so-called parametric shape grammar implementations similarly rely on some form of associative emergence using a graph-based representation to support parametric-like shape grammars (Wortmann 2013, Strobbe et al. 2015, Grasl and Economou 2018).

The SortalGI API has been specifically developed to support the integration of the SortalGI library within the Rhino modelling environment. In particular, it not only acts as a programming interface providing access to the underlying functionality, but also supports the conversion of geometric data from Rhino into the SortalGI interpreter and back. Note that although the entire library is available within Rhino, the API does limit the extent of geometric and non-geometric element types that are supported, due to the need to graphically visualize the data within Rhino. The conversion procedure accepts Rhino GUIDs referencing Rhino objects and translates these into an appropriate SortalGI shape representation. Upon applying any rule to the shape, the new shape resulting from the rule application will be converted back into Rhino GUIDs to be visualized within Rhino. Note that the SortalGI library maintains a rule register and every rule is automatically added to the register. As such, rule names must be unique and rules can be retrieved from the register by name.

2.2. THE VISUAL INTERFACE

The visual interface forms part of the Rhino environment and adds to the many functionalities already available there. The user draws the components of the grammar simply as Rhino objects. In order to make these components parsable for communication to the back end, the interface needs to use some of Rhino's structural capabilities, such as layers. At the same time, we want to keep those very capabilities available to users to the extent possible. In anticipation of this tension between structure and freedom, we followed a few working guidelines.

Firstly, shapes are composed of Rhino objects, currently line curves and text dots. That is, the objects themselves are the shape; there is not some symbolic representation between the shape and the user. They are in the foreground, available for manipulation by the user, and persist between work sessions as the record of the grammar.

Secondly, the Rhino work space is divided between the system embodied by the visual interface in communication with the back end, and the user. The system needs a place to do its work, and so do users. One way we try to accommodate both system and users is by having the interface display rules and all calculated shapes in the positive-*y* half of the three-dimensional virtual work space. The other half is left for users to use as they will. The other way is by assigning rules and calculated shapes to their own, automatically named layers. This way, the system can identify rules and calculated shapes, and users can also create and name layers for their own use.

Thirdly, commands are implemented as Python scripts; users invoke a command by running a script. This is an interim measure; in future versions commands will be available through more straightforward means, like menu items.

These working guidelines are intended to make users' experience easier and more productive. Their first step is to initialize the Rhino document by running the *initialize* script, among others, creating a new layer, *Shape 0*, for the initial shape. Shapes on layers named *Shape n* are scrolled so they stay above the *x*-axis, with the newest always closest to the *x*-axis. If the document already contains a grammar, the front end reads the rules into the rule register, and users can resume using the grammar immediately. Otherwise, they should create at least an initial shape and a rule. To create an initial shape, users simply draw it with line curves and text dots in the upper right quadrant of the *xy*-plane on the layer *Shape 0*.

To create a rule, users draw in the lower two quadrants on any user-named layer. Then they run the *create rule* script, which prompts them to select: 1) the elements of the left shape; 2) a reference point for the left shape; 3) the elements of the right shape (if any); and 4) a reference point for the right shape (if not empty). The new rule becomes part of the rule register. The interface then draws the rule in the upper left quadrant on a new layer *Rule 1*. Around each of the left and right shapes is a three-dimensional frame which indicates the shape's coordinate system. The elements of the two shapes and both frames are locked in a single group for easy selection for rule application. If users draw a second rule, both rules will be scrolled away from the *x*-axis.

Having at least one shape and one rule, users can run the *apply rule* script, which prompts them to select: 1) the shape; 2) the subshape; and 3) the rule. By selecting a subshape, users can, for example, apply a rule to a single cell in a matrix (figure 1). When there are multiple potential rule applications, the system applies them all in parallel and draws the results within a row in the upper right quadrant, each shape on its own layer, scrolling them - along with all earlier generations of calculated shapes - away from the *x*-axis.

2.3. THE 'TECHNICAL' INTERFACE

Notwithstanding the many advantages of a visual interface, an alternative 'technical' interface that provides access to a larger set of SortalGI functionalities is beneficial. Hereto, we opted for a Rhino/Grasshopper plug-in (Dy and Stouffs 2018) providing a range of Grasshopper (GH) components that support the creation and manipulation of shapes and descriptions, and the creation and application of rules, including rule predicates and directives. Descriptions are semi-structured textual descriptions that can be parameterized within a description rule (Stouffs 2018b). Descriptions can also relate to spatial elements by querying their properties or specifying conditions on the values of such properties. Predicates serve to express additional conditions on the application of an associative shape rule that cannot simply be explicated within the left-hand side shape, while directives are value specifications that are required when applying an associative shape rule, where this value specification cannot be derived from or expressed within the right-hand-side shape (Stouffs 2019).

Figure 1. The workspace of the visual interface. Left: The rule (with frames around the two shapes) is in the upper left quadrant, while the initial shape (the 16 squares) is in the upper right quadrant. The two shapes in the lower right quadrant are the shapes drawn by the user to define the rule. Right: Given the 16 squares, the same rule is applied 16 times, with the last 3 generations shown here; the first 13 generations are scrolled away from the x-axis.

While, in principle, the visual interface can also support these additional features, the important question is how these functionalities can be integrated visually in a way that doesn't impede the designer. In the GH interface, on the other hand, it is simply a question of adding one or more GH components. As such, additional functionalities can easily be tested and explored and provided to designers who are willing to put up with a non-visual interface. Note that the GH interface requires no literal programming or scripting, although creating a GH model can be considered as a form of visual programming.

The plug-in supports both "non-parametric" and associative rules, shapes including points, line segments, plane segments, circles, ellipses, (circular) arcs and quadratic Bezier curves, both with and without description attributes, and stand-alone descriptions. Descriptions serve to represent both labels (within double quotes) and more general descriptions (see section 2.1).

The plug-in defines both a rule object and a shape object. A shape object contains up to three components, the SortalGI representation of the shape, the Rhino visualization of the same shape (minus stand-alone descriptions), and any stand-alone descriptions. Stand-alone descriptions are necessarily typed, the predefined description types are specified as input to the *Setup* component. Shapes can be constructed using either the *Shape* or the *dShape* component, the latter allowing for the specification of stand-alone descriptions. Both components accept an optional reference point, allowing the left-hand-side and right-hand-side shape of a rule to be specified at different locations while relating them via their reference points. Attribute descriptions can be added to any geometry using one of the *Text Point*, *Text Curve* and *Text Surface* components. In addition, there exist components to move, rotate, scale and mirror a shape object, as well as find the sum, product (intersection) or difference (complement) of two shapes.

A rule object is either a “non-parametric” or an associative SortalGI rule. The *Rule* component constructs a “non-parametric” rule from a rule name and a left-hand-side and right-hand-side shape object. Similarly, the *pRule* component constructs an associative rule and additionally accepts a list of predicates and directives (see section 2.1). In each case, only the right-hand-side shape is allowed to be an empty shape.

There exist four components to apply a rule object onto a shape object. The *Apply* component returns a single rule application that can either be randomly selected from all possible rule applications or using a rule application index. The *Apply All* component yields a list of shape objects corresponding to all possible rule applications. The *Apply All Together* component applies all possible rule applications in sequence, ignoring the fact that some elements that would be required for rule applications may not be present anymore after the first possible rule application is performed. Finally, the *Derive* component accepts a list of one or more rule objects and applies these in sequence, each on the result of the preceding rule application. Here too, the specific rule application can either be randomly selected from all possible rule applications or using a rule application index. All four components also accept an optional subshape object to limit potential matches. Rule application is always performed on the entire shape, not the subshape. In the case that no rule applications can be found, the original shape is returned, such that any consecutive rule application component may still execute.

Additionally, a *Matches* component returns not the rule applications, but a list of the matched shapes that give rise to these rule applications. This allows, among others, for a divide-and-conquer approach, collecting the list of matched shapes, then performing a series of rules onto each matched shape separately, in order to increase efficiency. All application components, including the Matches component, also return a translation vector or list thereof for visualizing the resulting shape(s) aside from the original shape (in the *x*-direction) and separated (in the *y*-direction).

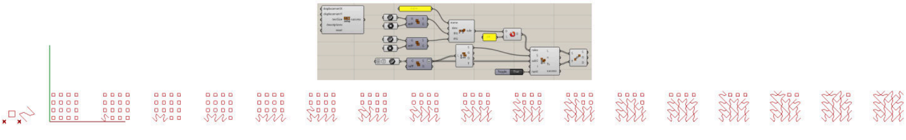

Figure 2. Working with the ‘technical’ interface. Top: The GH interface illustrating the basic template of rule specification: collecting the Rhino geometries, defining the left-hand-side and right-hand-side shape objects and defining the rule object, upon which the rule can be applied. Bottom: The Rhino workspace including the rule shapes and initial shape drawn by the user as well as the sequence of rule applications resulting from the ‘SGI Derive’ component.

3. Informal testing

In order to understand how designers would work with the interpreter, we ran three workshops with the two interfaces in different combinations: first the 'technical' interface, then the visual interface; first visual, then 'technical'; and, finally, 'technical' only. Most participants were design students with little or no previous exposure to shape grammars.

3.1. CAAD FUTURES WORKSHOP

In June 2019, we ran a four-day workshop before the CAAD Futures conference at KAIST, Daejeon, South Korea. The first two days were devoted to the 'technical' interface, the third to the visual interface, and the fourth to scripting for direct communication with the back end. One difficulty was that most participants had little or no experience with GH and therefore had to learn both the 'technical' interface and GH at the same time. Another difficulty was that all examples presented were constructed entirely in GH, resulting in models that were difficult for novices to understand.

Under these circumstances, the visual interface seemed particularly easy for users to grasp. Not only could they manipulate objects directly (e.g., by drawing them), but they had fewer capabilities (in terms of actions, matching, and data types) to deal with.

3.2. YUNTECH WORKSHOP

Two months later, we ran an eight-day workshop at National Yunlin University of Science and Technology (aka Yuntech), Taiwan. In this workshop, we presented the visual interface before the 'technical' interface. We also took advantage of the ample access to laser cutters and 3D printers.

Using the visual interface, and inspired by figure 1, the first exercises focused on using just one or two rules to apply to each cell of a square grid and to materialize the outcome as laser-cut coasters. By relying on just one or two rules to create interesting results, participants came to understand matching under similarity transformations, especially with respect to symmetries, and were able to iterate the process by simply updating or replacing a single rule. In fact, the physical materialization of the outcome greatly benefited the iterative process because of the different representations (drawing and physical object).

Halfway through, we switched to the 'technical' interface, but maintained the habit of drawing the rule's shapes in Rhino; then we used a GH template to collect the Rhino information and construct the left shape, the right shape, and the rule (e.g., figure 2).

We tried two approaches. The first was a 3D extension of the coasters, using a 3D grid and one or more 3D rules. The other was a recursive or fractal approach, in which one or more rules were applied iteratively through self-similarity. Both approaches are feasible with both interfaces, so the emphasis fell on the interfaces and how best to use them. Participants sometimes used additional functionality, including actions such as derivations, associative matching, and data types such as labels.

3.3. ECAADE + SIGRADI WORKSHOP

Subsequently, the first author ran a two-day workshop before the eCAADe + SIGraDi conference at the University of Porto, Portugal. In this workshop, participants used only the 'technical' interface. Learning from the previous workshops, he continued the approach of drawing shapes in Rhino and then from those shapes constructing rules in GH. Compared to the other workshops, there were fewer participants, and most of them had had previous experience with GH.

On the first day, participants used the similarity-based matching mechanism; on the second, associative matching. The rule sets were small, but participants were able to apply rules both in parallel and sequentially, and thus explore forms extensively (figure 3).

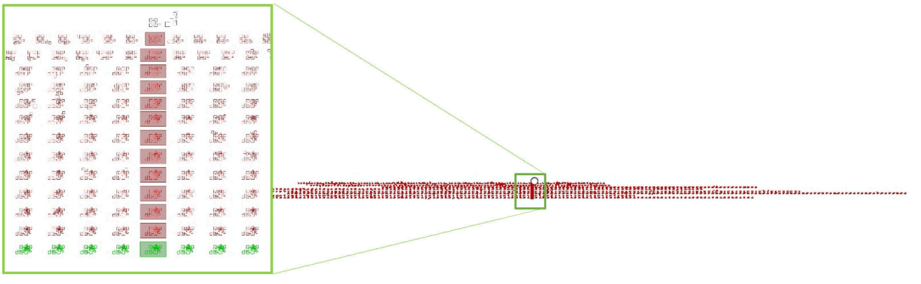

Figure 3. Exploration of forms using the 'technical' interface in a combination with other GH functionality (image courtesy of Šimon Prokop).

4. Discussion

Our observations of users come from workshops, not rigorous tests, but we believe that these observations suggest some lessons.

4.1. SHAPE GRAMMARS AND THE INTERPRETER IN THE LARGER DESIGN PROCESS

One lesson is that fabrication seems to complete a design iteration for users. It makes the virtual real, and gives designers another representation to evaluate. Furthermore, in such an iteration, the interpreter is used in combination with other tools in the Rhino environment.

Our aim is to create, not a pure shape grammar environment, but a tool for designers. And as Woodbury (2019) observed, designers are pragmatic and concerned more with results than with technical niceties. We aim to support designers, pragmatism and all, and we do so by embedding the interpreter in an environment that is rich in design tools. We help them generate designs rapidly and do not insist on, say, organizing those design according to a derivation tree. The derivation tree, of course, is a construct interesting to theoretical types like the present authors, but so far no user has ever asked about it.

4.2. THE RELATION BETWEEN THE TWO INTERFACES

The second lesson is similar to the first, as it also involves a tension between the two interfaces, specifically the complementary trade-offs they offer between immediacy and intuitive obviousness on the one hand and technical power on the other.

Of participants using the 'technical' interface, there were a (very) few who were familiar with both GH and shape grammars. Those participants were able to operate somewhat non-visually and, as with Rhino, see the SortalGI plug-in as adding to the many functionalities already available in GH (figure 3). They were able to consider higher-order issues like grammatical algorithms (Stouffs and Hou 2019). But they were a minority; most participants were not 'power users'.

This suggests that there is more than one type of user, and that we should consider how to fashion the two interfaces to accommodate as many types as possible. For example, some novices may be happy to remain novices as long as they can generate designs easily. But others may want to become power users. How can the visual interface help both types?

Should we aim to make the visual interface more powerful? Can we do so without compromising its immediacy? Or should we maintain both interfaces side by side? This may seem the more obvious approach, but we need more experience to be sure.

5. Conclusion

The two lessons above suggest that we still have much to learn about how designers use a shape grammar interpreter in their work. We will continue this process of development and informal testing in hopes of enabling designers to work easily and effectively with grammars. Having mainly solved the technical part, the emphasis is now on the human/designer.

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EXTRACTING AND COMMUNICATING UNDERLYING PSEUDO-FORMALISED PROCEDURAL RULES IN HERITAGE ARCHITECTURE

The Case of New Zealand's 19th Century Timber Churches

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Abstract. The research employs procedural modelling to investigate the characteristic rules present within a loosely defined architectural style. The 19th-century timber neo-Gothic churches built in the city of Wellington, New Zealand are examples of a particular interpretation of the Gothic Revival style. Although they all share common aspects, no prescribed rules are regulating how these churches were designed. This research explores a methodology for creating a procedural 'Timber Gothic Church Generator' that is generated from an understanding and interpretation of the design of the buildings examined. Once developed the procedural generator can be used to extrapolate, and produce other church designs as well as create hybrid designs. These outputs can be further refined through the creation of parametric rules. A key result of this methodology is to explicate better otherwise ambiguous design philosophies that are shared between the similar buildings. It shows how a design can be reverse-engineered and converted into procedural logic. The research establishes the process and logic to enable the creation of further rules to be explored.

Keywords. Digital Forensics; Digital Heritage; Gothic Architecture; Houdini; Procedural Modelling.

1. Introduction

The preservation of architectural heritage has utilised many different methods as computer-mediated design technology has developed. In the digital age, 3D digital reconstructions for both existing and lost architectural heritage have become increasingly employed to enhance critique and understanding of aspects of cultural significance (Brown and Webb, 2010). In particular, building types with pseudo-formalised rules such as ecclesiastical buildings, valuable and useful findings can result from such analysis, as shown by Webb and Brown (2016). Such developments are closely intertwined with the increasing capability of the 3D modelling software used to create the reconstructions themselves.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 163-172.

Work such as Novitski's 'Rendering Real and Imagined buildings' is an early example of digital reconstructions using Computer-Aided Design (CAD) software to create the geometry, and hint at materiality (Novitski 1998). However, some researchers have more recently employed 'Procedural Modelling' for their heritage reconstructions. Procedural or 'generative' design within the field of architecture describes the creation of forms and relationships that respond to a standard ruleset defined by the designer. Some of the earliest and most prominent examples of such a design process include the work of Vitruvius and Palladio. The processes and rules they espoused is defined within their written texts but not always strictly followed in the created buildings. In the digital age, this exploitation of the geometrical relationship has thrived and uses the increased computational power of technology to define and test these underlying procedural rules more comprehensively than ever before

2. Related Work

The book 'Possible Palladian Villas' by Hersey and Freedman is an early example of using procedural systems to represent and analyse architectural heritage (Hersey and Freedman 1992). The research looked at how 2D plans and façade elevations could be procedurally generated to create designs that mimicked that of Palladio. The procedural system was created using both rules described in Palladio's texts and from analysis of his villas, with this interplay sometimes revealing contradictions between the two. Although its outputs are simple, the resulting 2D programs give exact rules that are common within Palladio's designs, eliminating any subconscious bias that could skew the analysis. The authors mention this, as they state "because of the rapidity and completeness with which it [the software] can apply these rules, it can test them on a far wider and firmer basis than could an unaided human being".

Recently, however, procedural modelling has grown in popularity particularly within the game and film industry, spawning such events as 'PROCJAM' (2019). One of the main reasons for this is the efficiency of the technique. It can create a large amount of varied geometry relatively quickly compared to traditional modelling means.

The work by Parish and Müller (2001) shows key developments in procedural modelling software over the years, as they developed 'CityEngine', and then later Müller et al (2006) developed 'CGA shape'. CityEngine populates a given topography with buildings defined by the rules a user creates. The accuracy of the created buildings was limited, however, as the software was intended for large scale, low detail visualisations. CGA shape (Computer Generated Architecture) was developed in regards to this problem and is focused on creating individual buildings with more geometric rules. The combination of these software environments enabled researchers to create a reconstruction of Pompeii with reasonably high levels of detail at the street level, even considering the large scale of the project (Müller et al 2005).

In contrast to shape grammar approaches, node-based software such as 'Grasshopper3D' and 'Houdini' allow users to create custom procedural systems using a friendlier interface than that of traditional coding applications. The research by Kramer (2019) showcases the use of the Houdini to create a procedural model of American second empire houses. Kramer used both data from existing examples as well as 19th-century descriptions of the variations between the houses and how to build them. The outcome was a digital asset that could be adjusted via custom parameters to change the design of the second empire house. It allows both hybrid designs to be created as well as making a speculative design for lost examples both easier to model and more historically accurate.

The research presented here explores a similar method of modelling, as found in Kramer's work. Houdini is used to creating a procedural model of a specific style of building; The 19th Century timber Gothic Revival Churches of Wellington, New Zealand. However, the style we have selected is a blend of local and international styles that have less defined rules than that of the research previously mentioned. Our research is therefore centred more on the methods of extracting the unique rules present within these churches. To do this a comprehensive procedural system much the same as seen in Hersey and Freedman's work is attempted, except in 3D.

3. 19th-Century Timber Gothic Revival Churches

Gothic Cathedrals stand as artefacts from the times of medieval Europe. However, during the Gothic Revival in the 19th century, Britain was expanding its empire and sought to build new churches and cathedrals in colonised lands. The neo-gothic design was a standard for church architecture, and new settlers sought to replicate this tradition. However, the conditions in these newly settled locations often varied greatly to that of their homeland. Available building materials were also different and settlers took the pragmatic approach of using timber instead of stone to build their churches.

It was a crucial difference in the eyes of religious academics. In the article 'Wooden Churches' that was published in in the journal 'The Ecclesiologist', it stated that "We do not think these churches are in any respects good models of construction" (Turner 2014). It was predominantly due to the central motif of the style - the pointed arch - being a structural form that enabled stone cathedrals to be built taller. When the form is translated into lightweight timber construction, it becomes structurally redundant, leaving the pointed arch to become merely a decorative feature. This rejection of timber did little to stop settlers from building with it, and only fuelled the differences between Gothic churches built of stone to that of timber.

This aspect is a crucial difference in our paper. In the related work previously mentioned, researchers began with a collection of buildings that were already identified as belonging to a distinct style, with there being descriptions available on the rules that were used to create them. Nevertheless, for Wellington's timber Gothic Revival churches, there has been significantly less discussion and analysis of the designs. It is due to the nature of the early days of the colony, as there were little precedent and literary expertise available for architects to form the basis of their designs. Such an environment enabled the free interpretation of the neo-Gothic style within Wellington, spawning bespoke designs that somewhat refer to other designs in the area, but no set criteria. The goal of this research is to create a system that can investigate these rules. Whether deliberate or unconscious, the similarities between the 20+ designs were formed from a process that is unique to its environment and cultural mechanisms. We aimed to create a procedural model of these designs so we could compare them and begin to identify the developmental patterns these churches underwent.

4. Creating the Initial System

To create a procedural model of Wellington's timber Gothic Revival Churches, we began by firstly breaking down the buildings into their basic shapes/areas. By comparing the different combinations of spaces within the churches, it became clear that there were many variations between designs (Figure 1). The only distinct commonality between these designs is that they all centre around the central space of the nave, with other spaces such as the aisles, sanctuary and transepts connecting into it.

Developing further from these main shapes, the architectural details present in these areas were further categorised into additive and subtractive components. Additive components consisted of the various buttresses, parapets and eave details that are added on top of the basic shape; whereas subtractive components consisted of details that carve into the shape such as the windows and doors (Figure 2).

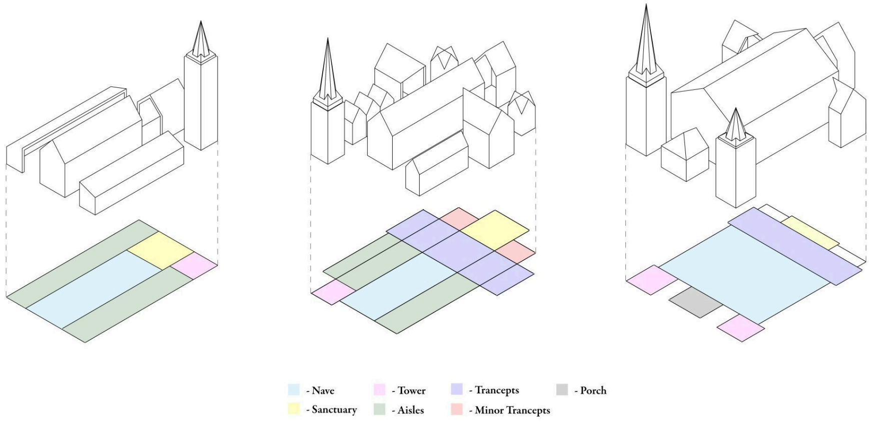

Figure 1. Spatial analysis of St Mary's, Old St Paul's & St Peter's Churches.

Houdini was then used to create the digital procedural models of all the component categories. The visual code that creates the 3D geometry is grouped within each category type much the same as it is organised in Figure 2. For each category, parameters that are used to construct the geometry can be promoted so that they are always adjustable. As shown in Figure 3, parameters such a length, height and wall thickness can be promoted so that they can be adjusted to create other designs. With there being a similar number of parameters for the other categories, all of them culminated into a single 'Master switch' node, which hosted over 240 individual parameters.

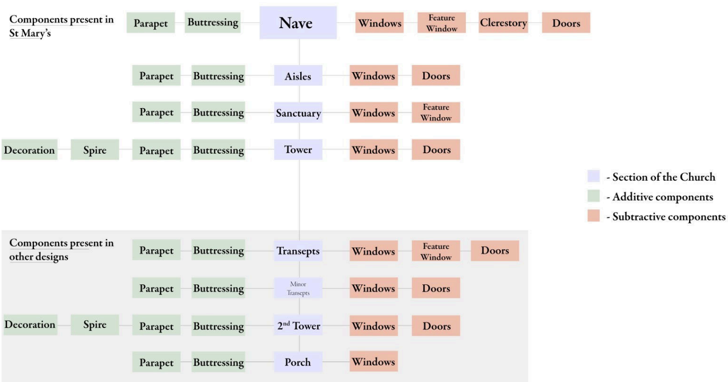

Figure 2. Breakdown of spaces and detail components, comparing one design's makeup (St Mary's Cathedral) to the other possible components in different church designs.

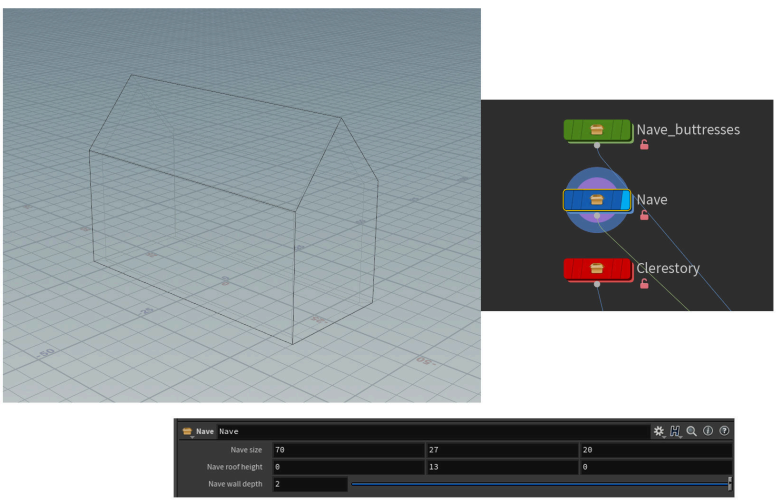

Figure 3. List of adjustable parameters for the nave component node.

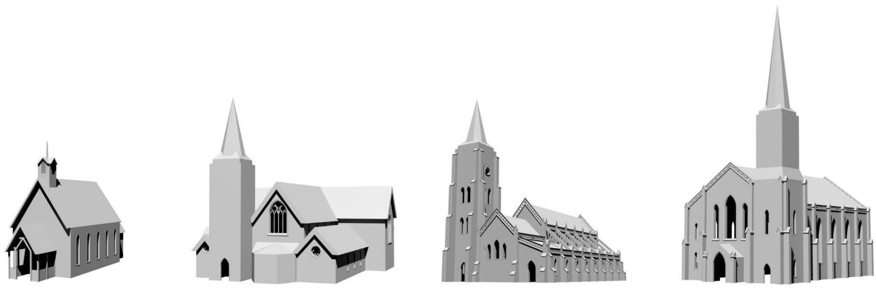

Figure 4. Initial designs the procedural system could create (Christ Church Taita, Old St Paul's, St Mary's Cathedral, & St Peter's Churches.

The procedural system started as a digital reconstruction for just one church design. However, in attempting to recreate other churches using the same system, more architectural components were added, and existing components were refined to become more adaptable. At this stage, the system could create 3D visualisations of four churches (Figure 4). These were selected for reconstruction as they were all significantly different from one another and would enable the model to become more flexible and reliable for further development.

5. Speculative Design Capabilities

Having established the procedural system to create multiple existing designs, we tested what else it could build. As timber is prone to fire, many of Wellington's Gothic Revival churches have been lost over the years. Of the 20+ designs that were researched in this paper, less than half of them survive. The age of these buildings also makes it difficult in some cases to retrieve accurate documentation. One of the ways of piecing together such gaps in information is to look at similar designs from the same architect or period. It has been seen in other architectural heritage research such as the reconstruction of Lutyens' Liverpool Metropolitan Cathedral by Webb and Brown (2016).

The Manners St Wesleyan Church was built in 1869 by Architect Charles Tringham. It burnt down in 1879, and from this research, only one close-up photo of it still survives. This photo only shows the front façade and gives little insight to both the side and rear of the church. Despite this lack of information however, a simple digital reconstruction was able to be created by the procedural system (Figure 5). This is because of the high similarities the lost church shares with the still existing design of St Peter's. St Peter's was designed by another architect Thomas Turnbull. He also designed two more similarly constructed churches. These churches all adopted an enlarged nave space that was supported by buttresses either side. Such a design was not seen in Wellington before Tringham's, making it plausible that the Manners St Wesleyan Church was a direct influence on Turnbull's church designs. Following this line of inquiry, it was assumed that the main nave space of St Peter's could be supplemented into the lost church's reconstruction. In identifying these churches as being descended from each other, a more holistic speculative model can be created combining multiples streams of historical evidence.

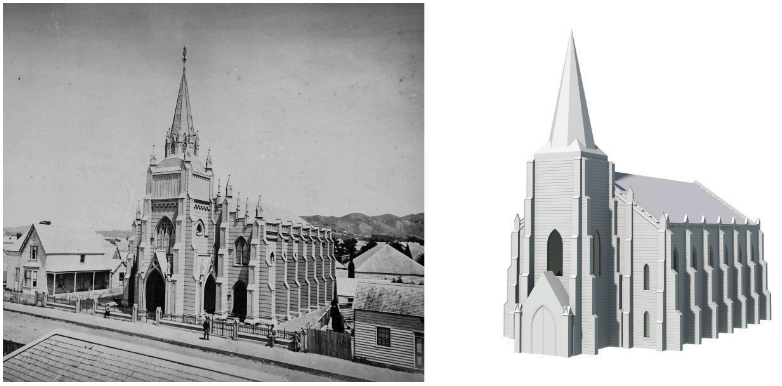

Figure 5. Photo of the Lost Manners St Wesleyan Church and its basic reconstruction using the procedural system. (Wesleyan Church, Manners Street. Ref: 1/2-002324-A-G. Alexander Turnbull Library, Wellington, New Zealand. /records/22576295).

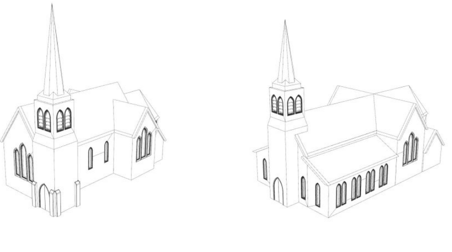

Figure 6. Reconstructions of the lost St James's and Turnbull's St Patrick's Churches.

For some of the Wellingtons churches, the people responsible for designing and building them are not recorded, leaving it open for speculation. One such design is the lost church of St James's in Lower Hutt, near Wellington. Comparing it to other timber neo-gothic churches in Wellington, one of the most interesting details is the design of the tower, specifically the bell vents. It is seen prominently within Turnbull's church designs. In investigating Turnbull further, it was found that another church of his - St Patrick's in Masterton, New Zealand - also bore a resemblance to St James's, having the same distinguishing bell vents. Through the act of reconstructing and comparing both of these designs (Figure 6), it was found that they shared other similarities too, such as the same transept windows, sanctuary design and general layout. From the analysis enabled by the procedural system, it would be plausible for St James's to have been either designed to resemble a church of Turnbull's or Turnbull himself designed it.

6. Creating a Fully Procedural System

Although the research up until this point has used procedural modelling, and entirely procedural system that outputs timber Gothic churches was still yet to be created. The system was closer to a parametric model than a procedural one, as new churches were created by adjusting the parameters by hand, often causing the system to produce distorted geometry. An entirely procedural system automates this process.

First, the user-controlled parameters needed to be supplemented by the computer. It was achieved by using nodes within Houdini to create an interconnected switch system that changed the value of a parameter from a user-entered one to a random or predetermined one. The use of coding languages such as VEX or python within Houdini would likely be a more efficient means of creating such a system, but this method worked very reliably nevertheless. The effect is a digital model that can still be controlled by hand to create custom designs, but when the switch is changed, it produces a hybrid/randomised church. The process of linking all the parameters to a random or predetermined value is where the rulemaking and testing begins.

The goal while creating the initial fully procedural system was to get it to produce random designs reliably simply. It is the current system, and at this stage, it does not account for any specific underlying rules, simply producing hybrids of the church designs it has already learnt to model. In our paper the creation of this initial system is further discussed, leaving the exploration for the underlying rules of the timber Gothic churches themselves for future research.

In the current system, the length for the nave component has been set to produce naves between 35 and 96 feet long. These restrictive values were based on the churches that the system could already build, giving an initial range. Set values control other parameters. However, when a church is generated the number of buttresses on the nave is set between 4 and 8, as that was the range within the examples the system could already build. The spacing between the buttresses, however, is predetermined by the length of nave divided by the number of buttresses, meaning that no random number between a range is needed.

This consolidation of parameters is where the refinement of the system can be achieved. Many of the current parameters are connected to random numbers when they perhaps should not be. For example, the number of buttresses on the nave and aisles are determined individually, making them often different when in reality, this would rarely happen. It is a similar case for the proportions of the churches too. The values for a generated church's nave height, roof height and length are created individually and between the ranges set by the examples, it can already build. The examples consist of the large size of nave churches such as St Peter's to the small Christ Church in Taita, near Wellington. These two opposing designs allow the system to create large nave designs with the width and roof height of a small church, something that again would never happen in reality.

Such mistakes are why the current outputs are so commonly odd and disproportioned as can be seen in Figure 8. A possibility for the further refinement of the system would entail the creation of multiple systems, one that produces large size nave variants, and one that produces the smaller designs with the added components of the more traditional aisle and transept designs.

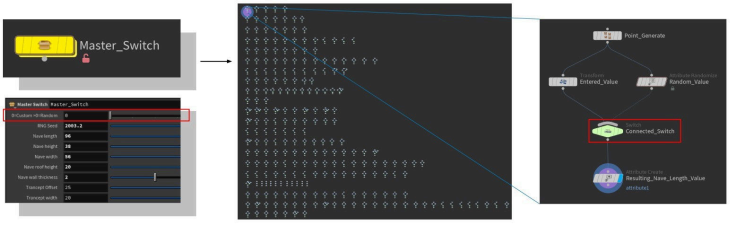

Figure 7. Diagram showing how the user controlled parameters were made fully procedural within the master switch. Red highlights the switch mechanisms controlled from the outside of the master switch node .

7. Conclusion

Our research has shown that procedural modelling, when applied to the field of Digital Architectural Heritage, offers many potential applications. The visualisation helps in a better appreciation of lost or damaged architecture. In order to create the procedural model, the underlying rules and processes have to be understood and extracted. It gives enhanced information that substantially improves architectural analysis and critique.

For us, one of the most significant aspects for the creation of a procedural system is that extraction of rules from multiple different - but related - designs of a specific style can be brought together to interact. The procedural design process of gathering historical data and categorising all the various components creates a rigour that can allow for comparison, analysis and conjecture.

The fully procedural ‘Timber Gothic Church Generator’ that was created gives a potentially robust process; from the analysis of the common characteristics to the application of the rules and testing of outputs. More details of our instrument can be found at www.dara.digital. Future work entails a more in-depth exploration of further cases, refinement of procedural rules, explication of more challenging geometric relationships and an enhanced rule-making process within the fully procedural system.

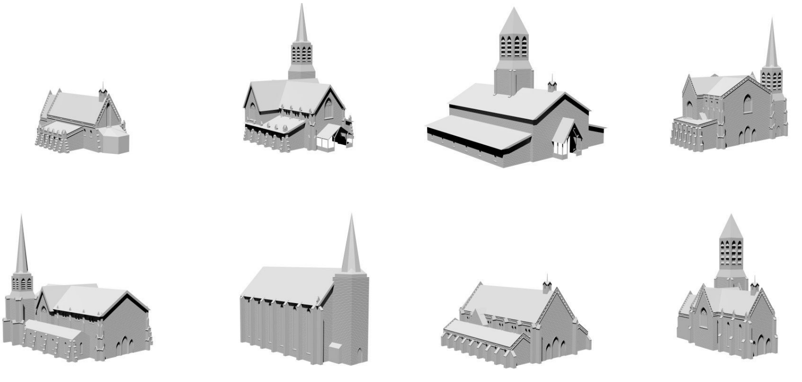

Figure 8. Examples of the current outputs of the fully procedural system.

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INHABITING ‘PROSPEROUS SUZHOU’ THROUGH SMART VR

Interrogating an Ancient Artwork and Documents to manifest Tangible and Intangible Heritage

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Abstract. The research investigates digital landscape heritage. It focuses on the application of Virtual Reality (VR) in a game engine. The aim is to aid the understanding and interpretation of ancient principles relating to sensitive and appropriate interaction of the built form and its associated landscape. The principles have at their root harmony of human inhabitation, the built forms and the landscape they are surrounded. This understanding can lead to re-application within a contemporary context, and the VR environment has the potential to augment and enrich it. For the first time ever, the research has reinterpreted a classical depiction of Suzhou, in an 18th-century handscroll painting, into a three-dimensional immersive virtual environment. It proposes that VR can be a way to experience and increase understanding of heritage landscapes; in our case one that now only exists in an ancient idealised painting. The reinterpretation aims to enhance the users’ experience and understanding of the Tangible and Intangible Cultural Heritage. The spatialised scene is augmented through the integration of other historical information, such as poems and travel notes, to embed intangible aspects into the gardens and landscapes.

Keywords. Digital Heritage; Cultural Landscape; Painting Reinterpretation; Immersive Environments; Virtual Reality.

1. Introduction

In China today, there exists a particular nostalgia for ancient values and practices. Such desires are often satiated by mental visualisations instigated by indulgence in China’s classic poems, paintings, or by visiting many of its ancient scenic locations. In reaction to this demise, a newfound interest in the resuscitation of these once disregarded entities is arising within contemporary Chinese society. The Built Heritage Journal was launched in China in 2017 noting that “There has been significant interest in both digital heritage and cultural landscapes over recent years, the junction between the two, however, remains essentially

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 173-182.

under-explored" (2019). Our case study, Suzhou, is a heritage city; it has the most UNESCO recognised gardens in the world. There are several examples of tangible and intangible heritage, acknowledged by UNESCO, such as Scholar's Gardens, Suzhou Grand Canal and Kun Opera (Sun, 2004). Suzhou is a landscape city, a picturesque landscape, where the classical gardens reflect the features and character of Suzhou (Chen, 2016). The complexity of the associated cultural history is difficult to depict fully through traditional modes of representation. Virtual heritage, propagated through new-media is able to influence awareness and better understanding of our cultural heritage (Aydin & Schnabel, 2016; Brown et al., 2005; Cameron & Kenderdine, 2007); and the potential for the 2D panoramic city painting as an initial inspiration for a 3D interactive environment has been explored by Brown et al. (2008). Our research seeks to reinterpret a classical depiction of Suzhou in an18th-century handscroll painting through an immersive, virtual medium. 'Prosperous Suzhou', is a product of twenty-four years of Xu Yang's labour, is an outstanding piece of cultural heritage, illustrating Suzhou's bustling ancient urban-scape. The handscroll is twelve meters in length. The handscroll vividly depicts the visual appearance of the daily life, natural and urban landscape in an area covering across the city (Qian, 2010). Most of the sites in the painting have disappeared. We focus on the lost heritage garden - 'Suichu Garden'.

2. Methodology

The reinterpretation process can be summarised as being in two components, the site context and the site content. Context refers to the geometry and built forms and landscape in the world, whereas content includes social and cultural heritage. The urban landscape represented in the painting is examined to enable intelligent reinterpretation. 'Suichu Garden' provides a particularly good opportunity to spatialise and visualise the tangible, and intangible, traditional design characteristics. 'Spatialisation' requires the third dimension, absent from the painting, to be intelligently inferred in the 3D environment created. The spatialised scene is then augmented through the integration of other historical information, such as poems and environmental sounds, to capture intangible aspects. To structure the heritage content and set up the scenes to guide the user in the Virtual Environment, 'Mise-en-scene', is used to translate the painting's sequence and set up content. Additionally, to improve the atmosphere and immersive qualities of the scene, appropriate sound cues, a day-night cycle, animations, and virtual interactions, derived from historical artwork and written information, are added. The additions result in an assemblage of sensory experiences that enhance understanding of the intangible aspects of the culture. Finally, after the context and content reinterpretation, we aim to manifest the rich cultural composition created between context and content, built form and associated landscape, as well as the tangible and intangible aspects. An aim is to enhance the VR-user's understanding of heritage garden design principles. To transfer these two-dimensional drawings into a three-dimensional space, a range of software including 3DS Max 2019 and Rhino 6 are used. The resulting VR environment involves the embedding of these aspects generated in different software environments into Unity 2018.3. The environment is made smarter by embedding scripted interaction that explicates Chinese garden design principles. Overall, we observed that the immersive and interactive virtual reality environment enhances the user’s experience and understanding through the informed interpretation of both tangible and intangible.

3. Chinese Scholar’s Garden

Our research showed specifically that it integrates poetic and artistic themes in line with Chen’s general observation “The classical garden of Suzhou...it is a ‘three-dimensional picture, a silent poem and a frozen music”’ (2016). Suichu Garden (figure 1), was notable for its extensive book collection and superb landscape design. It was owned and designed by Quan Wu, and his family had been collecting books for four generations (Yun, 2017). The garden was sited in Mudu town, the last official documentation of the garden was in 1950 when there were just a few original buildings and landscape left (Wei, 2019).

Figure 1. ‘Suichu Garden’ (section of the painting “Prosperous Suzhou”, Xu, 1759).

4. Heritage Garden Context Reinterpretation

This section discusses how the context of the heritage garden was reinterpreted. Context refers to the geometry, built form and space. Information was sought for this by interrogating both the artwork and written documents. This reinterpretation process can be divided into three steps: dimension measurement, architecture exploration and landscape exploration.

4.1. DIMENSION MEASUREMENT

To represent heritage carefully and precisely, it was necessary to represent the correct dimensions of each component as far as possible. In ‘Prosperous Suzhou’ the painter used the oblique perspective projection to draw the buildings; an initial question was whether it is ‘cavalier’ or ‘cabinet’ projection. Through the analysis of the painting’s techniques, it was discovered that this painting uses ‘cabinet oblique’ projection. This information assisted us to confirm the distance, scale and proportion of each component to an acceptable level of accuracy. This data was then converted into a plan and from this a 3D model was developed.

4.2. ARCHITECTURE EXPLORATION

The painting is finely detailed; however, it is initially challenging to fully understand the design decisions; for instance, what drove the geometric and spatial relationships, and why were the components arranged in this way? There needed to be more resources consulted to determine the details, such as the areas, functions, and human habitation within the garden. The research discovered six important references: 'Mudu Magazine' by Zhang Yuwen, 'Wenxianjia Tongkao' by Zhengweizhang, 'Suichu Garden Journey' by Shen Deqian, 'lvyuan Conghua' by Qian Yong, 'Poetry for Collections' by Ye Changzhi, and 'Xu' by Xu Taozhang. These written documents helped us to confirm the name of each component (figure 2) and consequently link built form and landscape designs. After gaining a basic understanding of the garden arrangement and the different segments, it was necessary to understand the associated activities and design details, to improve the user's experience and understanding in the virtual environment. Analysing precedents, helped in supplementing the details that the painting and written documents were deficient in. The existing physical model of a 'Complementary Hall' from the Kun Opera Museum helped inform the modelling of details (figure 3). The 'Mindfulness Library' (figure 4) interior design is not seen in the painting, and there are no historic written descriptions. Here, borrowing design elements from appropriate references was a successful approach.

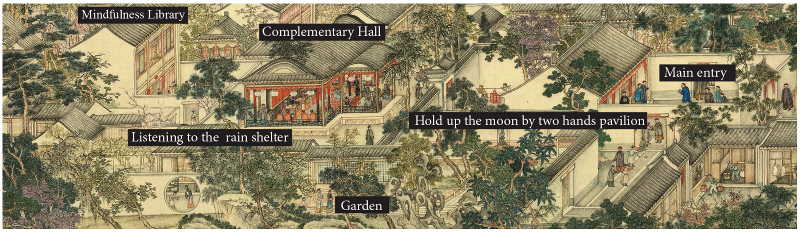


Figure 2. Naming each component of 'Suichu Garden'.

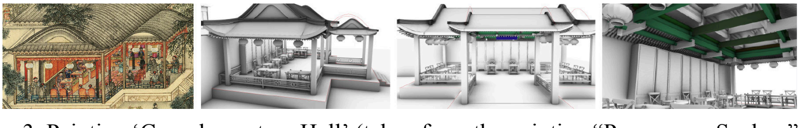


Figure 3. Painting 'Complementary Hall' (taken from the painting "Prosperous Suzhou", Xu, 1759) and Digital model (by author).

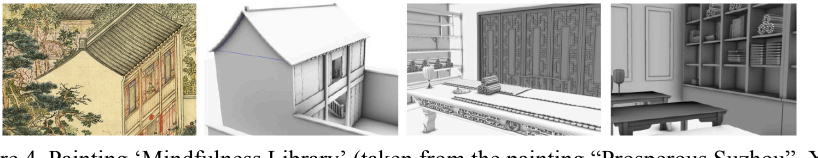
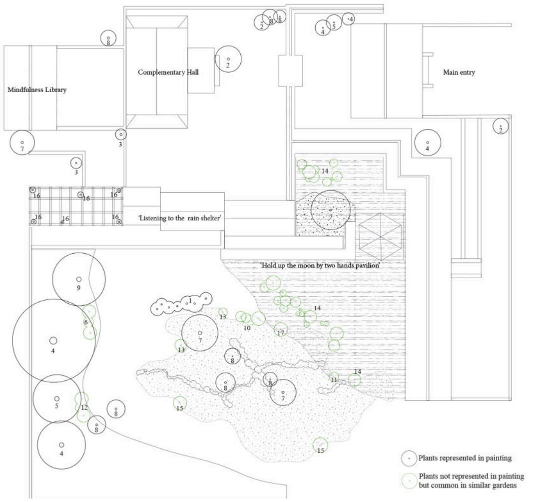


Figure 4. Painting 'Mindfulness Library' (taken from the painting "Prosperous Suzhou", Xu, 1759), and Digital model (by author).

4.3. LANDSCAPE EXPLORATION

Rocks, water and plants are three main design elements in the scholar's garden. The main theme of such Chinese gardens follows nature; in particular the harmony between human and nature (Wu, 2017). Extracting the design of the rockery and water is possible from the painting. However, from the historical written documents, it was found there was more planting than are shown in the painting. Therefore, planting study and analysis from the written document is crucial to augment the plant reinterpretation. Through reviewing the references, a possible plant table was made. The plants were then studied to determine which would have been popular in an 18th-century scholar's garden. The researcher then identified the plant species in the painting using the plant tables. The speculative planting plan (figure 5) locates the trees that are shown in the painting. The arrangement of shrubs and herbs have been informed through the analysis of similar gardens. For example, the Hardy Banana plant, with broad flat leaves has been located close to the 'listening to the rain shelter'. Notably, in the 'Humble Administrator's Garden' nearby there are several Hardy Bananas next to a similar pavilion.



Reference Number	Botanic Name
1	*Bambusoideae*
2	*Celtis sinensis*
3	*Prunus mume*
4	*Firmiana simplex*
5	*Magnolia denudata*
6	*Musa basjoo*
7	*Pinus* species
8	*Osmanthus fragrans*
9	*Punica granatum*
10	*Fatsia japonica*
11	*Hedera helix*
12	*Lilium candidum*
13	*Nandina domestica*
14	*Nymphaea nelumbo*
15	*Pyracantha crenatoserrata*
16	*Rosa chinensis*
17	*Trachelospermum jasminoides*

Figure 5. Speculative Planting Plan.

5. Heritage Garden Content Reinterpretation

This section focuses on manifesting heritage content that represents social heritage, human behaviour, along with tangible and intangible aspects. The content is often intentionally designed to form a narrative, the arrangement of a sequence of activities (Chen & Kalay, 2008). As Water (2014) suggested, the narrative is necessary because their value in heritage conservation; they convey the significance of places and it is through stories that people express their identification with heritage (as cited in Hoeven, 2019, pp. 61-68).

5.1. VIRTUAL ELEMENTS

This paper borrowed from filmmaking the idea of Mise-en-scène to set up all the elements, such as 'actors', lighting, sound, and costume, in the virtual environment. Actors and costume were extracted from painting, the lighting system is set by scripting, and the sound is represented by the digital aural landscape.

5.1.1. Aural Landscape

Aural landscape plays one of the most significant roles in the Chinese garden. It is important in the Scholar's Garden as it follows Taoist concepts of returning to nature and seeking close integration with natural scenery. The 'Book of Poetry' (11th to 7th centuries BC) is the oldest existing collection of Chinese poetry; 28% of poetry is related to aural landscape (Wu, 2012), demonstrating the importance of the soundscape. So, the aural landscape, such as insects, birds, rain, music instruments and water, were set up in the virtual environment. Through these intangible aspects, a narrative can be generated for the user in VR.

5.1.2. Animation

In the virtual environment animation is crucial because it enables designers to tell stories and communicate emotions and ideas in a unique way. It can help connect people to the depicted scene in a way that paintings cannot.

5.1.3. Painting Extraction

Mixing 2D and 3D environments is a classic technique in Virtual Reality design. A rendered background in 2D complements the 3D and can be more detailed, or more painterly. Extracting some elements directly from the 2D painting (figure 6), such as characters, and landscape can help heritage reinterpretation be more precise. But importantly, it is easier to render than GPUs that would otherwise handle hundreds of megabytes of 3D models for incidental art. To compensate, the 2D elements are made to be smart by setting up a 'Billboard' script that enables the 2D elements always to face the camera in the Virtual environment.

Figure 6. Characters, Trees and Rock extracted from 'Prosperous Suzhou' .

5.1.4. Lighting System

Lighting is an essential part both of visual communication, and of design intentions. To develop the atmosphere and visual identity in the VR environment, a dynamic lighting system was developed. The system is designed by scripting and it gives the ability to set the time of day and automatically control the light position, reflection, shadows, and light colour.

5.2. SERIAL VISION

Cullen (1961, 2015) developed the principle of serial vision, and it describes the experience of a continuous and first-person journey through space. This technique was linked to Mise-en-scène (figure 7) to structure the journey when individuals are moving through the garden in the VE.

Figure 7. Using sketches to manifest the experience in the garden.

5.3. COMPOSITION

‘Composition’ represents the arrangement of parts of a scene to form a particular atmosphere and outcome. Scholar’s gardens are a poetic landscape; a composition of different design elements that makes a direct appeal to the emotions and are devoted to serving all the senses (Johnston, 1991). Our VE construction techniques allowed discovery of such features not apparent otherwise, as noted below.

5.3.1. Borrowed, Hidden and Framed Scenery

Borrowed, Hidden and Framed scenery are significant design techniques used in the scholar’s garden, and manifesting these compositional principles can enhance the user’s experience and understanding. Figure 8 shows the reinterpretation of the ‘Borrowed Scenery’ principle in the VE. From the window, individuals can get an expansive view of the garden and distant scenery. This explains why this building is the only two-story building in the garden and is called the ‘Mindfulness Library’. An animated book on the table next to the window is introduced to guide the user to look out through the window. The ‘Hold up the Moon by Two Hands pavilion’ also adopts this technique. The ‘Suichu garden journey’ by Shen Deqian (1673-1769), notes: “There is a pavilion on the pond, which is called Hold up the Moon by two Hands pavilion, reflecting the sky; the shadow is shaking, just like playing with the moon”. By modelling the natural features, such as the day-night cycle, and water rippling in the VE, the name ‘Hold up the Moon by two Hands’ can be appreciated.

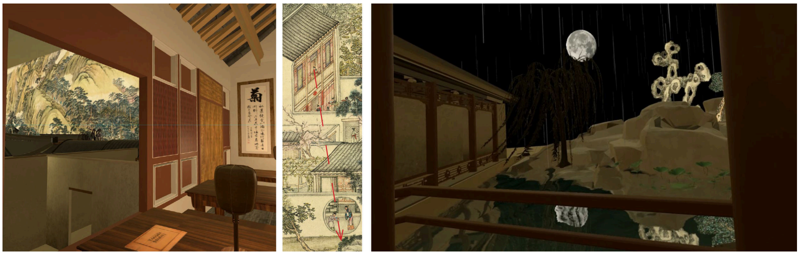


Figure 8. Reinterpreting the Design Principle 'Borrowed Scenery' for 'Mindfulness Library' and 'Holde up the Moon by two hands Pavilion' in the VR.

The design techniques of hidden and framed scenery cannot be properly appreciated by viewing the original painting. After the site modelling it was easy to ensure that individuals could see the interior from the entry door. Through analysis of the planting, we discovered the use of a tree to block and then reveal this view. We discovered from the process of framing scenery to tell the story; a specific viewpoint is selected by the Scholar Garden designer. He used a circular door to frame the view, which in effect creates a three-dimensional picture embedded within a frame. We also noted that this particular arrangement also enhanced the experience in the 'Listening to the Rain Shelter'.

6. Notes on Interaction

Figure 9 shows the virtual environment of the heritage garden, and this can be seen as a virtual sketch as well. This section outlines the different technologies used for creation and interaction; Headset based VR and Social VR (Figure 10), to allow users to experience the virtual heritage singly or as a group.

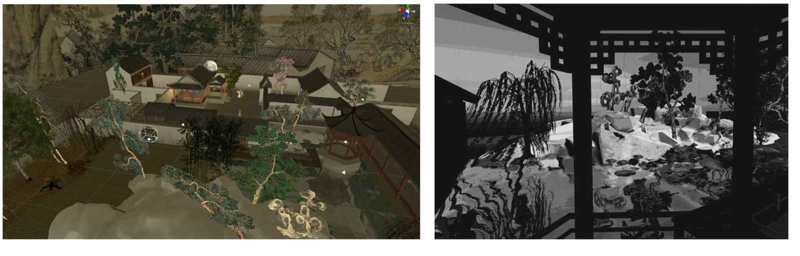


Figure 9. Virtual Garden Overview and First-person Perspective in a Pixelated Virtual Environment.

6.1. HEADSET-BASED VIRTUAL REALITY

'Touchpad Locomotion' was employed via a script to enable the user to have a continuous walking experience through the virtual heritage environment. This form or moving through the scene mimics a 'natural' walking movement. Since the immersive experience is headset-based the VR is a single user one; however, the user has primary control of movement and experience.

6.2. SOCIAL VIRTUAL REALITY

Based on earlier research of Digital Heritage dissemination (Silcock et al., 2018, Schnabel et al., 2016) our research also employed an immersive VR system using the ‘Hyve’ system that allows multiple users to simultaneously experience the virtual environment in a common social setting.

Figure 10. Singular Experience and Social Immersion.

7. Conclusion

Overall, the research explored the potential for creating a productive symbiotic relationship between Digital Heritage and Cultural Landscape. The method developed enables users to experience and better understand the cultural value of the Scholar’s Garden. It represents both heritage context and content, and the outcome manifests tangible and intangible heritage. Reinterpreting the painting in VR enables an immersive, continuous, first-person journey through the designed space where the environment and experience changes as the viewer move through it. This immersive experience enables users to gain a greater understanding of the design intentions embedded in the idea of a Suichu Scholar’s Garden. Reinterpreting a painting into a virtual environment has been undertaken elsewhere. However, reinterpreting a historical painting into a 3D virtual environment with a landscape application is novel and unique, and offers a fuller understanding of the garden. We have gone beyond making a virtual copy of the painting. The painting is a key reference to reinterpreting the landscape design ideas and principles, which was augmented by examining historical written documents. Using computational means to capture and link all of the information, we assimilated it first, then brought the findings together into the 3D environment. The research has explored the role of Digital Landscape Heritage, and it is unique in the way Chinese garden design principles are represented in VR. One application is intended to be in augmenting heritage education. Also, our work has value to reconstruct the lost Suichu garden in an informed way. Finally, the technique supports contemporary landscape design processes, i.e. in the urban context of modern Suzhou. The Social Virtual Environment allows the development of a respectful, and informed, new scheme with collaboration across all stakeholders.

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TOWARDS A DIGITAL TWIN FOR HERITAGE INTERPRETATION

From HBIM to AR visualization

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Abstract. Data-driven Building Information Modelling (BIM) technology has brought new tools to efficiently deal with the tension between the real and the virtual environments in the field of Architecture, Engineering, Construction, and Operation (AECO). For historic assets, BIM represents a paradigm shift, enabling better decision-making about preventive maintenance, heritage management, and interpretation. The potential application of the Historic-BIM is creating a digital twin of the asset. This paper deals with the concept of a virtual environment for the consolidation and dissemination of heritage information. Here we show the process of creating interactive virtual environments for the Pampulha Modern Ensemble designed by Oscar Niemeyer in the 1940s, and the workflow to their dissemination in an AR visualization APP. Our results demonstrate the APP feasibility to the Pampulha's building interpretation.

Keywords. Augmented Reality (AR); Historic Building Information Modelling (HBIM); Heritage Interpretation; Modern Architecture.

1. Introduction

The Digital Twin (DT) can be understood as a probabilistic, multiscale, multiphysics integrated simulation of a system that uses the best physical models, sensors, and history to mirror the life cycle of its corresponding twin. The DT can also predict the system's response to security-critical events and uncover previously unknown issues before they become critical by comparing current and predicted responses. Systems involving DT are capable of mitigating damage or degradation by activating self-healing mechanisms or recommending changes to the mission profile, thereby increasing the life and probability of success (Glaessgen and Stargel 2012).

The DT consists of three components: physical product in a real monitored space, data and information connections, and the corresponding virtual product in virtual space (Grieves and Vickers 2017). At the AECO industry, the

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 183-191.

virtual product in the virtual space corresponds to the BIM model, which in the case of the built heritage, is the HBIM. Real-time monitoring is performed by sensors, generating data in quantity. Data is communicated, stored, processed, and associated with the virtual product allowing awareness of physical space performance and simulation in virtual space for decision making on how to act in real space. The potential application of the DT for Heritage is its realistic representation in the form of an intelligent and semantically enriched 3D model (HBIM), becoming a tool capable of managing information collected and modeled, improving its availability and accessibility.

According to Nagakura et al. (2015), having a digital model of historical heritage is a cheaper tool to allow building investigations because, unlike other areas of study, there is no way to take buildings to laboratories or store them in museums galleries like other historical artifacts.

The use of digital scanning technologies to survey the current state of historic buildings, such as photogrammetry and laser scanning, expedites the process of generating a digital model. Photogrammetry is a low-cost method and captures building textures and materials by creating a 3D model from photographs (Nagakura and Sung 2014).

To assist in the understanding of 3D projects and to promote social interaction between architects, historians, and visitors to historical heritage sites, Augmented Reality (AR) is a tool that allows users to interact with the digital model (Nagakura and Sung 2017). AR supports the real experience of historical heritage sites without having to go there.

2. Research Aim and Roadmap

This paper presents ongoing research aiming to develop a AR APP from the digital twin of two buildings, the Ballroom and the St. Francis of Assisi Church, part of the Pampulha Modern Ensemble (PME) designed by the world-famous architect Oscar Niemeyer in the 1940s. The UNESCO's World Heritage Convention listed the Pampulha Modern Ensemble, in 2016, due to its Outstanding Universal Value as a cultural landscape.

This research explores how users, professional and non-professional public, can interact with AR to visualize, filter, and retrieve any information enclosed within the Digital Twin of historic buildings.

AR is a growing area in the AEC industry. It offers a new tool for visualization and interaction in the field of heritage preservation, operation, and maintenance, as well as for tourist purposes. Regarding the visualization and interaction purposes, the following research questions are drawn up: Is it possible to filter and access only specific components and information from the Digital Twin into an AR environment? How can the modeler prepare the BIM Model for the AR environment to retrieve the knowledge-based information?

The digital twins' creation employed terrestrial laser scanning (TSL) and a low cost unmanned aerial vehicle (UAV). The process was based on three fundamental steps: (1) collection of spatial and documentary data, (2) data processing and dense surface model (DSM) creation, and (3) HBIM modeling. The framework includes creating the HBIM model in Autodesk's REVIT authoring. For the AR process, the model organization is crucial. The heritage elements were organized in the HBIM model using the Dynamo visual programming tool. Dynamo allowed the creation of building components groups to make the HBIM model easy to import and interpret into the AR model-authoring platform.

The Diagram below illustrates the Roadmap of the research project and the distinct computational tools, which integrate each step. Step 1 addresses the HBIM creation of both buildings, which were created in previous research, in which the details of the Scan2BIM process were already published (Cogima et al. 2018, Cogima et al. 2019).

The focus of the present work is to present the results from the AR APP creation for the first building, the Ballroom.

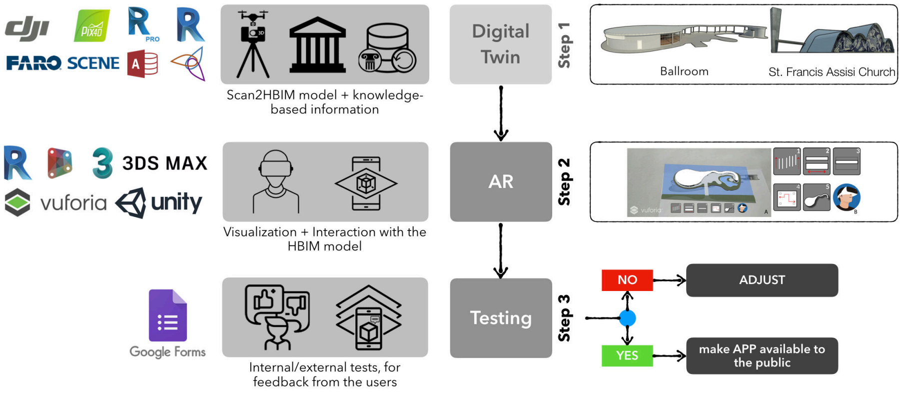

Figure 1. Roadmap of the AR creation and testing from the Digital Twin of Niemeyer's Pampulha Buildings.

3. Case Study: The Ballroom and St. Francis of Assisi Church in the Pampulha Modern Ensemble

The PME was the center of a garden city project created at Belo Horizonte, the capital of Minas Gerais State. Built between 1942 and 1943, the PME was developed by architect Oscar Niemeyer and by landscaper Burle Marx, in collaboration with great artists and professionals, among them, the painter Candido Portinari. The PME is composed of four buildings: St. Francis of Assisi Church, the Cassino (current Pampulha Art Museum), the Ballroom (current Centre of Reference in Urbanism, Architecture, and Design), and the Yacht Golf Club.

Although each of the four building offers a slightly different architectural solution to the challenge of adapting the common formal Modernist vocabulary to the climate and environment of the new city, overall what emerged was a fluid and plastic architecture that embraces views and joins to the picturesque qualities of the lake and mountain landscape. The PME and the selected buildings are relevant to the application of AR, as they are heritage sites of high significance to the country and receive thousands of annual visitors.

3.1. ST. FRANCIS OF ASSISI CHURCH

The church is constructed of five adjacent ellipsoid concrete shell structures of different heights. Although industrial buildings have used concrete shells previously, their use here marked the first occasion for a religious structure. The most massive shell faces the lake where a slender freestanding 'tower' in the shape of an inverted pyramid is linked to the church by the flat roof of the porch. Paulo Werneck decorated part of the outer surface of the shell with tiles, while blue and white murals by Cândido Portinari cover the facades of the lower shells facing the street. The unusual and innovative design of the church generated a significant disagreement within the Catholic Church, which caused the postponement of its consecration and, consequently, the opening to the public until 1959.

3.2. BALLROOM - CENTRE OF REFERENCE IN URBANISM, ARCHITECTURE, AND DESIGN

The more modest building from PME, the Ballroom, sits on a small island surrounding mostly paved minimalist gardens and linked to the shore by a bridge. The circular flat-roof ends in a curved walkway which connects the main building with the bathrooms facing the circular stage. The gallery is supported by expressive columns, which also contour the entire circular volume ending. Decorative blue and white tiles designed by Candido Portinari coated all surfaces.

The Ballroom worked as urban equipment for being a place of dances, shows, and dinner, to provide the public with the experience and the allure of the new region of Belo Horizonte. The Ballroom has been twice restored in the last twenty years and now houses the Centre of Reference in Urbanism, Architecture, and Design.

4. Methodology

The digital twins' creation employed terrestrial laser scanning (TSL) and a low cost unmanned aerial vehicle (UAV). The process was based on three fundamental steps: (1) collection of spatial and documentary data, (2) data processing and dense surface model (DSM) creation, and (3) HBIM modeling, as detailed in Cogima et al. (2018).The framework includes creating the HBIM model in Autodesk's REVIT authoring. For the AR process, the model organization is crucial. The heritage elements were organized in the HBIM model using the Dynamo visual programming tool. Dynamo allowed the creation of building components groups to make the HBIM model easy to import and interpret into the AR model authoring platform.

4.1. AR VISUALIZATION

Augmented reality (AR) overlays digital content on real-world objects that a computer sees employing a regular camera, which enriches our view of our surroundings. AR needs a device with at least three components : (i) a camera to provide input from the real world to the computer, (ii) a screen or glasses so that the user can see the real world enhanced by computer-generated digital information, and (iii) enough processing power for the device to retrieve features from the real world, using computer vision, and overlay digital information.

Smartphones and tablets are ubiquitous devices that already support these three components. They have been used in many AR applications, and at least while AR glasses are not widespread, they will continue as the primary resource for AR experiences. For successful augmented reality experience, some elements are desirable: (i) the augmented experience should bring new information to augmented objects, (ii) the digital models should allow real-time interaction, and (iii) they should convey accurate information. We kept these goals in mind when modeling the augmented experience of Niemeyer buildings aiming to keep the same visionary vision he had in mind when designing the buildings.

In our work, we would like to allow people to enjoy the buildings and the architectural details in compelling new ways. We are talking about four buildings that were constructed very close to each other. Any visitor traveling through Belo Horizonte would probably visit them on the same trip. Our goal is to create an environment where any user would do the same using the digital world. The user should have a clear notion about where the buildings are around Pampulha's lake and the proportions of each building. Therefore, we implemented an augmented map experience where the user handles a conventional map (like those we receive at touristic information posts) and installs the AR APP on the tablet or smartphone.

The intention is not to replace the experience of seeing these buildings in the site but bringing some aspects of them, which include the accurate 3D models, the surrounds, and some modern architectural supplementary information. This view is much more complete than just traditional means like videos and photos. Other than the augmented experience where overlaid digital information is additive to the real-world objects (map), we created a first-person view of the four buildings. The visitors can walk through the buildings, enter into the rooms, and look through the windows as if they were in the model site.

This paper explains each step of building the AR application, as well as the material and tools used, aiming replicability. The 3D architecture and source codes are publicly available at the GitHub home page Davilopesm/PampulhaModernEnsembleAR. Visitors have the choice to see the architectural matters in detail, which they are readily available to be inquired by the audience by clicking on icons designed to represent common themes in Niemeyer's design. Each icon is reduced to its minimal form, expressing characteristics of the buildings.

The best way to introduce our augmented reality application is by showing how it behaves as an application. We exercise the freedom to experiment during the development, so each detail is linked to a concept we want to convey, trying to bridge the gap between the real buildings and the technology. Figure 2a shows the city map that triggers the augmented reality environment and 2b depicts all components of the Ballroom (above) and the St. Francis of Assisi Church (below) Digital Twins in an exploded view. The buildings are around Pampulha's lake, and tourists may visit them in one single day. The fact that we are using a map highlights the spatial distribution.

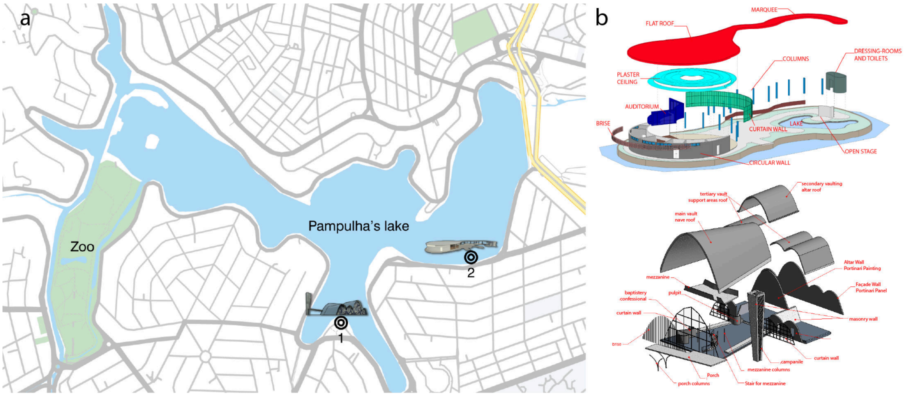

Figure 2. (a) Pampulha's lake map with St. Francis of Assisi Church [1], and the Ballroom [2]; (b) Exploded Views of the Ballroom (above) and The St. Francis of Assisi Church (below) . .

Figure 3 gives an overview of the proposed APP with the augmented reality triggered in front of the map and the first scene of the application. Some natural gestures like pinching with two fingers to zoom in/out or moving two fingers around each other to rotate are available. However, the most relevant features in this environment are those reached through the icons.

Figure 3. overview of the APP.

The Icons represent Le Corbusier's Five Points of the Modern Architecture, which could be identified in Niemeyer's proposal for the Ballroom. We can see in Figure 4 the five main buttons to engage with the augmented reality. The first icon shown in Figure 4 is called "The Pilotis". It has vertical bars and red arrows to recollect the fact that there is a grid of concrete columns supporting the roof structure to make the soil freely usable. The second icon is called "The Free Facade". It is reminding of open and closed sections on the facade that enable the separation and connection of the exterior design from the building structure. The third button, which is called "Horizontal Windows", is reminding the windows along the facades that provide the interior lightness and offers views of the surroundings. The fourth button, the free ground plan, reminds the user of the absence of load-bearing walls, which allows flexible use of the space. The fifth icon, called "The flat roof," is inspired in the building itself.

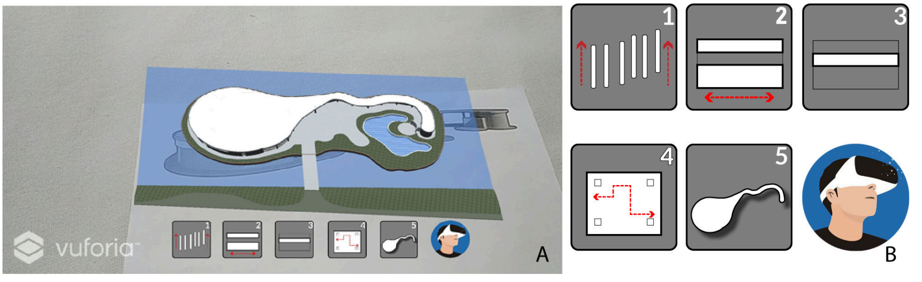

Figure 4. AR from the Ballroom (A) and the 5 buttons that represent the five points of Architecture, plus the First person View (B).

Figure 5 (left) shows the effect of selecting each icon. These views are helpful to students since they complement explanations found in their textbooks. By showing particular design patterns of modern architecture and allowing viewers to play with them, the APP provides valuable insights that could not be reached by merely reading about those buildings on books or looking at pictures of it. The Digital Twin enables an experience of first-person. The last picture right in Figure 5 shows a first-person user entering the building, getting close to the front door. The textures built are based on the real ones, allowing no specialists to enjoy the view and specialists to study it.

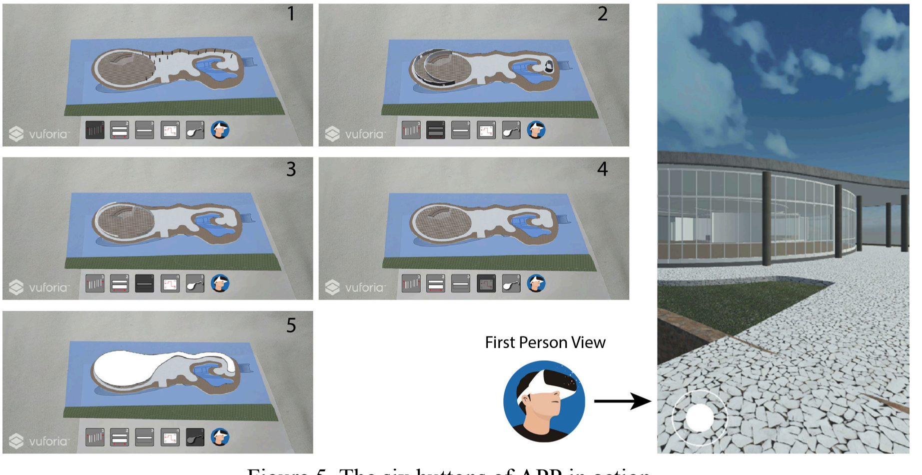

Figure 5. The six buttons of APP in action.

5. Results

To create the Augmented Reality application, the Unity Engine was used. Its main application is to create video games, but due to its integration with smartphones and its ability to create complex scenarios, it becomes a useful tool to create and deploy applications that uses 3D models.

The implementation of the application was entirely done within Unity. However, to get the 3D model from Autodesk REVIT to Unity, we first passed it through the Autodesk 3DS MAX, which allowed us to convert the RVT file format into the FBX. The native file format of REVIT cannot be imported directly in Unity; furthermore, all texture from the Revit model should be re-applied in the components using the 3DS MAX. Figure 6 shows the workflow to implement the application.

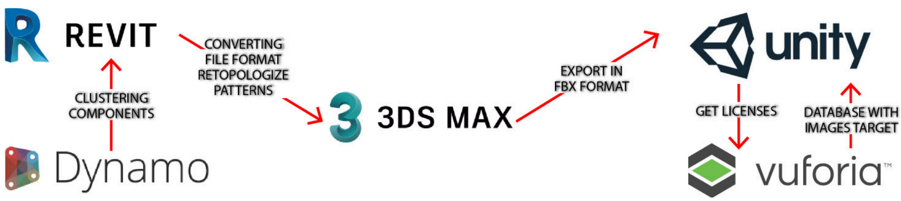

Figure 6. Workflow of Software for AR Application .

First, a new Unity Engine project was created to receive the 3D model. In the new project, the "Vuforia Augmented Reality" option should be selected for the appropriate downloads to be made. Six game scenes were created inside this project. These six scenes being one for the main app scene, one for the Pampulha's Modern ensemble explanation, and two for each model: The Ballroom and St. Francis Assisi Church.

The augmented reality was created using a plugin called Vuforia AR Camera that searches for Image Targets in the environment. When the search finds a specific image target, the proper 3D model is overlaid. In each scene, when the marker for the whole Pampulha map is tracked, meaning when it is visible on the smartphone screen, it triggers the AR visualization for the models onto the map.

In the main application scene, four buttons were created; each one of these buttons was given a C Sharp script that allows opening the corresponding scene. In the scene for the quick explanation of the Pampulha Modern Ensemble, two elements were created. One of them uses the same image used as a logo for the application, and the other provides textual explanations.

The other two scenes, concerning the Ballroom and St. Francis of Assisi Church, contain six buttons. Five of these buttons allow users to make specific elements visible or invisible at runtime, so, for example, the user can see inside the buildings after removing the roof. Sometimes, the user may want to visualize only one element while making all the others invisible. That is also possible by playing with the buttons. The sixth button transports the user to the first-person view scene. In this scene, it is possible to move around with a UI element that is used as a joystick.

6. Conclusions and Future Works

In this paper, we proposed and detailed a methodological framework to implement AR visualisation and interpretation of two masterpieces of Modern Architecture in Brazil, through the HBIM model, developed by the authors in another research.

This work aimed to use AR to promote the diffusion of historical content differently and innovative with the use of immersive environments, fully synthetic or mixed, with Augmented and Virtual Reality mediation, enabling to offer an interpretation and understanding of architectural objects of high historical and cultural value.

We assume that using AR solutions enhances visitors' engagement in Heritage data visualizations, but this remains to be formally studied. Preliminary tests with the members of the research team attested that they experienced a more significant interaction with the building, made possible by the AR application. Users highlighted the ease of accessing with one click the history of the building, the biography of the architect, and explore the components of the building, in an interactive way. The validation tests demonstrate that the proposed framework is consistent and is also able to support the intended goals for the interpretation of heritage. Future validation will include feedback from the users, including the usefulness, historical content provided, and ease of interaction with the interface. Additionally, future work will include knowledge-based information to be used for planning and decision-making by the building maintenance staff.

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EXHIBITING DIGITAL HERITAGE

The Curation of Un-Mediated Experiences in Museums

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Abstract. The aim of this paper is to examine how a museum exhibition can allow barrier-free access and engagement of visitors. This paper will discuss Immersive Legacies, an exhibition that presented the digital documentation and virtual representations of a significant heritage building, both physically and in virtual reality. Through the examination of the exhibition, Immersive Legacies and its broader museological context, this paper will discuss the emergence of these technologies in museums and its relation to the Anthropocene epoch. In an age of rapid advancement and destruction, it becomes essential to preserve heritage sites, architecture and cultural objects. Furthermore, connection and communication were, and continue to be facilitated by the technologies that began in the Anthropocene epoch. As a result of this era, heritage can be experienced anytime and anywhere, although it remains vital for citizens to have the opportunity to experience it in museums. In turn, this paper will examine how these technologies can be to help citizens understand and engage with heritage and the past in museums - now and in the future.

Keywords. Digital Heritage; Museums; Digital Technology; Un-Mediated heritage; Virtual Reality.

1. Introduction

Heritage is a legacy from the past that must be remembered and passed onto future generations. Digital heritage changes how these legacies are preserved; heritage architecture can be reconstructed with a range of digital technologies to record and remember buildings and sites. In the age of the Anthropocene, when the number of cultural sites at risk of damage or loss continues to rise, the importance of digital heritage increases alongside this statistic. As a field that continues to grow in prominence, digital heritage offers alternative opportunities to conserve, preserve and experience heritage. When a physical building becomes a virtual one, it is no longer constrained by the boundaries of reality and can enrich heritage sites that exist in reality. Digital heritage means that we no longer need only the physical building to visit, understand and communicate heritage.

In virtual reality, experiences are un-mediated because objects can be interacted with anywhere, at any time and with barrier-free access (Aydin and

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 193-202.

Schnabel 2016). As a result, interpretation is open-ended - there is a dialogue between the technology and the user (Thornton 2007). These technologies can widely disseminate heritage content and, as a result, increase public engagement (Affleck and Kvan 2005; Kenderdine 2016). Consequently, visitors can interact with virtual environments in ways that interest them, which makes these experiences more meaningful (Murray 1998). In contrast, the heritage objects and sites of reality are controlled by galleries, libraries, archives or museums (GLAMS) that mediate these experiences. This paper examines how the digital age is changing, not only the methods for the preservation of cultural heritage but how, when and where it is experienced. It will be argued that these organisations will continue to play a significant role in the preservation and communication of knowledge, to discuss how the contemporary museum must transform into a more appropriate and flexible environment (Christensen-Scheel 2018).

1.1. CASE STUDY

In many cases of digital heritage, for the heritage to be preserved digitally, there is, first of all, a call for digitisation. If the heritage is at risk, a virtual reconstruction means the site can be visited by future generations (Champion 2008; Schnabel & Aydin 2015). Because of this, digitisation prioritises the creation of authentic digital representations of the heritage in question - later comes the question of how it will be presented to the public.

In 2017, the digitisation of the Gordon Wilson Flats, an uninhabited modernist social housing building in Wellington, New Zealand, began. In 2019, the research was completed, and the resulting virtual reality experiences were exhibited in the exhibition *Immersive Legacies: The Making of Digital Heritage*. The aim of the Gordon Wilson Flats digital heritage project was to present the public with experience capable of informing them about the history of the building. Although the building is heritage listed, the significance was - and continues to be - heavily debated by the public despite little being understood about the architectural and social history.

Since the construction of the Gordon Wilson Flats in the 1950s, the building has been subject to a range of social and cultural influences, which has resulted in the deterioration of the building into its current state of decay. In the virtual reality experiences of the Gordon Wilson Flats, users can experience this living heritage from the collection of the building's tangible and intangible characteristics. The combination of tangible and intangible information that was collected to span across the building's lifetime results in a multidimensional experience. It means that users can experience the building over time, and hence construct an understanding based on a wide range of information that covers decades (Rushton 2018b).

Two systems disseminate the virtual representations of the Gordon Wilson Flats (Figure 1). The first of these is individual immersion, which uses the HTC Vive headset for a singular interactive and narrative experience. Secondly, social immersion is facilitated via a concave screen that immerses a group of users within non-narrative content.

Figure 1. Outcomes of the Gordon Wilson Flats digital heritage project.

From here, the question is asked: how can the digital heritage of the Gordon Wilson Flats be exhibited in a museum context and remain un-mediated? This paper will present the exhibition, Immersive Legacies, as a case study for curating digital heritage. Following a brief background to the problem presented by modern museums and current examples, the work completed for Immersive Legacies will be contextualised by recent examples of cultural heritage disseminated by museums using different technologies with different results. This research proposes a hierarchy and theory behind a method for presenting digital heritage in museums.

2. Museums Today

Since the origin of the modern museum in the nineteenth century, an intention has been education (Noordegraaf 2004). Museums display cultural heritage in a range of forms: from art to architecture, they illustrate the tangible or intangible, which exhibit the remains and evidence of humans and their place over time. Surviving relics from the past are preserved and fragments, images or objects are placed in museums. Established by modern museum practice, the viewing of these is restricted and controlled by curators and museum staff. Information is presented in a highly planned sequence, as the selection of objects in an exhibition is devised, and thus, mediated by the conditions of the museum (Muller 2002). Such a rigid display usually assumes some knowledge from the viewer, to inform their interpretations - as guided by the curatorial influences. Museums, therefore, exhibited, not only limited insights into history but histories that were perceived to privilege social and cultural hierarchies (Huhtamo 2010). Furthermore, with the addition of barriers and restrictions, the function of the museum becomes paradoxical - for cultural heritage to become visible, museum practice imposes a distance between the object and the observer (Noordegraaf 2004).

In recent decades, museums have set about responding to the challenges set by the past. As a result, the function of museums has changed - changing the focus from objects to the experience of visitors. Museums now acknowledge that visitors enter museums with different motivations and past experiences that will influence their understanding and interpretation of exhibitions. Integrating digital technology into museums facilitates this, as exhibitions can be more interactive and engaging. Moreover, as something that is an integral part of contemporary life, digital technology is something that visitors are beginning to expect in their museum experience (Parry 2008).

These change the way that heritage is experienced, understood and appreciated, the effect that computing has had on how exhibition content is made visible is undeniable (Parry 2010). Digital technologies and cultural heritage can be curated to be experienced by a variety of users in many different ways. As a result, these emerging technologies democratise heritage and change how culture is consumed (Gansallo 2002). In turn, the significance and narrative of histories can be understood and explored in novel ways that engage broader audiences. In order to understand how these mediate or do not influence the public's interpretation of heritage, and the role that the technology plays in the experience, this section will survey examples of different types of cultural heritage dissemination in New Zealand. These methods illustrate how technology redefines user experience. The concept of "the digital layer" (Devine and Tarr 2019), becomes an essential idea in explaining how digital technology is integrated into exhibitions. Here, digital tools work to extend the museum experience. Visitors do not only interact with digital technology in the exhibition but also before and after. In the digital age, everyone has access to computers and digital devices, with which they can visit the museum website and view the accompanying media.

In New Zealand, many museums have published their collections online. These include The National Museum, Te Papa Tongarewa; and The Alexander Turnball Library, which is part of the National Library. These are ongoing digitisation projects that embrace emerging digital technologies and make cultural objects available to a broader audience (Giannini and Bowen 2019). On both websites, users can explore collections. Objects can be selected or searched, then viewed in detail with further information provided. Te Papa's digital collection offers short interpretive text - and, thus, more mediation - within their digital collection. With tools such as these, visitors can look at the collection before they visit the museum, or explore the collection after they attend an exhibition - they can understand the full range of the museum's collection or engage with a body of work through the digitised collection online at any time and from anywhere. Although the images are usually available in high resolution and can be observed in great detail, they are two-dimensional. Therefore, they can be analysed, but the material qualities and scale of the real object are lost.

Another way to digitise cultural heritage objects is to create digital models that can be disseminated in Virtual Reality. The world's first gamified city (Wellington becomes the world's first gamified city 2019), Welltown VR offers a virtual experience of Wellington City. The experience aims to showcase the culture of Wellington City, and Te Papa and the National Library have been recorded to be part of the virtual experiences. The user navigates through 360° videos with interactive objects. Unlike the digital collection that features on each website, these preserve the three-dimensional qualities and scale of objects and spaces. Digital objects can be experienced in the same material qualities and scale as reality - if the creator chooses to do so (Rushton 2018a). Furthermore, this is an example of preserving the culture of a particular place or moment, which is essential in the age of the Anthropocene.

In the rise of new values within museology, ideas of social impact have changed exhibitions and their message (Scott 2003). An example of this is Te Papa's recent permanent exhibition, Te Taiao Nature. Produced by one of the largest museums in the world, this exhibition uses technology to immerse people amongst the natural world. It makes visitors more aware of the human impact upon nature and hopes to inspire people to change in the Anthropocene age. As a result, the exhibition explores three ideas: the unique qualities of New Zealand's nature, how it is under threat, and raise the need for action (Te Taiao| Nature 2019). Objects from Te Papa's physical collection feature alongside immersive technologies that facilitate engagement with these artefacts. These support the creators' aim for the exhibition: to feel an emotional connection with New Zealand's wildlife.

In contrast to the last two case studies discussed, Te Taiao Nature presents real objects alongside digital technologies - including interactive screens and immersive projections. The immersive experiences within Te Taiao Nature allow the audience to explore the idea of living cultural heritage, and how things change over time. In contrast to the last two case studies discussed, Te Taiao Nature presents real objects alongside digital technologies - including interactive screens and immersive projections.

Although each of these examples navigates a different topic, digital tools are utilised in similar ways. Museums have not fully embraced the possibilities for unlimited display space and communication (Muller 2002); as digital heritage projects continue and data is archived, it becomes essential to consider how these will be presented to the public. From these examples, it is clear that the museum and technology are separate mediums. Each has been developed to work together seamlessly. However, one is in aid of the other. Figure 2 illustrates the hierarchy of these concerning the curator, visitor and exhibition concept. These examples show that there are many ways to arrange and disseminate heritage to the public and although New Zealand's histories are well represented and explored across novel digital spaces, their experience is still mediated. Here, digital technologies assist the curation of physical objects. Technology as a medium only serves as a tool that supports the physical, or real, exhibition objects and curatorial idea. From here, it becomes clear that, despite being unmediated in nature, digital and interactive technologies can still be mediated by museums (Aydin and Schnabel 2016).

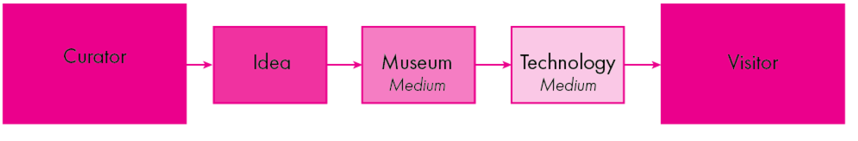

Figure 2. Curation of digital technology within the museum (Adapted from Parry 2008).

3. Digital Heritage in the Museum

Although today's museum cannot curate both cultural products, the intended outcomes of digital heritage. In contrast to these, digital heritage is recorded for preserving a place, time or object. In this case, the hierarchy with the museum is different. First of all, there is the experience, then comes the question of how to work with the space. A curator completes it, but with the intention of retaining the unmediated qualities of the heritage - not placing a curatorial influence on the audience interpretation. Figure 3 illustrates that the function of the space is to provide a medium for people to experience the digital in museums, which, in turn, allows these institutions to remain relevant and develop towards digital content.

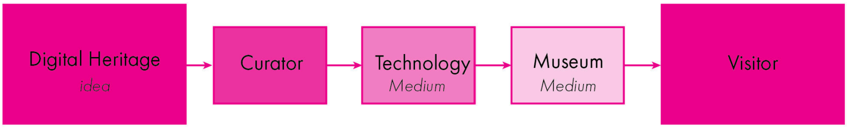

Figure 3. Hierarchy for curating digital heritage.

4. Immersive Legacies

Immersive Legacies was held in the capital city of Wellington, New Zealand, in the Wellington Museum. The exhibition was open for two weeks and was featured as part of 'Wellington Heritage Week' - a significant, annual week-long event that features a range of heritage in Wellington. The exhibition hosted a broad audience, including international, national and local visitors, and a broad range of ages.

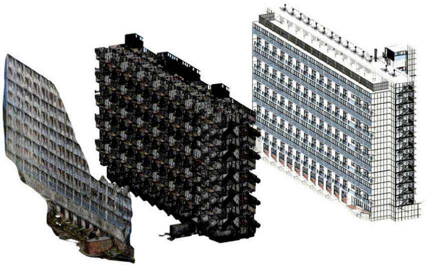

Figure 4. Representations produced using different technologies.

Along with bridging the physical and digital, the exhibition focused, not only on the final result but the digital process. It is as, in the making of digital heritage, it is the methodology - documentation, representation, and dissemination - that generates meaningful experiences. The different techniques throughout the documentation and representation stages, along with the different of skillsets required produced a range of virtual depictions of the building. These allow visitors to compare and interpret a variety of representations, and hence build an individual understanding based on their experiences in both individual immersion and social immersion (Figure 4). As a result, the exhibition aimed to celebrate the emerging technologies that made this digital heritage possible - not comment on the contested status of the Gordon Wilson Flats. Visitors were invited to reflect on the role these technologies will play for digital recording heritage in the future based on their introduction to it in the exhibition. Figure 5 shows the floorplan of the exhibition and the intended sequence for viewing the exhibition. The sequence of the exhibition shows the making of digital heritage, following the methodology from documentation, representation and dissemination.

As visitors moved through the exhibition, physical experiences changed to digital ones. The final stage of dissemination was accompanied by text but presented and focused on virtual experiences and representations. Immersive Legacies includes the two forms of dissemination that were used during the Gordon Wilson Flats digital heritage project. Additionally, a hologram displayed the digital models, to illustrate the contrast between each representation generated with the use of different digital techniques - changes in the architecture that was experienced by users in the virtual reality experiences. It corresponded to the models that are experienced in 1:1 immersion within virtual reality, again giving context - from their creation to dissemination. Finally, aural recordings play throughout the space; interviews with the creators of the Gordon Wilson Flats project about how they made digital heritage. These do not only detail the techniques and technologies used throughout the work, but also their experience inside the building as it is today. Sound added a further layer of information and combined with interpretative text, physical models, objects and virtual experiences, these components of the exhibition give a wide range of choice to visitors to engage with what was of interest to them - and construct their own experience and interpretation.

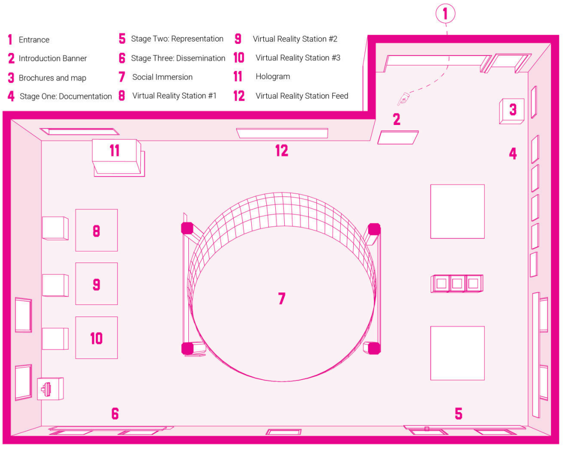

Figure 5. Exhibition floor plan.

It seems as though an intended sequence should contradict the purpose of digital heritage, however, the physical objects and interpretive media that are part of the exhibition serve to contextualise and replicate the digital objects in each of the virtual reality experiences Referring back to Figure 3, Immersive Legacies used physical objects to assist the digital objects and virtual experiences. This sequence of information, accompanied by sound playing throughout the space, shows that even in the mediated space of the museum, the curation has attempted to replicate the conditions of digital heritage. These different forms of media, which are represented across realms, are there to support the construction of interpretation - a range of interpretations for a wide array of visitors while moving throughout the path (Figure 6).

The experience of the Immersive Legacies extended and continues to extend beyond the exhibition. From the website, visitors could engage with some content before visiting, or after. Furthermore, the virtual reality experiences, particularly singular immersion - which is played on 'steamVR' - only need an 'HTC Vive'-headset and computer to run, thus can easily be experienced anywhere in the world. Social immersion, which requires a spherical screen becomes harder to replicate without the correct system. However, the 360° videos that play on it can be accessed and interacted in several different ways. Finally, for visitors to engage with the exhibition content, further brochures were given that included details of the published work from this digital heritage research. Included on these were QR codes that directed readers to their publication of interest, to tell them more about the building and the details about the digital heritage work completed about that aspect of the building.

Figure 6. Stages throughout the Immersive Legacies Exhibition (left to right, top to bottom): physical and interactive media, holographic display, social immersion (spherical projection), individual immersion (HTC Vive headset).

5. Outcome

Visitors to the museum became more engaged and interested in the social and individual immersion experiences. Due to the draw of virtual reality, it was found that people went straight to these experiences, missing the interpretative media. However, exhibition staff found that visitors spent a significant amount of time in both immersive experiences, investigating the content and interacting with different forms of media included within them. Therefore, on their own, these experiences provided adequate information for interpretation to be formed. However, visitors could go back through the exhibition to look at the physical media; or investigate the website, social channels or brochures and publications before or after visiting. What the visitors' path and experience in the exhibition space shows is that although the exhibition fosters an alternative space to digital heritage, the unmediated experience of digital heritage is enhanced by the museum context. Visitors did not use the physical media in the space as intended, but the Social and Individual Immersive experiences engaged them. These led them to interact with the media inside these spaces, and from what they learned within these realities further engage with the physical content in the exhibition or discuss the building and its history with the exhibition's volunteers. Ultimately, the exhibition enriches how digital heritage offers interpretation and engagement.

6. Conclusion

In conclusion, curating digital heritage and virtual content changes the hierarchy within museum spaces. It is as cultural consumption changes museums must continue to integrate digital technology into their exhibits to meet visitor expectation. This paper has argued that despite the shifts to digital media and virtual experiences - which can be experienced anywhere and at any time - the role of the museum remains as crucial as ever. In an age when heritage, and thus the experience of heritage is at risk, the importance of digital heritage increases - however, its un-mediated nature comes into question when it is part of museums or the wider GLAM's network. The Immersive Legacies Exhibition has shown how the museum can enrich the experience of digital heritage without mediating it. While these experiences are meaningful on their own, placing them in their broader context bridges the physical and virtual, which creates more opportunity for engagement and interpretation. Hence, although digital heritage is accessible anywhere, the museum plays a crucial role in enriching the experience in ways that are not possible elsewhere.

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POST-ANTHROPOCENE:

The Design after the Human Centered Design Age

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Abstract. The paper exemplifies possible traces of transition towards Post-Anthropocene that is envisioned as non-hierachical system. It is taking Morton's discussion on 'hyperobjectivity' further into multi-layered codesign performed in real time and real life across bio-digital agents, including humans. Though our planet might be recently experiencing drastic times and one catastrophic scenario follows the other, a natural succession often comes after most disasters.

Keywords. Post-Anthropocene; Systemic Design; Hyperobjects; CoDesign; Bio-Digital Design.

1. Introduction

'There cannot be a post-Anthropocenic "politics" in any recognizable, normative sense - a "politics" predicated on the self-regard of the human subject mapping [her] himself as a coherent agent within a stable historical unfolding. It's just not possible to distinguish between what is an existential risk and what is an absolute invention, and what is both at once, and mobilize "positions" accordingly. So mobilization must go on without that distinction. To govern-that is, to account for the general economy of decay and creation with some nominal degree of authorship-something else is required.' (Bratton, 2013)

The paper unfolds the transition from the design for 'Anthropocene Mass Extinction' (Dirzo et al., 2014) towards designing within bio-technological synergetic landscapes of cross-species co-living, following non-hierarchical models. This co-living involves human species in shared co-existence and contribution amongst the other ones. Although technology-related involvement of other-than-human species in co-creation and co-living in systemic balance might rise eco-environmental systemic as well as ethical issues, so has been tangibly rising their avoidance. The latter neglection is increasingly presented as the main cause of disturbance for the ecosystem causing major catastrophic incidents at a global scale, as some argue that we have recently started to witness what was once described as apocalyptic visions about our planet.

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Alternative pathways are sought in transitioning towards the Post-Anthropocene era. This involves realizing that nonhumans are installed at profound levels of the human, not just biologically and socially but in the very structure of thought and logic. Coexisting with these nonhumans is ecological thought, art, ethics, and politics, the ecognosis (Morton, 2016). This non-human centred design approach sets a new culture by which to readdress our sense of wellbeing as the main urgency of our times: a culture that even though it includes humans, it does not place human activity at the epicentre concerning global existence. Human activity is valued by its responsibility to minimize its environmental footprint as meanwhile, to live to the detriment of others including any other part that makes the world ecosystem may no longer be acceptable. Further to this idea, alternative views were explored in depth by pioneers of eco-systemic design thinking of the late-modern era (Doxiadis & Papaioannou, 1964; Tyrwhitt, 1978), to become relevant again recently as those early systemic attempts have been rethought under the computational design context (Zavoleas, 2014).

The paradigm transition suggests nature and its bio/geo-systemic operations as the primary reference model for computing. The results nature presents are rethought for example not merely as superficial testimonies of visual beauty to copy or to imitate, but as dynamic outputs of never-ending processes of exceptional rigour and wisdom continuously readdressed through iterations, recursive trial-and-error testing and feedback learning by which nature's 'designs' adapt, mutate, respond and evolve by being integrated into different contexts. In this model, highly sophisticated natural processes are 'computed' so to speak, by being set within a comprehensive spectrum of external and internal constraints in dynamic reciprocity and energy exchange, one that supersedes humanity and one that humans cannot but work along with and within it, as they must constantly try to understand, praise the vitality of its instances with regards to the whole and act accordingly in subtler also considerate and non-hierarchical manners, as the only way for the ecosystem's viability.

Recently, there has been some outstanding evidence of nature-driven operations highly supported by new technologies related to computing. For example, as a recent review (Heinrich et al., 2019) suggests, the study of bio-hybrid robotic architectures has been a rising field. The outstanding work of Terreform ONE has established a distinctive design tactic that investigates projects and prototypes through the regenerative use of natural materials, science, and the emergent field of socio-ecological design (Joachim & Aiolova, 2019) or Rewild My Street Team (Moxon, 2019). However, for the transition to happen there needs to be significant debating as to how changes might affect each of the various stakeholders that set the production workflows. Since the turn of this century, along with the evolution of computing the design projects have become far more complex for example with regards to size, contextual factors, regulations, linking with various specialisations, sustainability, resilience and energy performance. In effect, new computational design methods and the emerging digital technologies are incorporated into production from start to the real-life endless process to constantly advance performance. It has been clear that what might have seemed as a spontaneous digital updating sporadically affecting specifically targeted user groups or reductionist goals only, now involves many more other areas than those groups and fields directly being targeted in the production pipeline (Sevaldson, 2018); that is, any of the living and non-living beings (i.e. ‘resources’) well-beyond human’s direct influence, benefit, and impact, have an ability to control and play roles as active agencies within the global production system being infinite, also subject to constant negotiation, adaptation and improvement. Consequently, only a nature-driven model as one that is inherently flexible and in a constant state of openness and readiness towards change could possibly set the basis for a task that even with the most advanced computational tools is beyond humans to fully grasp, yet it incites the necessary shift of human’s mind towards a better for the planet and biosphere’s future.

2. The Post-Human-Centred CoDesign Model

Next, the above framework is proposed alongside some research-by-design examples. As explained, these projects of otherwise very different scope are linked by the hypothesis of a synergetic landscape resulting from a post-human-centred codesign model set by eco-social real-life parameters and performances, integrating bio-computational processes, targeting the highest possible complexity unachievable solely by humans or by any individual master designer alone. The presented ‘hyperobjective’ (Morton, 2013) ‘prototypical interventions’ (Doherty, 2005) unfold the interactions with larger systems through minor physical objects suggesting the ‘designs for transitions’ (Irwin, 2015). The related processes describe dynamic exchanging of matter, energy and data that is only possible through a cross-bio-technological co-design model. The three projects are:

- Hyperobjective co-design through engaging with ecosystem, new habitants and artificial intelligence - Villa Sophia (Davidová, Pánek, & Pánková, 2018; Pánek & Davidová, 2018);
- Enacting the circular economy and lifecycle of structures other than for humans: Bio-shelters design proposal for artificial coral reefs at the Sydney Harbour (Zavoleas & Heausler, 2017; Dunn, Haeusler, Zavoleas, & Bishop, 2019);
- Engaging with socio-ecosystemic networks and iterative DIY (Davidová, 2019; Davidová & Zímová, 2018)

Though different in their nature, all presented models are process-based and are being cocreated in real life and in real time, within so called ‘real life codesign laboratory’. They are therefore ‘allopoietic’, means they are autonomous, though dependent on an exchange with its environment (Dekkers, 2015)

2.1. HYPEROBJECTIVE CODESIGN THROUGH ENGAGING WITH ECOSYSTEM, NEW HABITANTS AND ARTIFICIAL INTELLIGENCE - VILLA SOPHIA

Villa Sophia (see Figure 1 and Figure 2) has been codesigned by Collaborative Collective with its natural environment, the clients and artificial intelligence system based on machine learning called Sysloop. This is occurring in real life and real time whilst the family is inhabiting the work in progress prototype in so called ’real life codesign laboratory’ (Davidová, Pánek, & Pánková, 2018). The local ecosystem and landscape driven initial design has been cocreated during its building process by new habitats on the roof and in its pond (the grass and algae water lands) and in the interior (the clients). Further on, its performance is real time cogenerated through the machine learning of Sysloop AI. From the initial input data, sensorial system, multilingual contextual library interpretations and its internet search and typical daily operations such as door lock, natural ventilation or self-playing piano interactions, the system collects, analyses and recognises various human and non-human users’ behaviours, their preferences and restrictions.

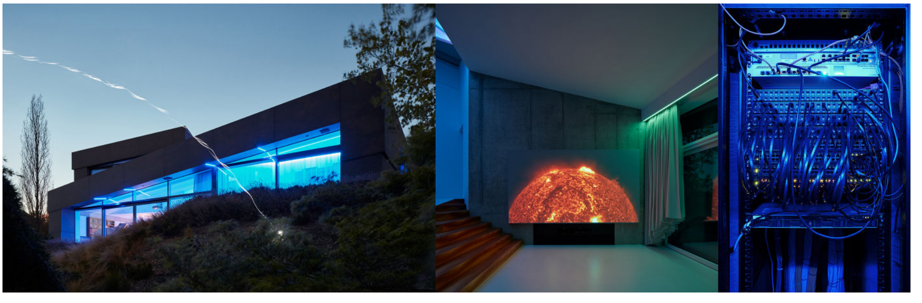

Figure 1. Villa Sophia operated with Sysloop from left to right: a) fitted into terrain the spiralling roof volume is an expansion of the grass land; b) a living room screen that next to video gaming and film screening enables communication with the Sysloop; c) one of the Sysloop’s racks (photos: Boys Play Nice 2019).

Figure 2. Living spaces of Villa Sophia with ‘self-playing’ piano (Left and right photo: Boys Play Nice 2019; central photo: Birke 2018).

For the future, the system is to be fully scalable and should be connected to the large city/state security and services smart systems (Pánek & Davidová, 2018) (see Figure 3). It is on a way to include industrial growing massproduction and other life crucial services. Therefore, the house is largely hyperobjective on multiple levels. Dependent on multiple past and real time criteria, parameters, actions and restrictions, performances and occurrences, the house can improve your and other environment's living conditions, spoil you and many other species and matters, save your or others life as well as it can decide to kill you when deciding on preferring life of someone else (non-human or human).

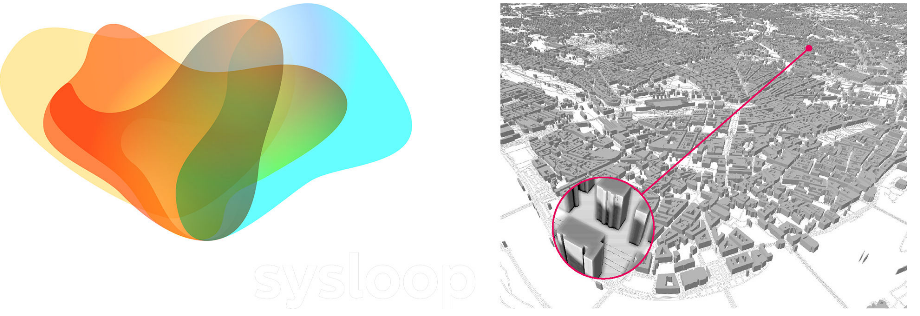

Figure 3. From left to right: a) sysloop logo representing the multiple interactive layers (Malík 2016) b) Element maps rendering within proposed system testing environment and its scalability (illustrative diagram: Davidová 2018, generative model: Pánek 2017) .

2.2. ENACTING THE CIRCULAR ECONOMY AND LIFECYCLE OF STRUCTURES OTHER THAN FOR HUMANS: BIO-SHELTERS DESIGN PROPOSAL FOR ARTIFICIAL CORAL REEFS AT THE SYDNEY HARBOUR

Figure 4. Micro features of Bio-Shelters with regards to temperature, tide and sun exposure as data-driven design inputs loaded in the script to produce alternative schemes (Zavoleas 2017).

The Bio-Shelters project applies advanced computational methods to design green coastal landscape infrastructure intended for threatened marine ecosystems. It aims to enhance the abundances of native habitat-forming organisms, which are often missing or found in low numbers due to environmental degrading (Zavoleas & Haeusler, 2017). The project claims its original character by its key point to employ nature's dynamic also context-framed logic of growth then to adapt it to artificial habitats of marine species. As they are first developed and installed into their intended site, the artificial structures may continue to grow as they are populated. As the physical structure is being populated by new marine species, nature takes over the design and co-evolves the initial scheme. The coming species manifest their water filtering function consequently cleaning the seawater and attracting more life and the cycle is restored. In effect, the growing structure alters the material, chemical, natural and life consistency of the urban coastline (see Figure 4, Figure 5 and Figure 6).

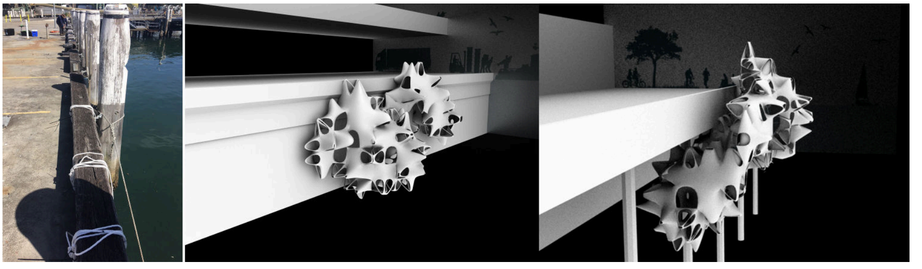

Figure 5. Indicative site (left: Yu 2019) and tests of the script adapted to different locations producing alternative results (middle and right: Zavoleas 2019).

Figure 6. Hybrid material composite samples made of concrete and crushed discarded oyster shells then used for the large prototype piece (Dunn 2019).

A series of alternative schemes are developed for different sites, set by the different environmental factors. Operational criteria described by the biologists of the research team are combined with the parameters and the specific values that describe nature's functions at each location. Such a dynamically informed approach drives design activity by natural constraints to fully integrate the resulting schemes with the lifecycle of oceanic systems. Moreover, integrating with the natural lifecycle entails that each of the results is seen as an infrastructure upon which life will build its further instances to the point that the initial structure is totally covered and is gradually superseded by the natural one. The outputs, produced out of the former marine life from the onsite fish market, due to their topological shape, typological resemblance and material consistency being similar to natural corals are sought as the sub terrain upon which marine life will find a suitable spot to build new habitats (Dunn, Haeusler, Zavoleas, & Bishop, 2016). To better support this co-evolutionary process, the initial structure ought to be fully compatible with nature's preferred design modes as a fluid structure rather than one that resists natural pressures; then, it should emerge as a site-specific solution; last, its material behaviour needs to be fully compatible with natural operations.

2.3. ENGAGING WITH SOCIO-ECOSYSTEMIC NETWORKS AND ITERATIVE DIY

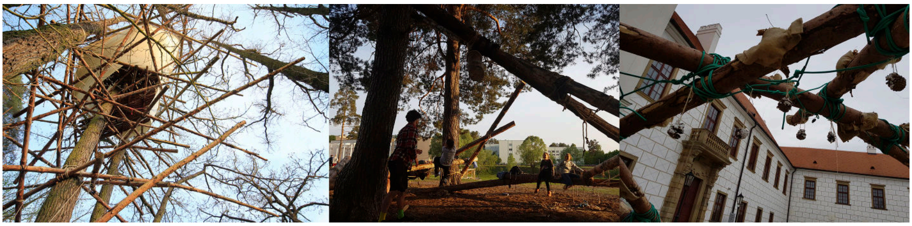

Figure 7. Spiral Projects that are exposed to human and nonhuman interaction, extending edible and habitable landscape (left photo: Zapletal 2013, middle and right photo: Davidová 2018 and 19 respectively).

Figure 8. TreeHugger insect hotels projects (photos: Davidová from left to right 2019 and 2018).

The COLridor projects (see Figure 7 and Figure 8) by Collaborative Collective are codesigned with human and non-human local communities, supporting edible and habitable landscapes trough prototypical interventions in cultural environments for their cross-related synergy. They are designed to generate biotops on biocorridors across cultural, often urban, landscapes. Those prototypical interventions are hyperobjective as they are interacting with the related ecosystemic habitats and food webs of i.e. algae, moss, early blooming plants, insects, bats and birds, providing a ground to live in and grow on as well as they are nutrients generators through their inhabitation (Davidová & Zímová, 2018). The interventions are to be scalable, parasiting or being integrated in new designs of existing and future infrastructures of dwellings, urban spaces and other landscapes. They are also hyperobjective because they provide recipes for their DIY (Do It Yourself) iterations accessible through QR codes that are engraved in them and presented at specific fairs (see Figure 9). This hyperobjectivity also covers an engagement with the community of makers of its Grasshopper plug in for Rhino users that releases it in its news (Davidová, 2019). It also covers specifically designed social events that often provide educational programs on how to support cultural landscape ecosystems. Therefore, the codesign here is performed through multiple iterations and real life modifications and redesigns as well as the interventions were codesigned with local communities themselves in their initial stage. At this moment, the project is expanding into larger Synergetic Landscapes project (discussed in a separate paper at this conference). Synergetic Landscapes project is integrating the above concepts with those of circular ecosystemic life cycle economy operated by blockchain to be codesigned by local communities from the 'bottom up'. It is asking the questions on if bats can buy an insect hotel that is their fast food restaurant or if we can pay the insects for their pollination of our community garden for which they could buy their homes, etc.

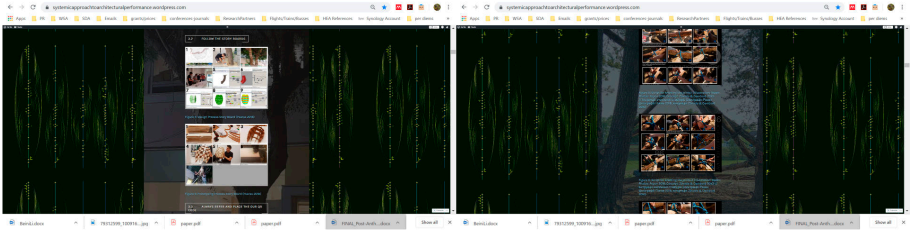

Figure 9. DIY recipes on Systemic Approach to Architectural Performance site (Davidová, 2019).

3. Nature-Driven Design: CoComputing with Humans and Nature

The post-human centred framework proposed and exemplified above assumes following extended bio-computational real life and real time codesign approaches throughout the creative course. Its main scope is not only to question the authorship and 'who' or 'what' might be the author or 'what' the outcome might look like, but to rethink the final state of design addressed through the endless interactive and iterative codesign dynamic processes that are hyperlinked and cross-related to multiple networks and interactive input flows across the biosphere. Capra (2002) states that our academic disciplines have been organised in such a way that the natural sciences deal with material structures while the social sciences deal with social structures, which are understood to be, essentially, rules of behaviour. However, Capra continues, in the future the strict division will no longer be possible because the key challenge will be to build ecologically sustainable communities, designed in such a way that their technologies and social institutions - their material and social structures - do not interfere with nature's inherent ability to sustain life. This research framework searches for synergy amongst such systems for a 'flourishing' (Ehrenfeld & Hoffman, 2013) togetherness, as well as one being inseparable.

In a typical computational approach, measurable data may enter the design scene to influence related decisions. As such, computational design may be compared with nature-driven operations, the idea being that measurable data is linked back to quantifiable information and so adding scientific flavour and validity to design strategies and the form being created. As data inputs describe natural phenomena, in a similar manner analysis and synthesis may be linked dynamically to each other. Computational models are information sources of objects (Carpo, 2011), allowing effortless data tweaks, modifications and trial-and-error experimenting as ways to carry out iterations, familiarise with the design constraints and techniques and gradually refine a design scheme. Since the 1990s, real-time simulation tools have supported dynamic occurrences on the screen such as forces, fields of attraction and repulsion, fixed and movable parts, dependencies, breaking points, and material behaviour, applied upon topological geometric shapes, which they transform. Due to their topological definition, these shapes are malleable and flexible and so they respond to any change of inputs that is registered respectively as a continuous adaptation of form to these changes happening along the design's course, in a way that simulates physical interactions in real life.

The 'real life codesign laboratory' (Davidová et al., 2018) methodological approach examined above proposes a transition of focus from a design that is purely driven by aesthetic and functional standards to one that is 'verified' / cocreated by its real time compatibility with ecosystems‘ life cycles. The notion of ecosystem refers to a totality of performances managed wisely by its operations and every instance of it is a manifestation of its principles, which with the synergy of multiple social systems and advanced computing may to some extent be studied, approximated and transferred to human-made interactions towards the Post-Anthropocene era. In other words, in the post-human-centered codesign model, computing becomes a collaborative agency within nature's complexity and cross-species social networks being an offer of often greater value of networking or compositional performance: an action by which humans as well as computers may surrender their control over a scheme's future, as the moment it is completed, it is when it also starts to colive on, coevolve, cogrow and cointegrate with nature. Bratton states that if the Anthropocene proves more a fleeting geopolitical instant than a slow geological era - waves of apes maniacally excavating ancient carbon and drawing loops on maps - then whatever comes 'next‘ would be formed not by the same anthropos but by something literally post-, un-, in-'human‘, for better or worse' (Bratton, 2019). Such a transition may however also happen through post-apocalyptic synergetic landscapes that are evidencing their natural succession, moving to ones of cocreation, coexperience and coliving.

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AN ETHNOGRAPHIC ENQUIRY INTO DIGITAL DESIGN TOOL MAKING

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Abstract. This paper presents an ethnographic pilot study into the design and application of digital design tools in a leading Shanghai-based architecture and engineering firm. From a participant observer's point of view, we employ qualitative research methods to enquire the conditions and experiences entailed in day-to-day collaborative activities in conjunction with the custom-development of digital design tools in advanced practice. The described initial ethnographic enquiry lasted for six weeks. While previous studies tended to favour post-rationalised and outcome-focused reports into toolmaking for design, we observe through participant observation that daily collaboration in practice is multi-faceted and overwhelmingly more complex. This paper further portrays and reflects on the concomitant opportunities and challenges of participant observation as a research method that can bridge academia and practice. We argue that, in order to appreciate and to inform digital design toolmaking practices, it is essential to recognise the richness of practice, in and of itself.

Keywords. Digital design toolmaking; custom-developed tools; collaborative processes; ethnography; participant observation.

1. Introduction

With the growing importance of landmark architecture and the digitalisation of advanced design practice, parametric façade design requires project-specific design workflows as well as custom-developed digital tools (Santos et al., 2012, pp. 87–88). In many advanced architectural and engineering practices, digital design toolmaking has prompted the rise of multidisciplinary teams consisting of architects, engineers, consultants, and other experts – who collaborate closely with one another on a day-to-day basis (Altintas et al., 2019, pp. 333–334). Despite having gained considerable importance in practice, however, design toolmaking processes remain largely unexplored as a subject of academic research.

Previous research tended to focus on features, capabilities, applications and outputs of digital (design) tools, often neglecting the conditions and the "design experiences" (Yaneva, 2009, p. 104) entailed in daily collaboration between tool users and toolmakers. This study investigates how custom-developed digital

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 213-222.

design tools take shape within applied façade design and fabrication practice, specifically at Rice Francis Ritchie (RFR) Shanghai – a firm that is known to create and apply custom tools on a per-project basis. We employed participant observation and the analysis of field notes – an ethnographic qualitative research approach that is gaining popularity across the architectural landscape. The purpose of our investigation is to shed light on a unique culture of practice-based collaboration, its design decision-making, its division of labour as well as other types of negotiation that underpin the day-to-day creation of digital tools in advanced practice. The data and insights presented in this study are expected to provide a foundation for further research in this area.

2. Digital design tools

"Tools mediate our engagement with the world." (Baber, 2003, p. 3) They are integral to our self-image as humans. Tools are artefacts or systems by which we affect change. They are particularly relevant to us where our agency relies on technology, which is the case, in particular, in the design context (Fischer, 2008, p. 12). In industrialised contexts, tools are typically created by someone for someone else, and, usually, the toolmaker (who can also be the tool user) knows and understands the future application of the tools (Fisher and Herr, 2007, p. 381). "It is assumed that the user of a tool has likely not been involved in its ideation and development" (ibid.). This is certainly the case in the development and application of Computer-Aided Design (CAD) software packages, as designers do not necessarily have software development skills (ibid., p. 382). Furthermore, tools are commonly made by few, to be used by many. The generalisation at play here may not be applicable in digital toolmaking, as the custom design tools tend to addresses highly particular design challenges.

2.1. COMPUTER-AIDED DESIGN (CAD) TOOLS

Following the Second World War, the initial development of CAD systems was a part of a broader effort to convert wartime technological advances for commercial use. Bottazzi (2018, pp. 9–11) explains that military technologies were stripped down to "their more general features in order to make them applicable to as many problems as possible, including unforeseen ones". Through recurring feedback and iterative evaluation from users, software engineers could generalise patterns of paper-based design practice to digital techniques. On the following years, this propelled the development of early CAD tools (ibid.). Collaboration between users (including designers) and software engineers prompted the development of more robust CAD packages which, as digital technology became more accessible to designers, infiltrated design offices and education (ibid.). CAD tools increased productivity, particularly in the transition of conceptual design from offices to construction sites. Architectural firms such as Gehry Partners, Eisenman Architects, and Objectile are known to collaborate with software developers from the ideation to the realisation of specific CAD tools (ibid.).

2.2. PARAMETRIC MODELLING

The increasing pervasiveness of parametric thinking and modelling in present-day architectural arenas can be seen as a response to the limitations of conventional CAD packages, which operate in chronological and linear ways – often defining geometric entities independently without any associativity with other entities present in the interface (Goldberg, 2006, pp. 102–103). Parametric systems introduce a shift from conventional drawing methods (as in the case of 2D and 3D drafting) that nurture "the propagation of the difference" and "repetition of the variation" – the *sine qua non* for "non standard", yet precise design proposals (ibid.).

In his dissertation, Davis (2013, pp. 14–15, 30–32) observes that numerous definitions of *parametric modelling* tend to focus on its propensity to generate output rather than on its functional mechanisms. In an attempt to link parametric modelling back to its original meaning devised through the collaboration of pioneer scientists and mathematicians in the nineteenth-century (ibid., p. 31), Davis suggests that a parametric model should be seen as "a set of equations that express a geometric model as explicit functions of a number of parameters". While it is understood that parametric modelling augments designers' agency through the variability of outcomes and potentially assists design processes, it has often been criticised for its reusing and sharing inadequacies (see section 6) (ibid., pp. 40–41, 45).

2.3. CUSTOM-DEVELOPED DIGITAL DESIGN TOOLS

"Digital design is now fully assimilated into design practice, and we are moving rapidly from an era of being aspiring expert users to one of being adept digital toolmakers" (Burry, 2011, p. 8). Designers are shifting from 'mere' parametric modelling to adopting scripting cultures – ongoing practices that are encouraged in both education and professional environments. They account not only for the extensive body of work in that area but *de facto* also for the rise of interdisciplinary collaboration between tool users and toolmakers to provide a more communicative and supportive interface for architects, engineers as well as other allies within and across AEC teams (Qian et al., 2010, p. 58).

The development of in-house project-specific digital design tools is now commonplace in advanced architectural and engineering firms such as Gehry Partners, Foster Partners, ARUP, and RFR, amongst others. These custom-developed tools are relevant where particular design challenges are addressed that include, but are not limited to: "(1) design task automation, (2) extension of CAD application features, (3) customisation and procedural generation of parametric models, (4) algorithmic exploration of different design options, (5) 3D printing optimisation, (6) implementation of digital fabrication protocols, (7) deal with complex models, and (8) pursue exhaustive design exploration through the manipulation of scripted parametric models" (Santo et al., 2013, p. 87). The current practice has generated a new group of specialised digital toolmakers who support "design projects with specific tools as needs develop in the context of applied design projects" (Fischer, 2008, p. 4). However, research on how digital design tools take shape and on the nature of collaboration among tool users and digital design toolmakers remains scarce as “failures and dead-ends” are often masked in reports (ibid., p. 245).

2.4. COLLABORATION AND CO-OPERATION

Digital (design) tools have changed collaborative activities among designers both across professional and educational platforms (Kvan, 2000, p. 409; Santos et al., 2012, p. 90). In his research on the nature of collaborative work in design practices, Kvan distinguishes two modes of joint creative effort among design team members – *close-coupled collaboration* and *loose-coupled co-operation* (see Figure 2) (Kvan, 2000, pp. 410–412). He postulates that many design activities constitute loose-coupled co-operation – with each actor within a particular design community contributing to different aspects depending on their expertise and “knowledge appropriate to the situation” (ibid.). However, based on the qualities of close-coupled collaboration, Kvan argues that “A loose-coupled design process requires a very much different set of tools and conditions to be successful than a close-coupled one” (ibid., p. 415). Fischer and Herr (2007, p. 383) echo Kvan’s position and suggest the possibility of having a “distinct type of tool appropriate for each kind of collaboration”.

2.5. RESEARCH GAPS AND MOTIVATIONS

There has been a large number of reports on the production and use of digital design tools in the CA(A)D field. Many of these reports are post-rationalised and outcome-focused, with a tendency towards describing features, applications and outputs of tools (Fischer, 2008, p. 245). The conditions and experiences entailed in their design and development, by contrast, remain unexplored. Furthermore, Yaneva (2017, p. 160) argues that theory-building has a propensity to simplify and purify the practice of architecture. In her ethnographic enquiries on diurnal collaboration in applied practice, she posits that other actors, such as clients, contractors, governmental bodies, and many others, possess the ability to influence design decisions, processes and making. Accordingly, in order to inform design practices, it is essential to do justice to the richness of day-to-day collaboration in practice. This paper investigates and highlights how custom-developed digital design tools take shape within applied parametric façade design and fabrication practice at RFR Shanghai. Through participant observation and the analysis of field notes, we record and examine the “performative and fluid” (ibid.) dances of agency embedded in daily collaboration between architects, engineers and other allies of the profession in support of digital design toolmaking.

3. Study framework

The scope of this pilot study is limited to the observation of a particular parametric design process for one of RFR’s commissioned projects. The participant observation enquiry was carried out by the lead author for six weeks from mid-October until the end of November 2019. Before engaging in fieldwork, we obtained the research ethics approval from our institutional body as well as consent from our professional collaborators at RFR. The site informants were briefed about this research and the role of the lead author as an *academic researcher* actively contributing to toolmaking initiatives for one of their projects while also ethnographically recording related negotiations, design decisions, strategies and considerations. Following consent approval from our industry colleagues, the lead author engaged *in-situ* at several weekly intervals to participate in, and observe, the design practice at RFR. Our initial observations focused on different modes of day-to-day collaborative activities among the architects, engineers and other professionals. The lead author collaborated with two structural engineers (Florian and Wanning) on the development of a tool to realise a particular idea of an irregular geometric assembly while harnessing sameness for cost-effective batch production for *Tai Ping Qiao Roof Gallery*, a project commissioned by Kohn Pedersen Fox (KPF) architects to RFR.

4. Ethnography and participant observation

Developed by cultural anthropologists, ethnographic research involves observing people's engagement and interaction within the contexts of their living or work to uncover "social data that is not theory-driven" (Lloyd and Deasley, 1998, p. 103). Formerly employed in Non-Western societies, ethnography concerns the study of "how culture is brought to life" (Ladner, 2014, p. 15) and shared through recurring activities of individuals or groups of people in a particular social setting. While ethnographic research seems scarce within the architectural landscape, it is growing in popularity in CAAD research – particularly in practice-based research (Bhavnani et al., 1996, pp. 244–245). For instance, Qian et al. (2010) employed participant observation at *Bentley's GenerativeComponents* to discover designerly patterns that could be generalised and applied within the contexts of parametric modelling.

As initially described and employed in the anthropological context by Bronislaw Malinowski, participant observation is an ethnographic data collection method that is also well-established in disciplines other than cultural anthropology, such as sociology, psychology, education and many others (Qian et al., 2010, p. 62; Yavena, 2018). It aims "to develop a holistic understanding of the phenomena under study that is as objective and accurate as possible given the limitations of the method" (DeWALT and DeWALT, 2011, p. 110). Spradley (1980, p. 58) explains participant observation as commonly entailing different degrees of involvement from the researcher. At one end of this spectrum, the researcher can be seen as a *complete participant* – fully embedded in activities and interacting with his informants. At the centre of Spradley's scale of involvement, the researcher is a *moderate participant* in the sense that the "ethnographer seeks to maintain a balance between being an insider and an outsider, between participation and observation" (ibid., p. 60). At the opposite end of this spectrum, the ethnographer can be seen as a *complete observer* of social scenes while also recording their observations.

In the same vein, Robson and McCartan (2016, p. 323) view the role of the ethnographer as someone who seeks "to become some kind of member of the observed group". While this indicates issues with subjectivity and is potentially criticised for not conforming with scientific research standards, Robson and McCartan (ibid.) suggest that, in the study of people and their context, scientific objectives “can be followed by explaining the meaning of the experiences of the observed through the experiences of the observer”. It is only through participation with those involved that we can “interpret” our observations (ibid.).

5. Data collection procedure at RFR

In the initial phases of the study, we carried out several rounds of interviews with the professionals at RFR to obtain an overview of the mechanics of their practice with regard to timing, modes of collaboration and frequency of office meetings to address digital design toolmaking initiatives. Acquiring and analysing this data allowed us not only to develop rapport with our collaborators but also served the scheduling and coordination of our field engagement and its alignment with the academic components of our research project.

Our ethnographic study at RFR encompasses two main activities – first, participation, observation and data acquisition, and second, detailed data analysis. In the first phase, the lead author played two different roles – first, “close to the actors and the course of their actions, intervening and participating in little tasks; and [second], at a greater distance so as to be able to translate and inscribe traces of actions and speech acts” (Yavena, 2018, p. 84). For each *in-situ* ethnographic immersion, the researcher gathered data in the form of extensive field notes, voice recording, texts, photographs, screenshots, digital drawings, codes and scripts. In the following stage, we analysed and transcribed the acquired data to find recurring patterns of collective acts and actions, division of labour, the rhythm of design processes as well as different modes of collaborative activities in support of toolmaking initiatives.

As participant observation involves immersion of the researcher within the observed context, the researcher is exposed to a wide spectrum of information, both physical, virtual, and, potentially both interrelated with one another. Spradley (1980, pp. 81–83) designs an ethnographic matrix that serves as a toolkit to dissect “social situations” encountered over the course of a participant observation study. He proposes “grand tour questions” (general questions, highlighted in blue in Figure 1) and “mini-tour questions” (specific questions) to obtain rich and descriptive accounts of the population and context. Spradley points out nine dimensions to observe and sample during field engagement (ibid.). These include *space*, *actors*, *activities*, *objects*, *acts*, *events*, *time*, *goals*, *feelings*. In our investigation on the social dimension and toolmaking initiatives in applied practice, we adapted Spradley’s matrix in an attempt to investigate the interrelationship between each of the abovementioned dimensions, as seen in Figure 1.

	Space	Object (obj.)	Act	Activity (actv)	Event (evt)	Time	Actor	Goal/ Objective (g/o)	Feeling
Space	**Where do t/m occur?**	Where are *obj.* for t/m located?	Where do acts for t/m occur?	Where do *actv* for t/m occur?	Where t/m *evt* occur?	When are spaces changed for t/m?	Where do actors work on t/m?	Where are t/m *g/o* sought and achieved?	Where do actors express feelings?
Object (obj.)		**What *obj.* are used for t/m?**	How *obj.* are used in t/m?	How *obj.* are used in t/m *actv*?	How *obj.* are used in t/m *evt*?	When are *obj.* used?	Who uses *obj.* for t/m?	How obj. are used in seeking *g/o*?	How *obj.* affect feelings?
Act			**What are the t/m acts?**	How acts affect t/m *actv*?	How *evt* affect t/m acts?	How t/m acts change over time?	How actors act for t/m?	How acts affect t/m *g/o*?	How acts affect feelings?
Activity (actv)				**What *actv* contribute to t/m?**	How *evt* affect t/m *actv*?	How t/m *actv* unfold over time?	Who are involved in t/m *actv*?	How *actv* affect *g/o*?	How *actv* affect feelings?
Event (evt)					**What *evt* contribute to t/m?**	How *evt* for t/m unfold over time?	Who are invloved in t/m *evt*?	How *evt* affect g/o?	What are the feelings in t/m *evt*?
Time						**What are the time periods for t/m?**	When do actors collaborate for t/m?	When are *g/o* archieved?	When are feelings evoked?
Actor							**Who are the actors involved in t/m?**	How do actors achieve *g/o*?	What are the feelings of actors during t/m?
Goal/ Objective (g/o)								**What are the *g/o*?**	How *g/o* affect feelings?
Feeling									**What are the feelings during t/m?**

Note: t/m refers to toolmaking processes

Figure 1. Ethnographic Toolkit. Image adapted from Spradley (1980, pp. 82–83).

6. Insights gained and future work

Over the course of our ethnographic pilot study, we gained several key insights pertaining to, on the one hand, day-to-day practice-based collaboration and on the other, the challenges concomitant with participant observation as a qualitative research method in the CAAD world. Firstly, we noticed that the purity of existing, post-rationalised and outcome-focused research is not quite similar to what the lead author encountered and experienced at RFR. As mentioned in Section 2.4, Kvan (2000, pp. 410–412) observes two modes of design collaborative systems within and across AEC teams – *close-coupled collaboration* and *loose-coupled co-operation* (see left side of Figure 2). Throughout our investigation, we observed that architects and engineers not only engage in loose-coupled co-operation but also close-coupled collaboration depending on the development and delivery time of projects. For instance, during the deadline period for one of *Tai Ping Qiao Roof Gallery's* design development phase, Florian and Wanning engaged in a close-coupled design process rather than a loose-coupled one. We hypothesise this observation as to ensure proper and productive communication and sharing of data between them as well as to meet all the delivery outcomes and requirements. Likewise, each of our industry informants collaborates in small groups on several projects (usually between 2 and 4) running in parallel, *de facto* implying the presence of mixed-mode collaborative design processes at the office (see right side Figure 2). In an interview with Florian, he revealed that knowledge sharing and data reuse between projects are desired targets to increase productivity.

Contrary to popular belief regarding the difficulties to reuse parametric models (Davis, 2013, p. 45), we noticed that our professional collaborators at RFR tend not to discard codes and scripts but, instead, archive and share them through a virtual library running on the office network system. Florian seeks to generalise his codes and scripts as much as possible in an endeavour to share them with colleagues who might not possess as much scripting expertise as well as for future reuse to support projects of similar kinds.

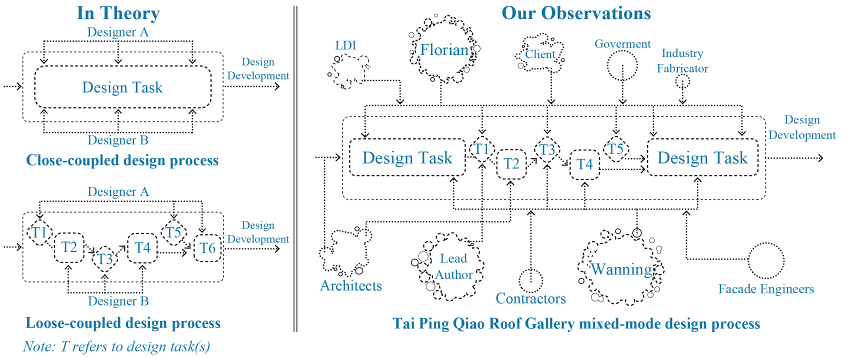

Figure 2. Left side: Collaborative activities in theory (adapted from Kvan, 2000). Right side: Collaborative activities in practice.

We encountered some challenges associated with participant observation. These challenges concern: striking a balance between academia and practice; the researcher's intended role at the office; staff retention and challenges beyond our agency. Initiating an ethnographic study in advanced practice, required numerous background processes prior to the start of the field investigation. While these involved multiple formalities such as ethics and consent approvals, one of the primary trade-offs was to find an alignment between the timeline of the academic research with the project schedule of our collaborators. For instance, by the time we were able to launch our investigation at RFR, the *Tai Ping Qiao Roof Gallery* project had already begun and passed some milestones in the design development phase. Secondly, we encountered a social challenge inherent to collaborative practice as we saw a change in the lead author's expected role at RFR. Entering the engagement with a particular understanding of his role, he saw his role change during the participant observation study. He expected to collaborate in support of design toolmaking initiatives with Florian and Wanning, but *de facto* found himself co-operating with them. We formulated several hypothetical explanations for this experience. This shift may have been: (1) an effect of the sitting order in the office since, due to space limitations, the lead author did not work at the same table as his industry colleagues, (2) a consequence of his experience in using digital design tools, which may have suggested that he can work autonomously. In future investigations, we are determined to engage over more extended periods of enquiry to explore and gain a better understanding of these socially-driven collaborative activities in practice – processes that we understand to be critically important and which may not be readily explicit.

We found Spradley's (1980, pp. 81–83) ethnographic matrix a valuable tool within and across the digital design field. Despite demanding significant time and rigour "to be able to translate and inscribe traces of actions and speech acts" (Yavena, 2018, p. 84) of our informants, however, we could not fully explore our adapted ethnographic toolkit in our six weeks of fieldwork. The reasons for this are twofold. Firstly, we witnessed an unexpected level of staff movement during our practice engagement. One of the firm's leading talents and our key informant changed the nature of his contract with the company and decided to launch his own start-up practice. While this should be acknowledged as a feature of ethnographic research, within the time scope of our study, it effectively became an impedance to our investigation. Secondly, around the same time, the COVID-19 pandemic restricted people's movement. It changed the nature of collaborative work in practice and severely limited the possibility of academic fieldwork. In future studies along this avenue, we intend to carefully consider to what extent the nine dimensions of the toolkit may need to be adapted to particular social and practical contexts while remaining open to unpredictable economic, social, environmental, and political events.

7. Conclusion

As others have pointed out, the inadequacies of standard CAD packages have prompted the increased use of parametric modelling systems while also encouraging the emerging scripting culture among practitioners in the field. In advanced architecture and engineering practices, multidisciplinary teams comprising architects, engineers, consultants and other experts are orchestrated to collaborate on a day-to-day basis in support of project-specific digital design tools (Altintas et al., 2019, pp. 333–334; Fischer, 2008, p. 4). While previous reports on digital design toolmaking have a propensity to be post-rationalised and outcome-focused, we presented in this paper a short-term ethnographic enquiry that sheds light on how in-house project-specific tools are crafted within applied design practice at RFR Shanghai.

Throughout our participant-observer study, we gained key insights that fall in two categories – day-to-day practice-based collaboration, and participant observation as a qualitative research method. In theory, it is often understood that designers engage in loose-coupled design processes rather than close-coupled ones. However, depending on our projects' schedule, we observed that our collaborators at RFR employ a mixed-mode collaborative practice which we assume serves to increase productivity during deadline periods. Despite frequent references to the challenges of reusing and sharing codes and scripts, our informants maintain a shared repertoire of generalised digital tools to address future and recurring design challenges.

One of the early issues we encountered was a challenge to coordinate between academic research and practice-based enquiry. In our view, this entails numerous uncertainties that can impact prospective investigations during critical design phases. We also noticed that collaboration in practice is socially-driven and may not be readily explicit to record and analyse. In future studies in this direction, Spradley's ethnographic matrix is expected to serve as a valuable tool to decipher the mechanics of these social processes. Finally, we reported some challenges beyond our agency that are associated with participant observation. We believe that the CAAD research and design field has an under-utilised need and potential for ethnographic enquiry of this kind, offering opportunities to engage and to better understand design practices in their full richness.

Acknowledgements

We gratefully acknowledge our informants at RFR Shanghai for their valuable time and contribution to this participant observation study. We also thank KPF for sharing details of the *Tai Ping Qiao Roof Gallery* project.

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SENSIBILITY AT LARGE

A Post-Anthropocene Vision for Architectural Landscape Editing

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Abstract. The irreversible imprint of humankind on Earth calls for revisiting current construction practices. This paper forwards a vision for post-Anthropocene, large-scale, architectural, and landscape construction. This vision relates to transforming natural terrains into architecture using on-site robotic tools and enabling greater sustainability through increased sensibility. Despite advancements in large-scale digital fabrication in architecture, the field still mainly focuses on the production of objects. The proposed vision aims to advance theory and practice towards territorial scale digital fabrication of environments. Three notions are proposed: material-aware construction, large-scale customization, and integrated fabrication. These aspects are demonstrated through research and teaching projects. Using scale models, they explore the deployment of robotic tools toward reforming, stabilizing, and reconstituting soil in an architectural context. Together, they propose a theoretical ground for in situ digital fabrication for a new era, relinking architecture to the terrains upon which it is formed.

Keywords. Digital Fabrication; territorial scale; on-site robotics; geomaterials; computational design.

1. INTRODUCTION AND BACKGROUND

1.1. DIGITAL FABRICATION: FROM OBJECT TO ENVIRONMENT

Architecture and construction held a significant role in the Anthropocene epoch, marking an irreversible geological imprint of humankind on the planet. In light of this acknowledged imprint, the ethics of various practices are revisited and reiterated (Gibson et al. 2015). As the construction industry is a significant contributor to global energy consumption, waste-creation, and greenhouse gas emissions, the continuing expansion of built environments demands a new approach towards the further shaping of natural terrains into the built fabric. In this context, natural grounds can no longer serve as canvases and backdrops of architectural intervention - they must become central factors in design. This voice is increasingly present as the ecological imperative shapes architectural

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 223-232.

discourse. In this discourse, theorists and practitioners alike call for advancing more sustainable construction practices; reducing construction waste; limiting material transport; and returning to raw, locally sourced materials derived from the earth (Přikryl et al. 2016).

Since their introduction to the field, digital tools and computational design have changed the way architecture is approached, designed, and produced (Carpo 2013). Initially, the industrialization and automation of building processes laid the ground for standardization and progress in construction. But it was also the beginning of massive material transport in the construction industry (Bock and Langenberg 2014). If deployed sensibly, though, the very same tools that enabled architects to industrialize construction can now help to improve sustainability in the building process (Agustí-Juan and Habert 2016). Applying in situ digital fabrication, relying on native materials, and deploying sensible autonomous tools can help to tailor construction to local conditions and environments. The reconstitution of geomaterials can both limit the material extraction in the industry and reduce the transport practices that characterize contemporary construction.

In situ fabrication research presents new capabilities to adapt to the site, scale, material, and environmental conditions (Loveridge and Coray 2017). Such tools allow architects to go beyond the confinement of factory and laboratory walls and couple advanced fabrication abilities with a sensitivity to the building site, terrain, and geomaterials. Though one might argue that the field of landscape architecture has always maintained such sensibility, throughout time, the distance between the designer and the site increased (Girot 2014). Current construction practices typically involve significant earthwork, soil removal, and transport during site preparations. As scale increases, so does the extent of soil removal from the site on the one hand, and material transport to the site on the other. This practice is profoundly impacting humankind's alteration of the earth. Post-Anthropocene fabrication at a territorial scale, therefore, calls for relinking architecture and the terrains upon which it is built. This paper begins to test this approach through several explorations in robotic groundscaping and reconstitution of soil from the Negev Desert, southern Israel (Figure 1).

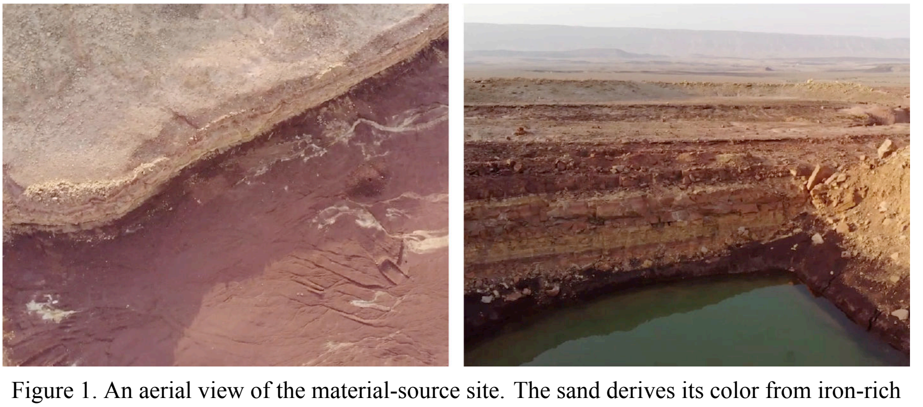

Figure 1. An aerial view of the material-source site. The sand derives its color from iron-rich minerals that have gone through thousands of years of oxidation processes (MTRL, 2019).

2. PAPER AND STRUCTURE

This paper proposes a vision for a revised relationship between natural terrains and autonomous tools, which can enable architects to practice sensibility at large. This vision relates to material, scale, and process in digital fabrication in architecture, and is illustrated by preliminary research conducted towards it. Three core notions are presented and demonstrated:

1. **Material-aware construction** - Responsible material approaches at a large-scale can encourage returning to geomaterials for reforming, repurposing, and reconstituting them to architectural artifacts. This can be supported through adaptive fabrication processes allowing to handle the uncertainty which geomaterials involve.
2. **Large-scale customization** - Applying variability and custom tailoring to large-scale architectural construction can assist designers to more accurately edit landscapes, and not only shape objects, but entire environments. This can enhance sustainability and alignment with the site's ecology during architectural construction.
3. **Integrated Fabrication** - Combining subtractive, additive, and formative techniques can facilitate multimode fabrication processes. Digital fabrication typically distinguishes between three processes: subtractive - resulting in removing material; additive - accumulative material formations; and formative - handling or assembling materials in the construction of the artifact (Chua et al., 2010). Large-scale digital fabrication challenges this distinction, as these processes may be applied repeatedly, in parallel or sequence, going beyond existing notions of hybrid fabrication.

3. STATE-OF-THE-ART AND THEORETICAL CONTEXT

3.1. MATERIAL-AWARE CONSTRUCTION

This notion will be examined through the following aspects:

1. **Material processes** - The importance of materials in digital architecture is increasing, as their position has shifted from a selection determined at the end of the process to drivers of design (Kretzer 2017). Additionally, awareness of material behavior during fabrication processes emerges, leading to the development of iterative, material-aware fabrication protocols (Raspall et al. 2014). However, current research on material awareness remains object-focused and not context-related. In other words, current practice is centered on questioning how material informs the shape or nature of an artifact but does not relate to the material-relations the object has with its environment.
2. **Material sources** - Material sourcing in architecture is gaining increased attention. This attention is manifested in mapping and analysis of material sources and flows, as well as in documentation of the transport involved in large-scale and landscape construction (Hutton 2019). This awareness is related to the cradle-to-cradle (C2C) approach emerging in the field of design, which seeks to promote holistic material cycles (McDonough and Braungart 2010). Contemporary earth construction shares a similar motivation, renewing the link between community, native matter, and traditional skills (Heringer et al. 2019).

This practice could greatly benefit from its coupling with robotic tools. The latter can enable faster construction, reduced manual labor, and advanced formative processes. Although digital fabrication with earthen materials is beginning to be explored, reforming materials in their environment remains marginal.

3. **Native matter and geomaterials** - While advancements in additive manufacturing enable to 3D print a growing range of materials, aside from a few examples, contemporary digital fabrication is only beginning to return to native matter -soil and clay found on-site (Rael and Fratello 2018). Utilizing on-site resources was an elemental feature and the necessity of ancient building practices across the globe. Material availability, climate, and environmental conditions unique to each region, therefore, determined earth-building techniques (Jarzombek, 2014). Digital fabrication allows designers to reestablish this link between architecture and on-site matter.

3.2. LARGE-SCALE CUSTOMIZATION

Despite growingly larger scales reached with digital fabrication, and increasing in situ manufacturing capacities, the current focus is still on the production of objects (Labonnote et al. 2016). Digital fabrication of architecture or landscape architecture in vast, territorial scales is only beginning to be explored (Wallis 2016). Additionally, increasing in situ capacities enable the adaptation of robotic tools to complex production environments. Deployed in this context, robotic tools require an increased sensibility to non-even substrates, unstructured production environments, and unpredictable materials (Loveridge and Coray 2017).

Research on large, on-site digital architectural manufacturing includes explorations of digital fabrication in remote, hazardous, or extra-terrestrial territories. These present ideal case studies in coupling autonomous in situ digital fabrication with on-site resources (Cesaretti et al. 2014, Lim et al. 2017). In landscape architecture, this capacity is demonstrated in employing advanced sensing, visualization, and autonomous robotic tools for the manipulation of natural terrains (Hurkxkens et al. 2017). The integration of digital tools into landscapes is used to enhance and manage natural systems, signaling a new role for technology in forming responsive landscapes. These exemplify ways to simulate an alternative course of operation or directly enhancing natural environments and systems through sensing, monitoring, or corrective-operation capacities. To this end, computational design tools are employed in tandem with advanced sensing and programming (Cantrell and Mekies 2018).

Recently, digital tools began to encompass the physical shaping of landscapes and terrains, using a topological approach (Girot 2014). In many ways, this re-establishes a lost and intimate link between architecture and landscape architecture - the two ‘topographical arts’ - to the ground upon which they are formed (Leatherbarrow 2015). Current research exhibits the potential for addressing territorial scale challenges with digital tools (Wallis 2016). However, this shift requires a focus change from object-oriented to environment-directed fabrication. While the former is structure-centered, the latter requires factoring a range of natural, material, and environmental considerations into the production.

3.3. INTEGRATED FABRICATION

As digital fabrication advances, the role and relationship between the conventionally distinct fabrication categories - subtractive, additive, and formative - are being challenged. This challenge is manifested by coupling distinct techniques into multimode protocols, as well as by blurring the distinction between them. This shift is largely supported by introducing industrial robotic arms to architectural fabrication. Though the coupling of techniques was explored before this process (Hur et al. 2002), the ability to integrate custom robotic end effectors greatly contributes to the possibility of performing multimode fabrication. In this context, detachable end effectors provide the necessary flexibility to apply multiple tools in the course of a single production process. This process is referred to in the literature as multimode, hybrid, or compound fabrication, and involves either sequential or parallel processes, multiple materials, and various scales (Mostafavi et al. 2019). This paper argues that large-scale digital fabrication upon natural terrains or using geomaterials challenges these notions as it may involve multiple processes performed on a single material.

The distinction between the three processes is challenged when addressing a territorial scale. For example, when robotic tools are deployed for shaping natural grounds, performing autonomous earthwork, and direct landscape manipulation (Hurkxkens et al. 2017). While one might argue that robotic excavation is a subtractive technique exercised on a large-scale, if, for instance, the removed material is then repurposed for filling a nearby embankment (as an autonomous cut and fill operation), this definition is rendered limited. The shift from object-based to territorial-oriented robotic fabrication thus challenges conventional notions. In a territorial scale and on-site robotic fabrication, each robotic act is part of a more complex fabrication process. When the material of the site is used to form the architectural artifact, and when this process takes place through robotic tools, the processes are better defined by their role and sequence in the specific fabrication protocol. To support multiple fabrication processes in natural environments, the paper suggests the notion of 'integrated fabrication.'

4. EXPANDING THE FIELD: CASE STUDIES

A series of experimental protocols were explored, each referring to the previously discussed frameworks: material-aware construction, large-scale customization, and integrated fabrication. The experiments demonstrate avenues for post-Anthropocene digital fabrication of architecture.

4.1. MATERIAL-AWARE CONSTRUCTION

Recent research on geomaterials, defined as inorganic materials sourced from the crust of the Earth, marks an environmentally-driven return to construction with native matter (Přikryl et al. 2016). The coupling of geomaterials with robotic tools enables the expansion of fabrication by reconstituting materials on-site. Preliminarily research focused on testing material reconstitution was conducted using a small-scale, in-lab robotic cell in order to examine the feasibility of large-scale, in situ 3D printing of on-site soil.

The cell was comprised of a six-degrees-of-freedom, waterproof KUKA KR6 industrial robotic arm, further equipped with a custom pneumatic extruding end-effector. The extruder has an ¼" air inlet and operates at an average air consumption of 6 CFM, which can be provided by either a stationary or mobile standard air compressor. The extruder can hold up to ˜300ml in reusable cartridges and was filled with mixtures of sand extracted from the Ramon Crater (Negev Desert, southern Israel) and silicone, mixed in a 1:1 and 3:2 rations. The diameter of the printing nozzle in the set up varied between 2-7mm (Figure 2).

In contrast to conventional 3D printing methods, which employ the use of off-the-shelf proprietary or open-source slicer software (Cura, KISSlicer, Slic3r, etc.), the goal was to develop a custom-toolpath generation method. This method is an inherently scalable - enabling to focus on the relationship between the printing parameters, and not merely on the production of specific geometries. Instead of conforming to off-the-shelf software limitations, toolpath planning for the robot was generated using a combination of digital tools (Rhinoceros 3D, Grasshopper, and KUKA WorkVisual). The results, a series of robotically 3D printed stabilized sand structures, explore ways and processes for reconstituting native matter (Figure 3). While the results are preliminary and in a limited scale, they enabled to test multiple material compositions, various geometries, and detailing. Future research will examine this method in a larger scale, with more advanced material compositions, and using enhanced sensing capacities.

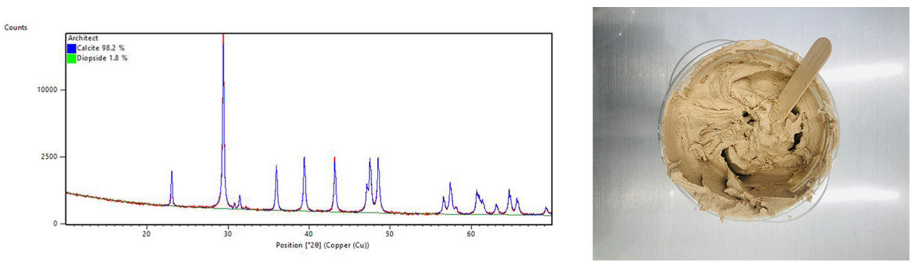

Figure 2. Mechanical and chemical material analysis conducted for developing a recipe of a cementitious material using locally sourced aggregates extracted from the Ramon Crater. The tests were conducted at the Laboratory of Alternative Binders, Technion IIT (MTRL, 2019).

Figure 3. Printed samples of architectural details using the various sands available on-site. Work by students Elena Tabakova, Hala Hamzi, and Noa Gigi (MTRL, 2019).

4.2. LARGE-SCALE CUSTOMIZATION

The freedom from machine boundaries enables digital fabrication to be extended outdoors, and applied towards manufacturing both architecture and landscapes. This allows applying variability and custom-tailoring, at no extra cost, to formerly unaddressed and potentially very large-scales. In this context, customization can increase in scope and scale, beyond the manufacturing of parts and elements. Large-scale customization may include digital fabrication of environments, as well as their reshaping into architecture. This is exemplified through a design-to-fabrication studio led by the authors. Here, architecture students examined strategies for robotic-forming simulating the autonomous construction of lunar habitats. The research drew upon the iterative methodology for robotic groundscaping (Bar-Sinai et al. 2019). The context of extra-terrestrial architecture presents an ideal case study in coupling in situ digital fabrication, large-scale, and on-site resource utilization (Lim et al. 2017).

The presented project envisions a robotic preparatory ground strategy for aggregating lunar soil into distinct piles, serving construction by enabling easy in-situ resource utilization (Figure 4). The objectives were: to devise a ground-forming strategy and design tools that will allow to expose, aggregate and sort local soil, and to enable movement between the piles on-site. The robotic sand formations were tested in a 70*70cm sandbox using custom design end effectors. In terms of large-scale customization, these formations allowed to explore and analyze the relationship between the robotic toolpath and tool (Figure 5).

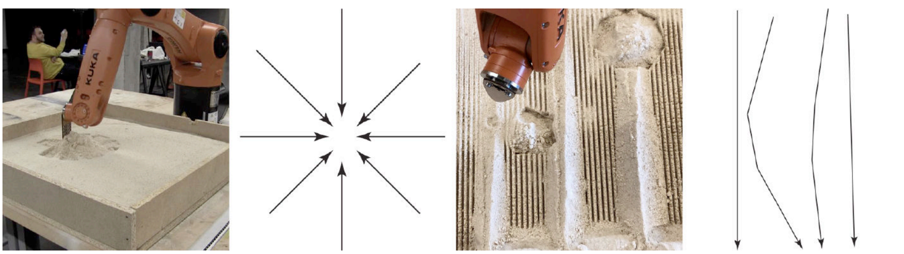

Figure 4. Exploring robotic groundscaping. Work by students Jihwan Hyeon, Aidan Newsome, Advait Patel, and Rui Zhong (Confluence Institute, 2019).

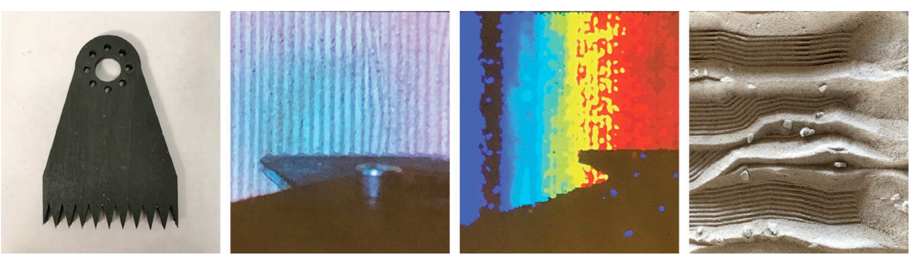

Figure 5. Exploring robotic sand sensing: the groundscaping end effector is mounted with a depth camera allowing the tool to react to local material conditions.

4.3. INTEGRATED FABRICATION

When digital fabrication and robotic tools reach a territorial scale, they challenge the enduring distinction between the conventional fabrication processes - additive, subtractive, and formative. In this context, the design-to-fabrication workshop explored an integrative fabrication approach combining ground-forming, soil stabilizing, and cave drilling towards lunar habitation. The simulated lunar site was analyzed based on imported data from the NASA 3D Resources site, and scale models of the various space missions landing sites. The explored site included a delta and a rille - which research suggests to be the result of volcanic vents and lava flows. The group explored ways to form structures in the rille, based on its unique topographical condition (Figure 6). To this end, the proposed strategy included: moving lunar soil; stacking it into large-pile structures; solidifying the piles; and milling caved elements within the structure (Figure 7). While preliminary and limited in scale, this strategy exemplifies a blurring of definitions in terms of processes in relation to large-scale autonomous fabrication. The combination of subtractive, additive, and formative techniques, often inseparable, is proposed here as ‘integrated fabrication’. Though demonstrated in the context of a lunar analog, this approach is also applicable to robotic architectural fabrication at large.

Figure 6. Exploring large-scale construction: using robotic tools towards remotely forming lunar structures with the given topographical conditions. Work by students Meriem Benkirane, Maelle Kolimedje, Charles-Edgar Lincoln, and Jihla Prentis (Confluence Institute, 2019).

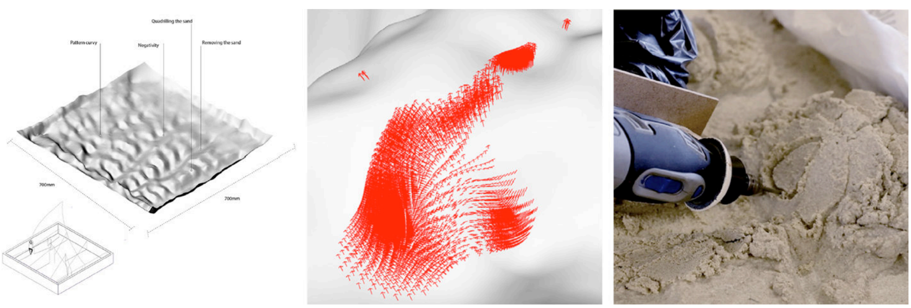

Figure 7. Performing integrated fabrication on a single material: a milling toolpath executed on solidified sand that was previously shaped using robotic tools.

5. DISCUSSION: TOWARDS ROBOTIC FIELDS

Progress towards sensible robotic construction lies not only in the advancement of new tools but also in a critical reflection regarding their evolving role. As tools enable to shape larger environments, small scale explorations can underscore potentials and inform future practice. The paper explored a renewed approach to territorial scale digital fabrication in the post-Anthropocene era. To this end, three notions of transforming natural terrains into built environments were presented and illustrated through explorative case studies - material-aware construction, large-scale customization, and integrated fabrication.

Though the presented experiments were performed in an indoor lab setting and on table-sized models, they look at fundamental capacities at the core of scaling digital fabrication - material-aware construction, large-scale customization, and integrated fabrication. Together, they demonstrate different ways to reform, stabilize, and reconstitute soil, at various scales, using robotic tools and custom end effectors. They illustrate how advanced tools can expand and challenge existing notions of in situ fabrication, and transform terrains and native matter into built environments.

Scaling these experiments to on-site robotic construction presents numerous challenges in terms of robotic processes, localization, materials, tools, and protocols. However, small-scale explorations can address missing protocols which hinder this scalability, and contribute to advancing the field. Future research will further explore the implications of forming 'robotic fields' - the types and scales of tools involved; the ways in which mobile robotic tools would move, operate and coordinate; and the relationships between robotic tools and manual labor which such operations will involve.

While these issues are increasingly important for architecture, they become crucial for territorial scales. In large-scale construction, material extraction, dislocation, and transport to the site are massive and significant in volume. Therefore, the return to earth-based construction and on-site material resources with advanced tools can re-establish the kinship between architecture and its environment. This kinship, in turn, can lead to a more sustainable construction - sensible at large.

ACKNOWLEDGMENTS

The presented research draws upon a workshop led by the authors in February 2019 at the Confluence Institute for Innovation and Creative Strategies in Architecture, France, as well as on the Technion IIT 2020 Winter semester's "Locally Sourced, Purpose Oriented: From Geomaterials to Architectural Structures" Digital Studio. The authors would like to thank Director Odile Decq, Nicolas Hannequin, Martin Detoeuf, and the participating students at the Confluence Institute. The authors would also like to thank the Technion - IIT, the participating Technion students, research assistant Yarden Elah and the Azrieli Foundation for their generous support of this research.

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DESIGN IN THE AGE OF DISSIDENT CYBORGS

Xenofuturism as caring-curing practices

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Abstract. This paper synthesizes several years of research in the field of the theory of architecture and design, and its subsequent undergraduate and graduate teaching. Specifically, it is a work that reflects on how architecture and design should face the three most important paradigmatic phenomena of our present and near future. Paradigms as things we think with, rather than as things we think about (Agamben, 2008), or in other words, it matters what ideas we use to think of other ideas (Strathern, 1992). These phenomena refer to environmental, technological and anthropological aspects, and the strategies to cope with them, involving alternate design thinking and practice in which futurabilities and futurizations depart from the displacement generated by post-utopian visions based on dissidence and subalternity.

Keywords. Chthulucene; Cyborg Design; Dissident Futures; Futurization; Xenofuturism.

1. Diagnosis

From an environmental point of view, there is no longer any doubt that we live in a context of transformations on a planetary level and that these are a consequence of the impact of human activities on the earth. It is clear that if we do not change the ways in which we extract primary resources, produce and consume stuff and food, and manage waste, we will be heading towards mass extinction. Humanity is losing the ability to control the effects it is having. It is no longer enough to "stop" negative behavior or have a "sustainable" relationship with the environment. For this reason, to think about the future we chose to speak of Chthulucene instead of Anthropocene. Donna Haraway (2016) says that Anthropocene will be short. It is more of a border event than an epochal event, similar to the K/Pg limit (the massive extinction of the Cretaceous-Paleogene). And she wonders if it is possible that the brevity of this Anthropocene/Capitalocene/Plantationcene "border event" is due to the fact that multispecies entities, including human beings, forged in time powerful alliances with the generating powers of Chthulucene, to provoke

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 233-240.

resurgence and partial healing in the face of irreversible loss, so that old and new world-makers could take root. In this sense, the earth of the current Chthulucene is simpoietic, not autopoietic, it does not close on itself, it is not complete. “Bounded (or neoliberal) individualism amended by autopoiesis is not good enough figurally or scientifically; it misleads us down deadly paths. Barad’s agential realism and intra-action become common sense, and perhaps a lifeline for Terran wayfarers.” (Haraway, 2016: 34). Following that, by refusing to reduce the urgency of the earth to an abstract system of causal destruction, Anna Tsing (2015) argues that precariousness (the failure of the lying promises of modern progress) characterizes the life and death of all earthly creatures in these times. She seeks contaminated and non-deterministic, inconclusive and continuous practices of living in ruins. She shows how it matters which stories tell stories as a practice of care and thought. “If a rush of troubled stories is the best way to tell contaminated diversity, then it’s time to make that rush part of our knowledge practices”.

From a technological point of view we were using the concept of postdigital, a concept inspired by a paper by Nicholas Negroponte (1998) where he states that “the digital revolution is over”. Postdigital is also a paradigm, but as in posthumanism, for example, the understanding of post-digital does not aim to describe a life after the digital, but tries to describe the opportunity to explore the consequences of the digital. While the computer age has improved human capacity with attractive and unusual prostheses, post-digital thinking can provide a framework with which it is possible to examine and understand this improvement. Following Negroponte, there is no doubt that we have been living in a digital age for a long time, to the extent that our culture, infrastructure and economy allow. But also that truly amazing changes will occur elsewhere, in our way of life and in the way we collectively manage ourselves on this planet. In addition to the broad scope of artistic discourse, the notion of postdigital describes the exploration of our relationship with the information age as the dominant paradigm in an age of global mixing, intertwined economies, demographic certainty and planetary boundaries, for example in Berry’s work (2014). In this sense, Mel Alexenberg (2011) defines “post-digital art” as works that address the humanization of art as a whole, postdigital technologies through the interaction between digital, biological, cultural and spiritual systems, between cyberspace and real space, between embodied media and mixed reality in social and physical communication, between high technology and high contact experiences, between visual, haptic, auditory, and kinesthetic media experiences, between virtual reality and augmented reality, between roots and globalization. Works of art created with alternative media through participation, interaction, and collaboration, in which the role of the artist (architect or designer) is redefined.

In continuity with the two previous points, from an anthropological point of view, we establish the need to think architecture and design in relation to a cyborg corporeality and subjectivity. A cyborg is simultaneously a cybernetic organism, a hybrid of machine and organism, a creature of lived social reality and a creature of fiction (Haraway, 1991). A cyborg, on the other hand, does not require a stable and essentialist identity. The physical attachments that humanity has with the most basic technologies have already turned us into cyborgs. In this sense, Haraway's question that we must transfer to architecture and design is: when do changes in degree become changes in species, and what are the effects of the biocultural, biotechnological, biopolitical and historical situation of people (not man) in relation to the effects of assemblages of other species and other biotic/abiotic forces, and combined with them? Haraway's cyborg calls for a non-essentialised metaphor, semiotic, capable of uniting all political coalitions in planes of affinities. It calls for a reconstruction of identity, no longer dictated by naturalism and taxonomy, but by affinity, in which individuals can build their own groups by choice. In this way, groups could build a kind of postmodern identity from otherness, difference and specificity as a way of counteracting Western traditions of exclusive identification.

Finally, we add a fourth theme to take into account, which introduces social and geopolitical aspects into the above, from the reflection on how to think about future scenarios from Conjectural Design based on dissidence and subalternity from the crisis of certain cultural hegemonies. That is what we have called Dissident Futurities. Following, we develop these aspects from a theoretical approach, specifically in the field of architecture and design, although using pedagogical and design experiences that we have carried out in the last years.

2. Therapeutic

According to paleoanthropology, the possibility of making tools, that possibility that we would call design today, was a feature that originally characterized the hominids of the species Homo Erectus and that Homo Sapiens have assumed singularly thanks to our ability to project uses, functionalities and applications. In this line of thought, archaeologist André Leroi-Gorhan (1993) stated that already in that original manufacture two supposed and intended purposes converged: the expected of the tool once finished and the expected of the action that the tool should perform. The tool would be, thus understood, the end of an action, that of its manufacture and the means of another, that of its use. Continuing with this reasoning, it can be stated that what is expected of the tool is at the core of the production of the tool itself. In this sense, to produce also requires a thought of the effects, those desired and/or possible, in terms of a desire to make-make. This is what we mean when we speak about design.

Recognizing the importance of planning and imagination when designing something was also among the interests of Karl Marx, who in Volume I of Capital stated that "what distinguishes the worst architect from the best of bees is this, that the architect raises his structure in imagination before he erects it in reality" (1977: 344). However, almost two centuries later, according to Franco Berardi (2017), the current social and productive conditions that mark contemporary capitalism are precisely the separation between planning and imagination regarding socially assigned and differentiated productive functions. Berardi finds in the current specificities of this separation not only a decisive dilemma of our contemporary context, but also a strength point that can reopen the possible of design, its factual power. Emphasizing the type of productive act rather than the subject that carries it out, Berardi understands that it is key to overcoming the fragmentation of cognitive work if we want to make viable a bet for a creative society without exploitation, extraction, or private appropriation of what is socially produced.

In this critique of contemporary separation, which can be traced back to Marx's 1844 Manuscripts, the inclusion of design is significant. Indeed, we live in a world deeply conditioned by design knowledge: Information and transport systems, flow governance, logistics, agronomy and rural exploitation, genetics, finance, urbanism, and algorithms are the backbone of a design and planning matrix that in the last half-century has expanded its exploration towards information processes and systems, from large entities to the atomic and molecular. It could be said that this is not a common form of design to present itself, but it does underlie in this definition a possible creative torsion, even artistic, of itself. In this sense, it is worth highlighting the use of the expression "virtualities" that Latour uses because it allows us to think that there is a virtuality in the materials that participate and configure the extended virtualities, those of potential uses, those of futurities. Because, as Etienne Souriau wrote, "if this table is physically made by the carpenter, it is still to be done as far as the philosopher or the artist is concerned". They discover what is missing, in a process that recognizes milestones and openings. When Umberto Eco (2011) spoke of unsurpassable objects (such as the spoon or the book) he referred exclusively to the conscious functionality of these objects; when Otl Aicher spoke of the difficulty of architects in understanding that the concept of building must include use and not only construction and completion he referred to the functional definition of things (1991: 269). Almost supplementing these openings, Souriau allows to extend that panorama to incorporate heterodox uses, interpretations, reconfigurations in so much possibility always there, always available. They are not exhausted because they belong to heterogeneous dimensions, to "other modes of existence".

In these pages, futurity is understood as that figuration that seeks to overcome the notion of future from its exclusively teleological dimension. Here it is worth following Souriau, who first of all seeks to distance the future from an enigmatic condition but also from its consideration in terms of final cause. It is not something that can be, in terms of a potential act, but something that is in a certain way, that way is the futurity, that is: "the virtual consummation that completes the movement of this present inclined towards the future, of that future falling into the present" (1943:179). Futurity is a power that is never fulfilled or completed and that allows acts to be fulfilled and completed. Futurity is the possibility just before it emerges; it is the virtuality of that consummation. "The event to come is called and captured, then released and referred to the past by that constant form, by that "and after", by that "and then", whose essence is to be located, not in the instant, but between two (think of this expression: the intermission, the interval, the interim), in the inter-world, between the instant that departs and the one that comes" (1943:180). Futurity is that interval that is born of the encounter between two forces, a way of naming the fact of the possibility that there are supports, propensities, precipitations, landings. It is the way in which conditions, projects, possibilities exist as a virtuality of events. Continuing with this reasoning, futurization and futurability refer to the ways in which we link with futurity. If the first is defined by planning, in terms of an act in the future; the second is understood through transitions and journeys, a power that does not close its definition.

Perhaps the aforementioned ways of approaching the world and invention are a valid way to renew our ideas about futurizations, futurabilities and virtualities. In this way design appears, "the point of articulation between the artistic and the engineering" (Berardi, 2017). It emerges as a field of problematization and exploration of contemporary links between projects and discoveries. Materials and knowledge, the futurizations of which they participate, the improvisations they propitiate, become a decisive zone in the social production of open links with futurities. A field to explore inventiveness.

Let us start then from an affirmation of Arturo Escobar, "design generates the structures of human possibility" (2017:58), to rethink its way of linking up with futurities as a redefinition of the conditions of the possible. Design thus becomes a methodological input or, in the words of Bruno Latour: "There is neither a manufacturer, nor an owner, nor a creator that can be said to have mastered the materials; or, at least, a new uncertainty is introduced regarding what is going to be built, as well as who is responsible for the emergence of the virtualities of the materials that are handled" (2005: 8). Social relations, institutional forms, political economies, infrastructures and design objects are literally emptying the planet of futurity through their incalculable social and ecological impacts and it is worth asking ourselves if designers have been able to deeply understand the disaster caused by the economy of hyperconsumption. As we see it, part of the apocalyptic risk that today flies over the planet, part of a link with futurity capable of making futurity itself impossible, corresponds to design.

According to Escobar, "design is ontological because each object, tool, service or even narrative in which it is involved creates particular ways of being, knowing and doing" (2017:47). Design is a way of linking with the virtuality of events that, while provoking them, seeks to explore and inscribe them. Can we, as the Spanish philosopher Amador Fernández Savater proposes, "hack into" the codes that hegemonically organize things, their uses, their circulations, their modifications? (Savater, 2016). What trends would we find where infrastructures beat? What would happen if we followed the advice of the coinners of the concept of Critical Design, Anthony Dunne and Fiona Raby, for whom the role of design can be "to facilitate visions and not so much to define them, to be a catalyst rather than a source"? (2013: 9). To elaborate questions that link materialities, fabrications, uses, ethics, is to discuss a design policy as the sensitive nucleus of our links with futurities.

If we assume that the goal of design is to fabricate not only the object (the service, the idea) but its world around it and that "every object, tool, service or even narrative in which design is involved creates particular ways of being, knowing and doing" (Escobar, 2017: 47), it is possible to think that, through the invention of objects, infrastructures and practices, design modulates time. It is a protagonist in the production of social semantics that include and propitiate, exclude and make impossible, links with futurities. In our terms, design is a component of futurizations and a vector of futurabilities. A practice in which futurabilities and futurizations do not disable each other, and which can articulate a dialectic between project and path. Because if to design is to maintain "a conversation about possibilities" (Escobar, 2017: 203), the open game of the feasible is a strategy that reveals the decision and its contingency, as well as the productive multiplicity of the world.

As Escobar (2017: 120) states, in the last decade "important trends have emerged in the world of design that seek to reorient its practice from traditional meaning, tied to the production of objects, technological change, the individual and the market, seen and led by professionals at the height of their expertise, to a way of seeing design as user-centred, situated, interactive, collaborative, participatory and focused on experience and the production of life itself". Something similar is indicated by Dunne and Raby when they refer to the emergence of "critical design" (2013: 34). Diverse groups, collectives and organizations of all kinds are oriented towards collaborative forms of design and designed forms of collaboration, propitiating a panorama of rearticulation of creations, knowledge, imagination and life that does not submit to the project of monetary valorization; even, more generally, that seeks not to submit to utopia as a project to be fulfilled. The challenge is to create links of post-utopian justice with futurities through the "creation of systematic domains in which definitions and rules can be redefined to make interdependencies and commitments (or their absence) visible" (Escobar, 2017: 212). This attests the shift from a design centered on futurization to one centered on futurabilization, a displacement that invites to produce sensible changes regarding figures of social and cultural transformation, and to open the ways in which these creative practices position themselves regarding becoming and build bonds of futurization. There is no final design, no final figure. In this sense, design practices can assume a logic of change and attention to what is effective, which utopian policies did not consider.

Taking into consideration these post-utopian potentialities of design, its ability to open new horizons, to counteract the advance of a hegemonic narrative to leave room for an imagination of differences, we wanted to design an exercise for the implementation of a thought towards futurabilization. The exercise was presented in different academic contexts within the framework of the public teaching of architecture in Buenos Aires. First the participants were invited to choose a space for dissident thought according to their own experiences, where by dissidence we recovered more the meaning of dissenting over disagreeing in the construction of diverse relationships. In other words, each participant had the freedom to choose the field of futurability of their design according to the construction of diverse relations of imagination and projection, whether from the point of view of class, gender, race, age, etc. From the understanding of this dissident space, the participants were asked to detect a common place that relates to the chosen dissidence and then to fictionate this commonplace in a possible future, from the dissidence. The interweaving of the common place with the fictional proposal reveals a certain kinship with predicative operations, operations that emerge from a bond of similarity, to pass from a "being like" to a "being", a performative bond with which to imagine new futurities, new semantic, material, and sensitive paths.

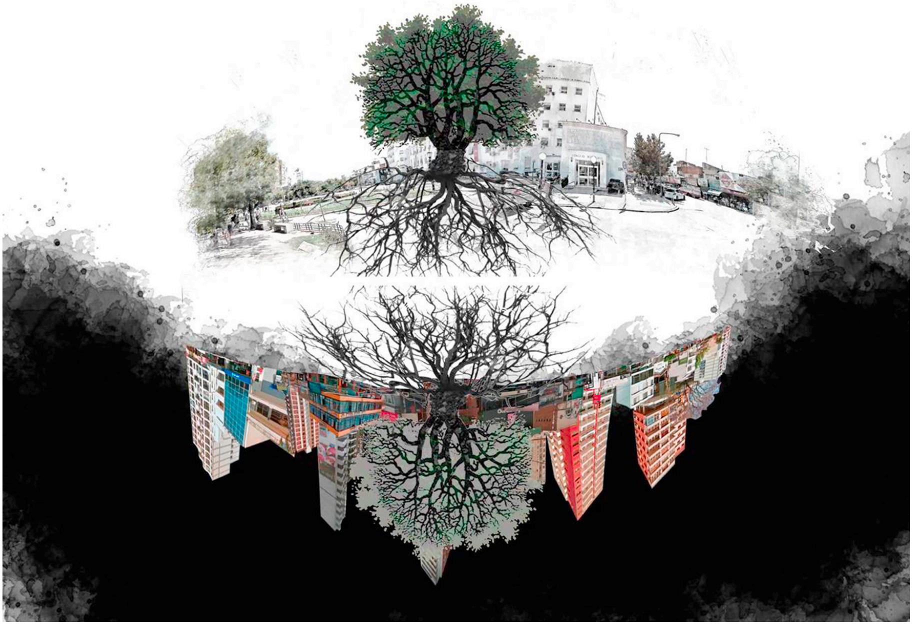

Figure 1. The Walking Ombú. Acosta, Vega, Carenzo, Petkovsek. UNLaM, San Justo, Buenos Aires, Argentina. 2018.

3. Design as caring-curing toward xenofuturism

From this epochal diagnosis referring to the context of Anthropocene/Capitalocene/Plantationcene and Chuthulucene, to the post-digital circumstance and to our cyborg condition, we propose design strategies that become new con-figurations where design is a component of futurizations and a vector of futurabilities. We take as paradigmatic and exemplary case of these strategies the project "The Walking Ombú" (Figure 1) developed by students of Architecture of the National University of La Matanza. The case reflects the post-utopian approach that we are unfolding in this article in counterpoint with Archigram's utopian Walking City (1964). The ombú (Phytolacca dioica) is a centenary vernacular tree whose roots have an extended reticular system and whose classification escapes botanical taxonomies. The project is based on the evocation of two huge urban ombus recently cut down and connects their presence-absence with the collective memories of local multi-species. Thus, students detected invisible networks of experiences related to each ombú and made them visible in terms of vectors of futurability.

These design strategies for futurization function as a therapy (from the Greek therapeia: care) that seeks to care-cure. From the proposal of a tentacular thinking (Haraway, 2016) we continue towards a radical thinking (in the most etymological sense, from the Latin radix) that cares-cure as holobiomatic-semiotic connectivity between-species and between stories. In this sense, "The Walking Ombú" takes care of the collective memory of the place as holobiont (Margulis, 1990), as an entity formed by the association of different species that give rise to semio-ecological units. The proposal of a design as a care-cure opposes that of a design that makes/unmakes worlds and opens up the possibility of collectively growing a xenofuturism, as a theoretical construction that makes it possible to elaborate a framework not only for the future of design but above all for the design of futures.

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Human-computer Interaction / Collaborative & Collective Design /Computational Design Education

AUTONOMOUS IN CRAFT

Embedding Human Sensibility in Architectural Robotic Fabrication

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Abstract. Recent advancements in robotics allow architects to explore the coupling of manual craft with digital tools. However, current methods remain limited in addressing high-skill, custom tasks involving material uncertainty. In this context, the paper presents three capacities that stand at the core of performing autonomous robotic craft. These include documenting the movements and gestures of local stone craftsmen; augmenting the robotic system with a custom end effector and a sensor toolkit; and enhancing the fabrication process through a protocol that translates the documented data to an autonomous process. The three capacities aid in preserving local crafts, expanding robotic tools with new capabilities, and enabling architectural fabrication with a broader range of materials.

Keywords. Robotic fabrication; simulation; feedback-based automated manufacturing; digital craft; stone carving.

1. INTRODUCTION AND BACKGROUND

The increasing role of robotic tools in architecture indicates a potential shift from the Anthropocene era - defined by the human shaping of the built environment, to an age in which this environment is shaped by autonomous machines (Young 2019). This calls for examining the protocols and processes guiding these tools, as well as developing a higher sensibility and a more nuanced relationship between humans and robots. Such a relationship has always stood at the core of craft - in which there is a direct relationship between the human, the tool, and the processed material. However, as digital fabrication methods increased the influence of the tool in forming objects, they physically distanced the human from the material in the making process of these objects (Mindrup 2015). This shift is often viewed as a signal of the demise of manual techniques, provoking fear of their replacement by autonomous machines. In contrast to that, this paper will argue that industrial robotic arms can introduce new human/tool relationships. These relationships feature increased sensibilities to the material and the production environment. In doing so, they assist in documenting, augmenting, and enhancing architectural crafts.

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The acceleration of industrialization correlates with the rise of automated tools in architecture, design, and construction (Giedion 1948, Negroponte 1969). In this context, digital fabrication and automation in construction are assuming higher centrality in architecture, redefining design, and production processes (Carpo 2013). However, despite this progress, current fabrication tools still fall short of addressing custom, high-skill tasks as well as in handling uncertain conditions or materials (Kolarevic 2015). This limitation is rooted in the nature of existing automated machines, which are mainly single-task in their orientation. The integration of robotic arms into architectural fabrication presents an opportunity to expand existing automation capacities towards an agile, multi-task performance for several reasons. First, the multiple axis design of industrial robotic arms allows them to reach any point in space within their range. Second, any tool can be connected to them as a custom end effector. Third, robotic arms enable the integration of sensors on the tool or in its vicinity, and thereby condition their operation based on measurable environmental and material data (such as distance from the material, material state, and resistance). These capacities enable the deployment of industrial robotic arms for intelligent fabrication platforms. Such platforms can adapt to changing material scenarios and therefore allow the production of complex architectural elements using a range of materials with an uncertain nature (Figure 1).

Figure 1. An autonomously produced robotic element based on traditional, region-specific stone carving techniques (MTRL, 2019).

2. PAPER AND STRUCTURE

This paper will present autonomous carving, drawing on recent research on traditional, region-specific architectural stone dressing techniques and their adaption to robotic fabrication. In this context, three fundamental capacities that enable robotic tools to autonomously perform craft will be presented:

1. **Documenting** - employing motion capture techniques to record and analyze gestures of craftsmen at work. The presented method enables the obtainment of higher resolution and finer understanding of the craftsmen's hand and provides an initial database for toolpath generation. This capacity is becoming increasingly important with the gradual disappearance of traditional craft.
2. **Augmenting** - equipping the robotic arm with a custom end effector and sensors that provide visual and haptic feedback. This setup enables the robotic arm to operate in relation to a range of measurable environmental and material data. These, in turn, support the production of complex architectural elements using a variety of materials with an uncertain nature.
3. **Enhancing** - producing a toolpath in real-time based on the sensor data. This enables material and spatial awareness that is expressed by an ongoing adaptation of the robot actions in response to the state of the fabricated artifact.

3. STATE-OF-THE-ART: FROM AUTOMATED TO AUTONOMOUS CRAFT

The literature review will refer to the issues standing at the core of autonomous craft: research regarding robotic fabrication in high-skill domains (namely subtractive processes such as stone carving), motion capture, and real-time feedback for robotic fabrication.

3.1. REAL-TIME FEEDBACK FOR ROBOTIC FABRICATION

Currently, the *modus operandi* in architectural robotic fabrication relies on a linear process in which a specific form is initially created using computer-aided-design software (CAD). Operating instructions for the robotic arm are then generated using computer-aided-manufacturing software (CAM). These processes determine the final geometry as well as the fabrication protocol (Gramazio and Kohler 2008). However, with the increasing prevalence of new technologies such as computer vision and open-source electronics, alternative practices emerge (Amtsberg et al. 2015).

Amongst these practices, two distinct approaches stand out. The first establishes a fabrication process that is modulated by real-time feedback to deploy design rules responding to different material properties (Batliner et al. 2015). The second is a process in which human action on a specific material is recorded, categorized, and analyzed to be interpreted as operative robot instructions (Bard et al. 2015). This paper presents a third approach, integrating the two frameworks. It envisions a practice in which a robotic arm could be taught to react to specific material scenarios, similar to the way a craftsman would. In this way, the robot would challenge the traditional concept of making by reenacting human craft.

3.2. ROBOTIC FABRICATION INVOLVING HIGH-SKILL TASKS AND UNCERTAIN CONDITIONS

Digital fabrication methods have the potential to form new links between robotic tools, craftsmanship, and local building traditions. Although this connection was formerly explored in the context of digital architecture in relation to the restoration of historic buildings (Hayes et al. 2014, Burry 2016), it is only recently explored in relation to specific regional crafts and high-skill domains for digital augmentation (Bard et al. 2016).

However, as high-skill tasks cannot yet be fully automated, there is a continued demand for skilled craftsmen for complex stonework, such as carving delicate features and three-dimensional patterns. The advantage of human craftsmen is the ability to negotiate with the material and overcome conditions arising from the inherent uncertainty of the stone as a natural material. This uncertainty is overcome by the craftsman's real-time decision-making process, which is based on the visual and haptic feedback enabled by the nervous system (Shaked and Dubin 2019).

In this emerging field of research, human gestures can be analyzed on a visceral and cerebral level, allowing architects to explore answers to questions such as: how do we perceive external sensory information? When acting on specific materials, what decisions do craftsmen make based on their perception? These questions are highly contextual, since varying local traditions, tools, materials, and even postural conditions can change the behavior of the craftsman. In a similar way in which a craftsman adapts to changing conditions through a modified behavior, this research seeks to enable adaptive manipulation in robotic arms. The enduring role of human decision making in architectural crafts highlights the need to recapture the sensibility and sensitivity of the gesture in the framework of automated construction (Figure 2).

Figure 2. The stone carver removes the sharp edges of a sawed stone in preparation for surface processing. In this example, the human eye notices the amount of material subtracted in the previous action. That knowledge guides the craftsman's decision regarding where to place the tool for the following action (MTRL, 2019).

3.3. MOTION CAPTURE

The translation of high-skill human crafts to robotic fabrication methods requires a thorough understating of the action and gesture constructing the craft. Since the craftsman's knowledge is tacit (Sennett 2008), a full analysis of such gestures requires motion capture and subsequent data analysis. In the context of translating manual subtractive techniques to robotic methods, existing research focuses on documenting single tool-strokes (Steinhagen et al. 2016, Brugnaro and Hanna 2019). A single-stroke recording indicates the force, position, and orientation of a tool, providing the ability to convert them into a robotic action. However, the data of a single-stroke is limited in its ability to construct a full picture of a craftsman at work - specifically in relation to traditional patterning. In this context - craftsmanship does not amount to the sum of repetitive singular actions. These represent only a fragment of a much richer motion-choreography. This motion is not prescribed or predetermined but is a result of real-time response to various changing environmental and material conditions. In robotics, these conditions are defined as uncertainty.

4. CASE STUDIES

The three stages of embedding human sensibility in architectural robotic fabrication are demonstrated here through the transfer of manual stone carving to an autonomous robotic process. The selected technique is traditional stone dressing typical to The Middle East (Figure 3). The tools used are the three classic chisels: point (Shawkah), flat (Izmil) and tooth chisel, in tandem with a round wood hammer.

Figure 3. (left) Traditional stone carving tools and (right) examples of stone dressing techniques as classified by T. Canaan (1933): rusticated (Tubzeh), coarse (Taltish), and pointed (Musamsam). Photo taken at A.Grebelsky & Son (MTRL, 2019).

4.1. DOCUMENTING

The presented research employed the use of a customized Vicon motion capture system to record the hand gestures of a stone carver at work. The specific system includes seven high frame rate cameras surrounding a carving workstation to capture the motion from multiple angles and provide full coverage of the actions.

In parallel, an adapter consisting of five markers is mounted on the chisel (Figure 4). Using Vicon Tracker software, each tag receives a unique ID, which is later used to model the adapter in 3D and to derive the chisel's position and orientation in space throughout the carving session. Following each session, the trajectories are reconstructed and exported as a two-dimensional table in a CSV file format.

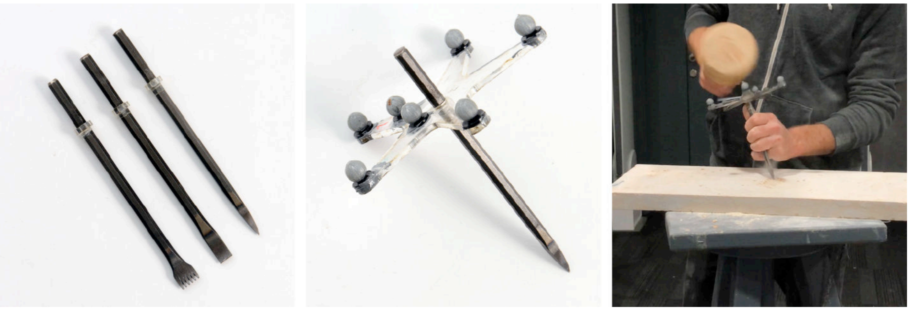

Figure 4. The chisel mounted with an adapter that is tracked to produce the tool's position and orientation throughout a carving session (MTRL, 2019).

The data is then read using a custom Grasshopper component and visualized in Rhinoceros 3D, as well as with Python Matplotlib (Figure 5). The reading allowed to construct a continuous toolpath for observation and analysis, as well as to directly transform the human recording into a functional robotic toolpath. The analysis includes extracting the key tool and pattern parameters: (1) the chisel speed; (2) entry angle; (3) carving path and (4) exit angle; as well as the (5) session duration; (6) carved area; (7) number of strokes and (8) amount of strokes per second. A computer vision application was also developed employing OpenCV (an open-source library aimed to facilitate real-time computer vision), allowing to detect: (1) the total amount of material removed from the stone surface; (2) the carving areas; and (3) each carving area's circumference (Figure 6).

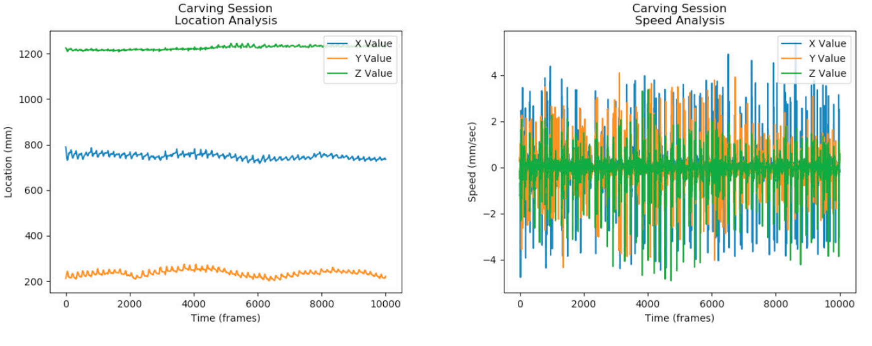

Figure 5. For each chisel type, a plot is produced detailing its spatial position (XYZ locations) and speed (m/s). The outcomes of the point chisel are displayed here.

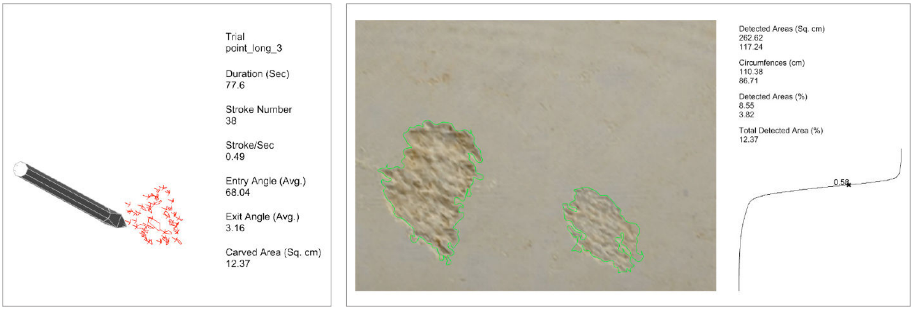

Figure 6. (left) The session is analyzed to derive a specific carving profile per technique; (right) In parallel, an image processing app is used to analyze the outcome material removal.

4.2. AUGMENTING

Stone is a complex substrate to operate upon - its geometry is irregular; its texture is uneven and coarse. Additionally, when force is applied, it behaves unpredictably (Siegesmund and Snethlage 2014). These characteristics contribute to a high degree of uncertainty in a robotic fabrication context. This uncertainty is dealt with through continuous visualizing, sensing, and motion-correcting processes.

To this end, the robotic cell is equipped with a stone carving toolkit, enabling it to adapt as it operates within specific material conditions. The toolkit includes a high-definition camera, depth and distance sensors, and a custom multi-tool end effector capable of alternating between a variety of chisels (Figure 7). The sensing capacity enables the robot to see and feel the material and its environment. Employing this capacity, however, requires a specific protocol that can facilitate these actions.

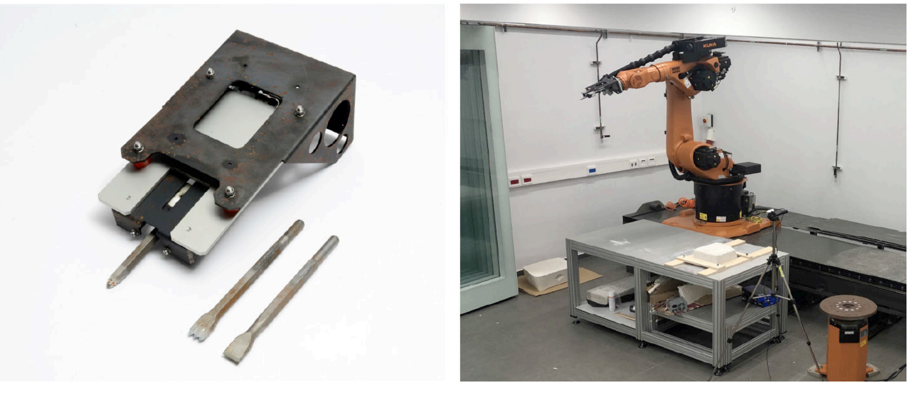

Figure 7. The toolkit: (left) a custom multi-tool end effector; (right) the robotic cell - including a KUKA KR60 robotic arm mounted on a KL1000-2 linear rail, an XY positioning table, and peripheral cameras (MTRL, 2019).

4.3. ENHANCING

In stone carving, the key consideration in positioning the chisel on the stone-face is the outcome of the previous stroke. The craftsman assesses the material state before each stroke and repositions the tool accordingly. Previous research performed material removal analysis following the completion of the carving session, to quantify the carved material in relation to a specific stroke and stone-type (Steinhagen and Kuhlenkötter 2015). However, the capacity for real-time material analysis is central to ongoing human decision making during manual subtractive techniques. Locating, positioning, and timing a stroke is conducted in response to a specific material state, rather than a predetermined motion plan. Therefore, enhancing the robotic process with real-time material analysis can promote the transformation of craft into an autonomous one.

The enhancement is achieved through a fabrication protocol that links the robotic operation with gathered material and environmental information. This is achieved by employing real-time robot control. In practice, this is done through a client-server software architecture in which the robot runs a native KRL loop-program (Figure 8). The program is built to receive motion commands and to handle interruptions initiated by the sensor data. In parallel, each sensor acts as a client, collecting information and updating the model (which resides within a 3D environment). The information includes the surveyed geometry, detected forces, and collected images, which, in turn, are used to determine the adequate motion-plan for each iteration.

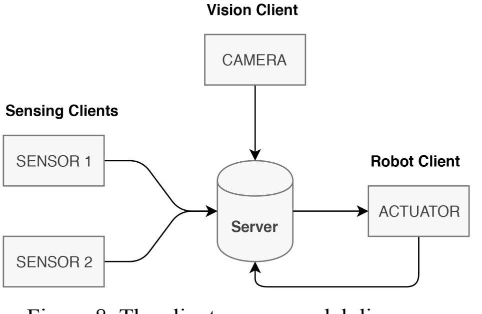

Figure 8. The client-server model diagram.

Before the first iteration, the robot enters a listening state, waiting for a command to be received. Meanwhile, a high-definition camera captures the existing material condition, marking the cracks and the veins in the stone and integrates them into the virtual model as no-carving zones. This action limits the risk factor during the process since these are inherent stone features that are prone to failure when force is applied upon them. Additionally, a stereo vision depth camera produces a high-resolution point-cloud (depending on the specific experiment, this ranges between 19,200-307,200 points). Afterward, the robot approaches the stone and begins the carving operation. As the action length is obtained, the robot moves away, the stone is captured again and analyzed, and the virtual model is updated (Figure 9).

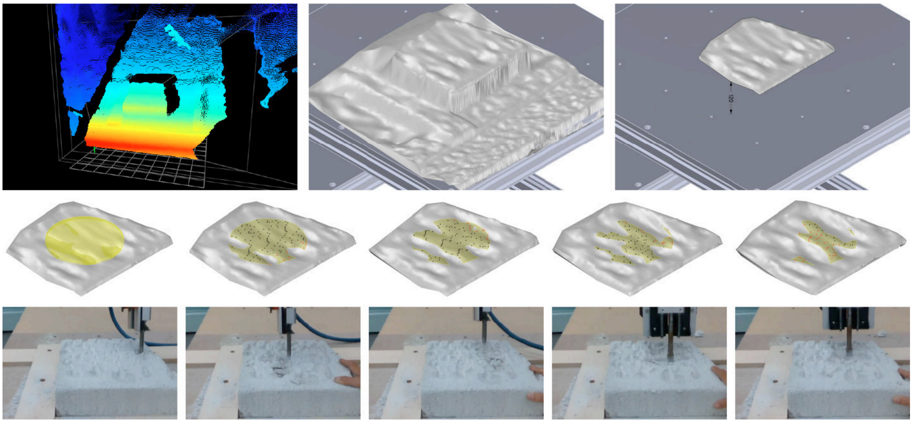

Figure 9. The autonomous fabrication processes: an initial point cloud is produced and converted into a mesh. A carving plan is aimed at creating a circular indentation, and a 10-stroke action is defined. In each iteration, the geometry is updated and an additional carving action is performed. This is repeated until the target geometry is achieved (MTRL, 2019).

5. DISCUSSION AND CONCLUSION

The paper explored the potential of autonomous fabrication in the face of a decline in manual craftsmanship in architecture. Despite the growing availability of digital tools, they are limited in their capacity to perform custom, high-skill tasks. This limitation stems from the challenges presented by unstructured environments, material uncertainty, and the physical distance between the designer and the manufactured object. This implies that the designer cannot engage in an ongoing dialogue with the material - an essential characteristic of historical craft.

To produce a tool that is autonomous in craft, the paper presented a three-step framework demonstrated through regional architectural stonework. The steps included: documenting the gestures of local stone craftsmen, augmenting the robotic tool with a custom end effector and sensor toolkit, and enhancing the fabrication protocol with material and spatial awareness. Future research will document additional techniques and augment them on alternative materials or in untraditional ways. Additionally, as the paper presented autonomous decision-making based on specific conditions, future work will employ machine learning methods to expand this ability towards performing craft on-site.

Achieving autonomy in craft does not rely on increased precision and predictability. Rather, it is rooted in the ability to contain imprecision and handle uncertainty. While the former approach has previously resulted in favoring docile materials, the latter opens the possibility for robotic engagement with a range of overlooked ones. Furthermore, the global disappearance of historical crafts and local workmanship carries a risk of erasing fundamental cultural knowledge and practical skills. In an age characterized by increasing proliferation of digital tools - persevering and transferring these skills supports the continuation of the longstanding dialogue between the architects and the material at hand.

ACKNOWLEDGMENTS

The authors would like to thank the Technion IIT and the Azrieli Foundation for supporting this research; Yotam Carmel of Arco Preservation and Restoration; and A.Grebelsky & Son stone manufacturers for sharing their expertise. The research was conducted at the Material Topology Research Lab (MTRL), Technion IIT

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FROM HCI TO HVRI

How different will the interaction of digital architecture design be?

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Abstract. This paper contributes to the conference theme by looking at the human impact factors in the context of virtual reality interaction. The creation of architectural design drawings was done through pens and rulers in the beginning. Although the process is time-consuming, the connection of the mind and body is very close and every line drawn are done through the motion of the human body. The development of computer speed up the design process but the generation of the drawings are done with the keyboard and mouse. This human-computer interaction (HCI) disrupted the body-mind connection since the controls are now pointing, dragging and clicking. Architects were having a hard time accustoming to the new methods but gave up to the speed of its efficiency. However, architects never lose their skills to draw and sketch when brainstorming design. The coming of virtual reality (VR) provides an opportunity to bring back this connection. This paper explores the possibilities of human-virtual reality interaction (HVRI) through analysing the currently available VR tools and understand how close they are to this mind-body connection.

Keywords. HCI; HVRI; Interaction; Digital Architecture Design; Virtual Reality.

1. Introduction

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. From the visualisation of the interface to the controls of the functions and from keyboard & mouse to the touchscreen to tracking sensors such as *Leapmotion* and *Kinect*, the types of HCI differ based on the content on the computer. This research looks into the development of the interaction between the architects and the drawing throughout the design process to understand how the pen and paper are later accustomed to keyboard and mouse.

The appearance of the smartphone has then extended this HCI research towards hand-carried devices. Manoeuvring the digital model requires only certain finger gestures and also allows the users to interact with the interface wherever they want to be. However, the interaction was still limited to just viewing the model and not

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 253-262.

working on the design. The need for precision in the modelling process makes it hard for design to be done with just fingers. Even with the help of a stylus pen, the accuracy required is still hard to be met.

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. Although the hardware is still considered 'computer,' the interaction is very much different. Since the human is immersed in the virtual environment, the interaction is already beyond the traditional keyboard and mouse. The introduction of VR into gaming and education has also encouraged architecture to integrate VR into its course of the design process. However, the current integration of Augmented Reality (AR) and Virtual Reality (VR) components is mostly limited to enhancing visualisation, especially towards the corresponding design tasks. This opportunity lead to an increase in attempts to bring the modelling process into the immersive environment.

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 behaviour towards human-VR interaction (HVRI). By examining various types of VR equipment and how its system could assist the design process, this research will study the different 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 contemplate future trajectories for the novel strategies to improve HVRI, that one day may lead to genuinely immersive design interaction.

2. Human-Computer Interaction (HCI) in Architecture

Before diving into HVRI, it is necessary to understand the development of related technologies and tools, as well as limitations in the development process. The traditional architectural design is based on the 2D design model, using paper and pen as the main sketch tools. Architects paid more attention to the form and the details while ignoring the relationships among the body shape, space form, and environment. This leads to the constraints between the environment and the development of space and body shape. The plan, elevation, and section of the building act as three primary means in the process of design and presentation. However, limited by the design perspective of the architects' experiences and aesthetics, there will inevitably be deviations between the imagination and reality of the spacing effect.

Although the theory and method of traditional architectural design are quite mature, design and planning have been struggling with insufficient tools to cope with the increasingly complex challenges to the built environment (Fricker, 2019). The rapid development of computer technologies has brought about significant impacts and challenges in architecture. The long-held of architectures' design modes, ideas, methods, skills, and tools have been challenged and need to adapt themselves to these new changes and make a quick response to them. Computers in connection with aided tools represented by *AutoCAD* have been widely used for architecture design since the 1980s. Pen and paper are taken over by keyboard and mouse. It possesses great potential for increasing productivity, processing data sets, and making vivid presentations while the full applications for 3-dimension (3D) modeling such as *Rhino3D* has achieved significant progress in transforming architecture design from 2D to 3D.

However these tools are struggling with several disadvantages:

- the presentation of the design can only be from the bird-eye view instead of first-person fail to reflect real feelings of spaces and architectural narratives (Liu & Zhang, 2019)
- the architectural renderings, although with realistic and robust dynamic expressive force, can only provide static and local visual experience. This is also the same for 3D expression that the model is unable to interact real-time (Zhu & Zou, 2008)
- although the hardware still is considered as 'computer,' the human and his/her body gestures are entirely excluded from interaction in both real-world and the virtual environment (Lo, Xiao & Yu, 2019)

3. Human-Virtual Reality Interaction (HVRI) in Architecture

Then comes the developing digital technology together with immersive tools such as Virtual Reality (VR), Augmented Reality (AR), Augmented Virtuality (AV), and newly emerging Mixed Reality (MR), which provide an opportunity to comprehend, design and construct buildings (Fricker, 2019). Different from HCI, the interactive mode in HVRI is supported by a head-mounted display and game controllers, such as joy-sticks or body interaction with *Kinect* (Fig. 1). Users gain information from a special helmet that simultaneously presents different images to the left and right eyes, respectively, to provide an immerse experience to the designer. Meanwhile, a controller is essential for navigation. The designer can move in the virtual space without moving in the real world. It enables an excellent understanding of distances, heights, and depth. With improvements in future versions, there will probably have the ability to sense emotions and expressions in the model as well (Kreutzberg, 2014).

Figure 1. Design Process With VR (Kreutzberg, 2014).

The most widely known definitions of the reality-virtuality continuum and its segments are derived from a relationship between reality and virtuality and technological advances from their respective eras, most of which are already outdated. Besides, the definitions emphasize displays rather than on users‘ experience. A redefinition of the continuum from a perspective that does not rely on technology and augments users’ experiential aspect into the reality-virtuality relationship is crucial.

The reality-virtuality continuum and segments are widely defined by the relationship between virtuality and reality environment as well as attached technological advancement (Milgram & Kishino, 1994). Bekele and Champion redefine the continuum from the perspective of user experience instead of technology (Fig.2).

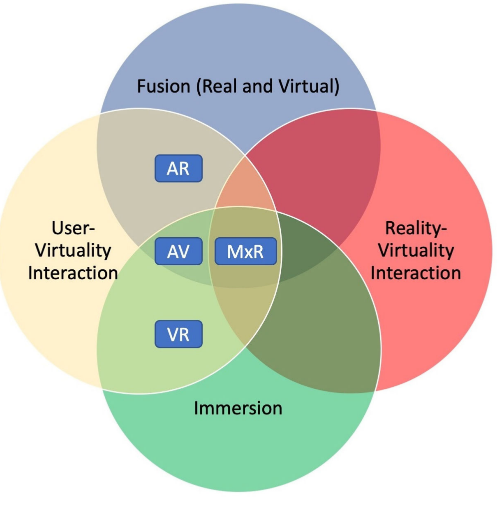

Figure 2. User-Reality-Virtuality (URV) Relationship Space (Bekele & Champion, 2019).

The latest VR equipment allows users to immerse themselves in a virtual social environment with multi-dimensional elements to enrich design engagement. At the same time, the standard architectural software can easily be visualized in real-time, interactive, and social design experiences in a VR realm by innovative game-based platforms. Building information and other data are linked in real-time that it enriches and offers additionality within an immersed virtual environment. The long-held conceptions of space and time in architectures are being challenged as the virtual scene is replacing or even superseding the reality (Asanowicz, 2018). Compared to traditional methods, approaches based on immersive tools hold many unique advantages. This paper concludes them into four major points.

3.0.1. VR provides easier interaction with open-source data for smarter visualisation

Bondakji (2018) introduced a project named ViBe, aiming to investigate the possibility of VR in a combination of of-visualizing high-dimensional urban data. The immersive reality technology allows both architects and planners to visualize and distinguish multiple and complicated urban-planning data sets, containing information about buildings ownership, land use, populations, and street networks. These tasks used to be indispensable but time-consuming to analyze, evaluate and present. In this project, all links of different factors in the various data sets are shown in a clear and easy-to-understand 3D-environment for users (fig 3). Simple gestures included in ViBe enable users to maneuver the data sets in the environment intuitively increase the visibility of the information compared to looking at the same 3D-data through a screen.

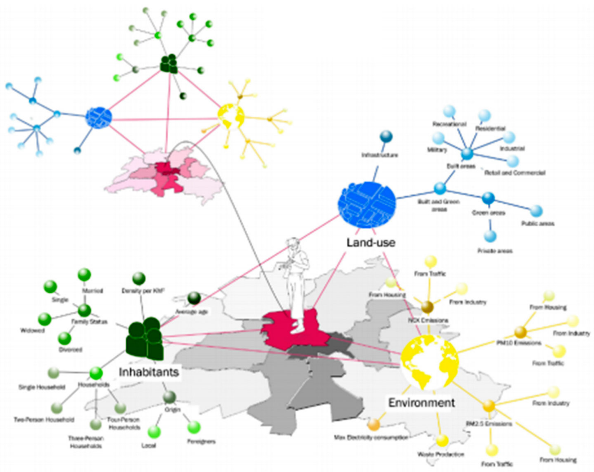

Figure 3. ViBe (Louna Al Bondakji et al., 2018).

3.0.2. Interacting directly with the model in VR, although using a remote control, provides a heightened sense of immersion and spatial awareness which offers a unique opportunity for designers to perceive and evaluate scale and space

Arnowitz (2017) developed a project called vSpline to explore the blurred boundaries between drawing and modeling, both digital and physical, as well as the perception of scale. The motivation of this project is to figure out whether the 3D model could be printed directly without additional processing, which is a particular use-case of geometry. Models are designed and modified in a virtual 3D environment instead of the real-world environment. They discovered that working in this 3D environment has a distinct feature that the relationship between the users and the scale of the space is more visualized and convertible. To get a better perception of surroundings on a human scale, users are allowed to switch his/her position in the 3D virtual environment in the room-scale VR systems (fig 4). Immersive reality technology makes the microcosmic designing and adjustment possible, however, which is hard to achieve with traditional methods.

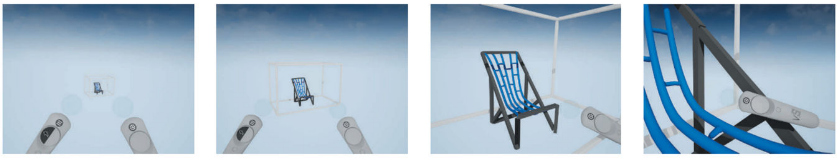

Figure 4. Different scales during design process (Arnowitz E et al.,2017).

3.0.3. Interacting in immersive VR environments can adequately support the process of designing architectural spatial experiences and their perception through architectural artifacts of higher quality than those spaces designed making use of traditional and more commonly used representational methods

Angulo A and Velasco GV experimented with sophomore architectural design students who were assigned the task of redesigning the signature space of a local medical clinic. Students were divided into two groups based on their preferences of media usage patterns in this project. One group uses a physical model (control group), and another one applies VR 3D visualization (experimental group) as the presentation method during the final project reviews.

The two groups are further divided into sub-groups to reduce the effects of judgments due to the design outcome. Fig 5 and 6 show the results using two evaluation factors, affective appraisal, and environmental evaluation. The formal is to evaluate the design of the space while the latter is to figure out if the environmental factors are taken into account by the students and if the blind panels can see them. From the overall results, it is noted that the two highest scores are achieved by teams of the experimental group (VR) at the same time that the two lowest scores are attributed to teams in the control group (PM).

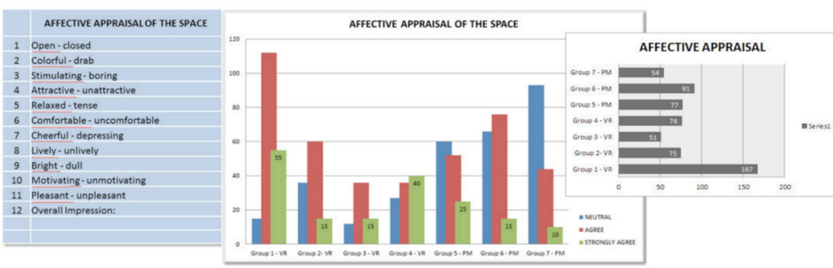

Figure 5. Affective Appraisal: questionnaire (left) results (center and right) (Angulo A and Velasco GV, 2014).

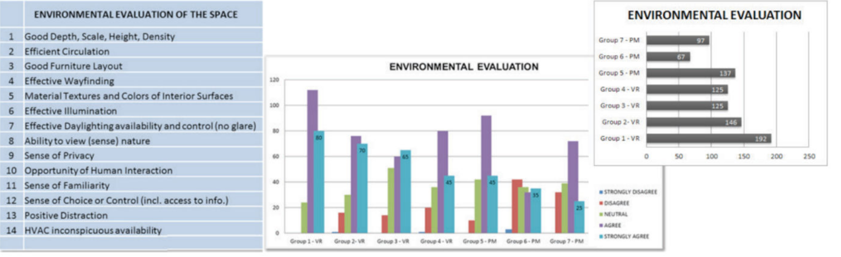

Figure 6. Environmental Evaluation: questionnaire (left) results (right) (Angulo A and Velasco GV, 2014).

Their study not only obtained evidence that suggests that the projects using the VR environment can adequately support the design of architectural spatial experiences, but also demonstrate that VR immersive environments may provide in□time feedback for improvement of spatial design, and may enhance the understanding of architectural experiences of space leading to meaningful results.

3.0.4. Simple VR "trigger" interaction could further enhance the design modelling experience by adding more optional detail into the design

Lo TT (2019) proposed an Action Trigger in Fuzor. Action trigger prepares a set of 'events' that users hope to achieve when they interact with their model. For example, they can merely be switching on the interior lights, playing the tv or radio, opening the doors and windows, or changing the environment from daylight to nighttime. The designers decide what 'action' types they would like the users to make to 'set off' the events. The action can be either active or passive, depending on what effects the designers want the users to experience. For example, a light switch can be set with an event to it such that users need to 'trigger' the light switch to switch on the light, or it could be set as a passive boundary such that when the users are within a certain distance away from the switch, the light will automatically be triggered on. Their study demonstrates that designers can consider more users' feelings during the designing process with the help of HVRI. Under this fashion, the design can be highly customized according to users' preferences and can be easily experienced, both for designer and user, during the designing process (fig 7).

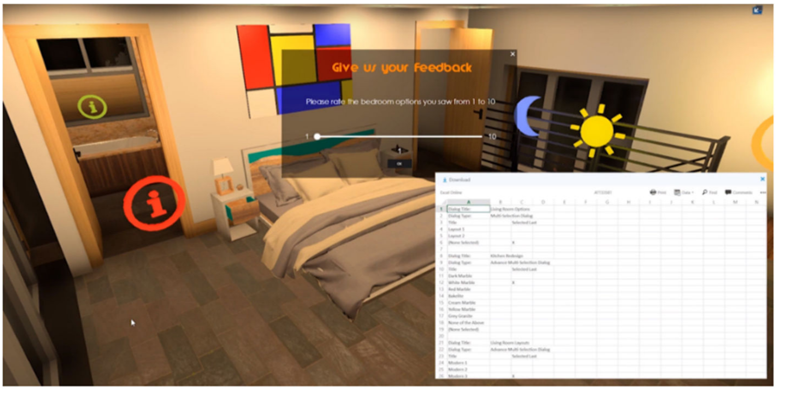

Figure 7. Environmental Evaluation: questionnaire (left) results (right) (Lo TT et al., 2019).

4. Discussion

This paper explores various systems and experiments that uses VR as a primary tool of interaction. The above studies demonstrate that designers can consider more users‘ feelings during the designing process with the help of VR. Utilizing the immersive VR capabilities gave designers a better understanding of the design for its intended user. It enabled an assessment of accessibility, navigability, and usability of the space. In VR, the model can be highly customized according to users' preferences and can be easily experienced, both for designer and user, during the designing process. Although the HVRI in the studied projects is limited to the hardware, it can be observed that there is still a significant difference in how the virtual model is being interaction. Bondakji's ViBe is still point-and-click, while Arnowitz's vSpline has to "draw" in virtual space. Angulo's experiment by simply venturing in static virtual models while Lo's system can provide active and passive interaction with the models.

Immersive reality technology's role is not just to enable interaction between users and information, but a more continuous relationship between users, reality and virtuality that puts users at the center, affects their senses and allows users to be part of any change and process in the environment. The critical role of immersive reality technology is to build a user-centric relationship among users, reality, and virtuality.

Besides, by challenging the most fundamental principles of sequence, form, and human perception (Asanowicz, 2018), new technologies could give possibilities of creating spaces form variety aspects, such as vision, touch, hearing, and smell, and even the intangible psychology which could accomplish the effect that traditional media can not achieve (Kreutzberg, 2014).

For designers, the spatial and real-time capabilities of these digital methods enable designers to get direct access to evaluating design ideas and concepts in the later stage (Abdelhameed, 2014). For users, the enormous potential of immersive technologies lies in the allowance of users to be a central part of environmental changes and development process (Bekele & Champion, 2019), and the ability of intuitive interaction through visualizing different environmental ideas from people with various disciplines, professions, and backgrounds. Thereby, it brings the participative design to a new broad sense of co-design (Huang et al., 2012).

Compared to the traditional method of presentation through renderings and drawings, even though the immersive technologies provide a high sense of presence, it is still not frequently used in the design studio, because the HVRI is still very limited. The familiarity of the VR equipment is not as intuitive as a keyboard and mouse to the extent which users can simply just pick up and start interacting. In order to create a realistic digital environment, the designers must invest a more significant amount of time and effort if compared with the use of other conventional digital methods. There are a lot of extra tasks that need to be implemented when working with the immersive environment:

- The manipulation of the geometrical characteristics of the space-defining elements (shape, depth, rhythm, scale, proportion, etc.).
- The incremental application of shading, textures, and light - from primary to photorealistic.
- The real□time manipulation of objects in the virtual environment. Beyond being able to move some items in the space, ready□made alternative solutions can provide direct feedback from cause and effect in the virtual environment.

All these tasks dramatically increase the workload of designers, which significantly limits the use of immersive technologies. In other words, how to lower the cost of working in an immersive environment is a key issue. At the same time, the corporation becomes harder during the design process due to the limitation of equipment. Every designer must dress their VR equipment to get into the immersive environment. It dramatically raises the expenses of designing since the related equipment are still much more expensive than computers. Besides, how to interact with users in the same virtual space is another technical issue that needs to be addressed. Current VR technology allows players to see the interaction of each other in the virtual environment only if they put on extra gears such as gloves and having sensors around the physical space to detect the motion of the users. A single user VR can only be observed through a screen.

5. Conclusion

This paper brings together a series of projects that give light to how HVRI can help architects to visualize and interact with their project, data and also user-behavior in a virtual environment. The needs and potential of better HVRI are presented, and these are capabilities that HCI is unable to do. However, to achieve the ideal interaction and bring closer the gap between the body and mind during the design process, there is still much to explore. One major problem is that the HVRI is still very much dictated by what equipment is available - using a hand-held remote to control objects in a virtual environment is still not breaking away from keyboard and mouse like in HCI. The next research would be to explore various means of gestures, body movements in a virtual environment and integrating them with types of equipment such as sensors that could allow architects to intuitively work with their design in the virtual environment creatively better than pen and ruler.

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A BIOFEEDBACK PROCESS: DETECTING ARCHITECTURAL SPACE WITH THE INTEGRATION OF EMOTION RECOGNITION AND EYE-TRACKING TECHNOLOGY

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Abstract. This paper coincides with the conference theme that people have gradually become a vital force influencing the environmental system. In the future, it is necessary to study the influence of not only the built environment on people but also people's feedback on environmental design. This study explores the processes of interactive design using both emotion recognition and eye-tracking of users. By putting on wearable devices to roam and perceive in a virtual reality space, the physiological data of the users are collected in real-time and used to analyze their emotional responses and visual attention to the spaces. This method will provide an auxiliary way for non-architectural professional users to participate in architectural space design. At present, there is a lack of research on the comprehensive application of eye movement knowledge and emotional feedback in architectural space design. This integration will help professional designers to optimize the design of architectural space. For this paper, we review existing research and proposing an interactive design workflow that integrates eye tracking and emotion recognition. This workflow will help with the next stage of research to understand the design of a new International School of Design building.

Keywords. Perception detection; Architectural space environment; Interactive design; Virtual reality.

1. Introduction

In recent years, architectural design has gradually shifted from pursuing spatial aesthetics to focusing on the users' physiological and psychological feelings in using and perceiving space. The user's experience of the space environment has become a core issue in the design of the built environment and needed to be quantified(Cho and Kim 2017). It is also one of the essential criteria to evaluate whether the design of the built environment can meet the needs of users. Yet, there are limitations in applying biofeedback in the design of architectural spaces.

On the one hand, the traditional spatial design feedback relies on two-dimensional drawings or abstract text descriptions. With digital tools,

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 263-272.

designers also start using 3D model but only to show the architectural visual outlook without and interactivity with the users. There is still a gap for users to intuitively understand the architectural design and provide accurate feedback to designers during the design phase. On the other hand, designers are unable to accurately and objectively capture the spatial perception of the users through subjective descriptions.

It is essential to know the users' evaluation of the architectural space so that buildings and public spaces answer to the real needs of future users. The common strategies used to get the feedback of users are observing their behaviours in spaces and collecting subjective questionnaire data. However, subjective feedback is easily affected by personal preference and professional level. Researchers have to rely on a participant's memory and subjective judgments as a means of gaining insight into cognitive processes and emotional states. A common finding within cognitive neuroscience is that a person's subjective perception of their behaviour does not always correspond with their underlying neural activity (Kretschmar et al. 2013).

This paper will explore relevant methods and techniques and analyse how our research target: the new International School of Design (ISD) building can use the interactive design method integrating these biofeedback methods to evaluate the scheme. The research results can provide inspiration and scientific design methods for the interaction design of architectural space environment design.

2. Background

2.1. VR IN ARCHITECTURAL COGNITION

VR emerge as an applicable computing technology allows the study of all kind of architectural spaces in a short period of time by using simulation, interaction, artificiality, immersion, and full-body immersion, sense of presence. (Jansen-Osmann 2002).

Research on comparing the users' perception of different architectural space presentation proved a virtual environment could, through the visual dimension of perception, in combination with interactive feedback, understood as the sensation of actually being present in an architectural space (Hermund 2018). In the process of cognitive spaces, people tend to process the information acquired by the senses automatically and produce pleasant or unpleasant psychological feelings. This subjective and perceptual psychological feeling which can elicit emotions is called ”aesthetic”. VR scenes can induce the user's emotions to change mostly through visual stimulation and will do evoke emotions, even behavior changes of the users.

2.2. PHYSIOLOGICAL SIGNAL INTERACTIVE FEEDBACK

Psychophysiological responses are believed to be more reliable and more truthful for the reason that they can hardly be controlled by awareness (Li et al. 2015). Identifying and analysing people's interest points and emotional changes in virtual space and combining them with space design elements can help designers to improve the design of the architectural space environment (Fernández-Caballero et al. 2016).

From measuring emotion in VR to understanding how the emotion of people are controlled by various physiological signals, technologies now play an important role to collect and analyse such data. With the development of information science, some software and hardware can accurately measure the real-time physiological data of users' cognitive process in the architectural space (Fig.1).

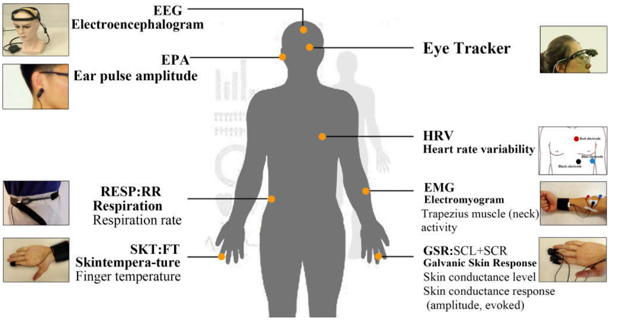

Figure 1. Physiological Signals Correlated with Emotional Arousal.

The first application of these emotional models was in environmental psychology (Plutchik 1980), and architectural studies have widely accepted them. Besides, they have been extended to the study of virtual spaces that evoke emotional states in a controlled way in the VR field (McCall 2016). In recent years, researchers have also proposed the idea of merging two emotional models: expressing the discrete emotional states in a dimensional way.

Biofeedback also includes the analysis of eye-tracking information. By capturing the eye movement information of users, eye-trackers can obtain the objective evaluation information of users on the design of the space in the VR environment. As a research tool in spatial cognition and related fields, the eye-tracking data can be merged with the user's spatial behaviour data quickly and accurately (Zhang et al. 2018). Roaming in the VR spaces to evoke emotional experiences while recording physiological signals from the peripheral nervous system, and real-time eye gaze patterns provide an effective strategy for evaluating the usability and impact of architecture space on its' users (Bekele et al. 2017).

3. International School of Design building

In the leading research, we are preparing to analyse the exterior axial space of the new ISD in our university. There are many discussions and disputes during the design stage. This site of ISD is between the main entrance of the campus and the tall administrative building representing the spirit of the school. The designer made an axial space from the access of the campus to the central plaza (Fig.2). He hopes this can become a dynamic axis, where people gradually enter the university and can feel the solemn and robust academic atmosphere of the school and have a sense of awe.

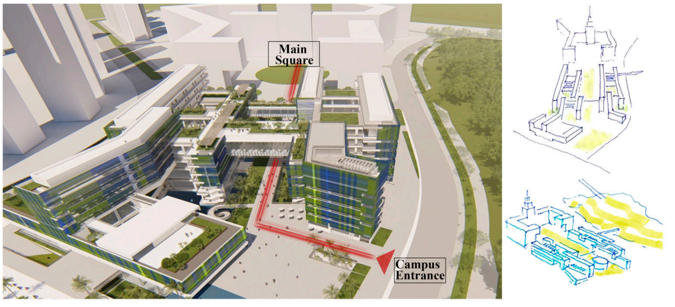

Figure 2. Aerial View of the ISD showing the axial space (Design from Ateliers 234).

This research aims to get the user's perception feedback of this outdoor space in advance, which could help the designer to check whether the existing design meets the requirements of this space. At the same time, in the VR environment, space elements in the 3D space can be changed easily; designers and users can adjust design and get biofeedback of users in real-time, which will help designers gradually improve the design of the spatial environment.

In order to achieve the aim of this research, it is important to look into some researches on emotion recognition, eye-tracking and focuses on analyzing relevant indicators and data processing methods that are of enlightening significance to the research of this experimental object.

4. Emotion recognition based on physiological signals

The premise of interactive design is that designers can collect and analyze users' physiological signals in the process of spatial perception to obtain users' emotional information.

4.1. DEAP: A DATABASE USING PHYSIOLOGICAL SIGNALS FOR EMOTION ANALYSIS

There are three main components of emotional response: experiential response, physiological response, and behavior response. In the past, emotion recognition mainly based on the analysis of facial expressions and subjective expressions, while the DEAP database is a public database for emotional analysis based on Physiological Signals (Koelstra et al. 2012). Through sorting out DEAP research, we can understand the different reflections of several level physiological signals on emotion.

The DEAP database used Russell's valence-arousal scale, which places emotional states on a 2-D plane in which horizontal and vertical axes are arousal and valence. The ultimate purpose of DEAP research was to establish a relationship with emotion through the algorithm calculation of physiological signal data.

The experimental study used music videos as effective emotional stimuli materials, and physiological signals were collected while watching videos. The physiological signals, including EEG and peripheral physiological signals (GSR, Blood volume pressure, Respiration pattern, Skin temperature, EMG), constitute the DEAP data module database. At the end of each video, participants were organized to use a visual scale to evaluate the video in four dimensions (arousal, valence, liking, and dominance), which were used to mark the physiological data. DEAP database research completed the collection of subjective and objective data of the experiment.

After emotional calculation, different physiological signals will reflect emotions from various aspects. They can extract power spectral density (PSD) to see the amplitude and reflect the changes of the brain in real-time (Fig.3).

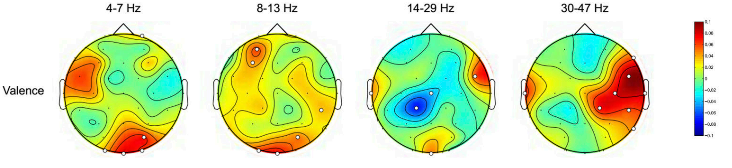

Figure 3. Power Spectral Density (PSD) (Koelstra et al. 2012,p9).

4.2. APPLICATION RESEARCH: PHYSIOLOGICAL SIGNAL AND ARCHITECTURE SPACE ASSESSMENT

Like music or video can arouse the emotion of people, there are also positive and negative attributes of the architecture environment. Besides, users also have corresponding emotional needs for different spaces. Dias et al. (2014) conducted a study on this, hoping to help improve the architectural design by understanding residents' potential feelings for the architectural space. They designed several types of spaces that might trigger high arousals, such as stairs, moats (explored gaps dizziness and fear), narrow corridors (claustrophobia), large room after a narrow passage (surprise), and dead-ends (disappointment)(Fig.4). They proposed the central hypothesis that basic user sensations of 'comfortable/positive' and 'uncomfortable/negative' architectural spaces can be derived through objective measurements of biometric data. They used a semi-immersive VR system to show these spaces, and selected electromyography (EMG) and electrodermal activity (EDA), which are closely associated with emotional arousal as indicators of physiological signal testing.

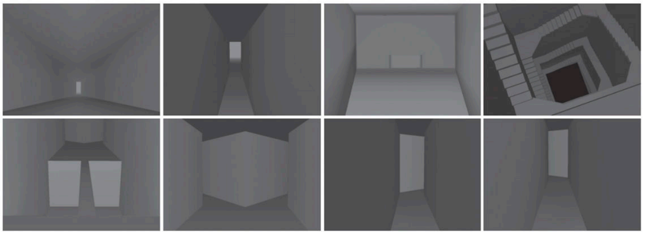

Figure 4. Eight Kinds of Designed VR Environment (Dias et al. 2014, p742).

Subjects' EMG and EDA data were captured using an acquisition system from Plux (2013). The analysis of two physiological signals includes two steps; the first was visual analysis. This part was mainly to observe a typical pattern between subjects at key event nodes in the process of spatial perception. There were clear event-related skin conductance responses (SCR) in most subjects. However, facial EMG signal proved to be quite variable and requires more research and analysis. This result shows that multi-signal collection is necessary to provide more comprehensive data support. Finally, each subject had to choose one adjective from the following three pairs: happy/sad, pleasant/unpleasant, confident/fearful to describe their subjective perception of space. The experimental results support the primary research hypothesis.

This work shows that with EDA sensing, the designer can objectively discriminate arousal responses related to "positive" or "negative" emotions when users are confronted with architectural spaces in VR.

5. Eye-tracking and spatial perception

After analysing a variety of physiological signals to understand the user's arousal and emotion in visual spaces, we can use eye-trackers to know more information related to spatial cognition, even which users cannot describe. Eye-tracking allows us to measure an individual's visual attention. This process produces physiological responses such as fixation, saccade, smooth pursuit movement, and change of pupil size, and the eye tracker can accurately measure the relevant eye-tracking data (Fig.5).

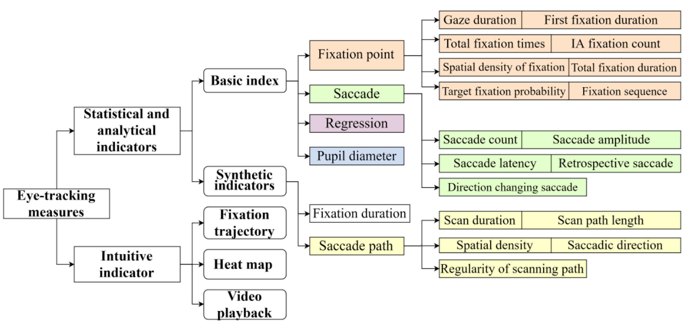

Figure 5. Measurement of Eye-tracking Data.

5.1. EVALUATION OF INDOOR GUIDANCE SYSTEMS IN AN IMMERSIVE VIRTUAL ENVIRONMENT

Schrom-Feiertag et al. (2014) used an immersive virtual environment in combination with a mobile eye-tracking system to present a novel method for evaluating guidance systems using. The main goal was to "investigate the applicability of an immersive virtual environment with embedded interfaces for natural locomotion combined with mobile eye-tracking systems for wayfinding studies."

They get an overview of the space that identifies the attention from the results of the second and third lines provide. Density plots help identify decision areas where participants are looking for further information and where signs should be visible (Fig.6).

Figure 6. Gaze Points from Saccade and Fixation(Schrom-Feiertag et al. 2014,p177).

In the same research, they get the visual attention of all participants and overall four tasks through 3D gaze visualization. The results mainly include the distribution of fixation points at the start position, Start 1 of the experiment, and the three main attractions in the main hall of the Vienna central train station(Fig.7). The result reveals that the information desk is used as a landmark that was the primary point chosen when people enter the main hall but does not belong to the guidance system.

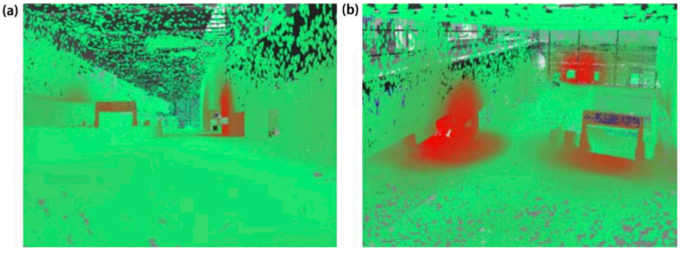

Figure 7. Distribution of Visual Attention(Schrom-Feiertag et al. 2014,p179).

The study suggests projecting eye-tracking data onto the 3D models that reflect the distribution of visual attention in a virtual environment and help identify the most compelling elements of the space.

5.2. INTEGRATION OF VR AND 3D EYE-TRACKING TO RE-DESIGNING STREET SPACE

Zhang et al. (2018) developed an eye-tracking technology combined with a VR environment for experimental research of traditional street design. The study takes the street scene drawn from the Hong Kong Street historic street of ancient Zhangzhou. Their behaviour in the VR environment was tracked in real-time. The software can collect the spatial activity data is on the virtual scene and provide the 3-D point-cloud data of spatial behaviour. Besides, there was an inquiry for subjective description to verify the subjects' eye-tracking data/and unusual eye movement phenomena were corrected.

When the subjects viewed the 3-D object, the apparent heat value of a specific object surface will increase with viewing duration. Therefore, after stacking the spatial behavior data of each subject, it will be shown in red in the thermal map, which can be regarded as hotspots(Fig.8).

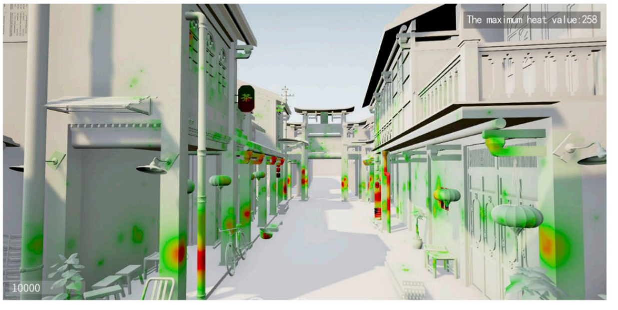

Figure 8. Composite Thermal Map of 3-D Eye-tracking Spatial (Zhang et al. 2018,P437) .

They, through the regression analysis of the observed position data, obtained the relative elevation of the object. The eye-tracking data shows that the professional subjects paid more attention to the second-floor features. However, naive subjects' paid more concentrate on the colonnade, the wooden bucket arch, the lantern, the memorial arch, and nostalgic objects primarily.

From this case, we know that the combination of eye-tracking and virtual reality will have a broad application prospect in the research of architecture space. They use the related eye-tracking indicators according to the characteristics of architectural spaces and related research needs. For instance, by processing the primary eye-tracking data, some meaningful indicators can be obtained for the evaluation of the architectural space, such as height distribution, line of sight, and 3D spatial viewpoint distribution.

6. Integrating two technologies for ISD

Having ISD as the research object, we will build the virtual simulation model of ISD, and then organize participants to put on both VR helmets with eye-tracker (Tobii Pro Glasses 2) and wearable physiological signal detection equipment to roam and perceive the virtual space. The change of morphological features on the axial space reflects the design motives, such as complexity, proportion and rhythm. The outdoor axial space of ISD is located in the middle of the two buildings. From the entrance through the axial space to the plaza of the campus administration building, the designer set up two connecting bridges in the different heights, hoping to form a gradual change of spaces under the connecting bridges. The purpose of this contrast is to build up the visual impact and emotional arousal brought by the main administration building.

In the virtual simulation environment, the use of portable ECG, EMG and EEG device, with eye-trackers and other measuring instruments, can accurately and objectively measure people's cognitive process and psychological feelings in the axial space. Multicategory physiological signal collection will provide more basis for the final emotion recognition. The collected physiological signals are superimposed on the roaming path so that the designer can determine the location and the interaction between the user's emotion and spatial cognition. We can understand whether the spatial elements (such as the admin building, the bridges, plaza) affect the users' emotions as how we imagined. At the same time, we can understand how the change of the spatial design scheme can make users more interested in certain spatial elements and increase the possibility of generating emotional inducing spatial flow? Besides, by integrating the corresponding relationship between emotional data and spatial data, we can detect whether there are environmental factors in the axial space that trigger negative experience and improve the design.

Through the understanding of DEAP's emotion recognition method, it can help us to process a variety of physiological signals to get users' emotion changes in space. It allows designers to observe the user's moving process in the VR axial space and whether they can form the same perception of spatial sequence events as expected. Dias's study used different VR spaces to stimulate people's emotions. Similarly, in the axis space of ISD, we can also flexibly change the spatial elements in VR. Although, at present, it is still challenging to determine the specific emotional type of users, but combined with the subjective survey, the designer can know the specific emotion of participants. The visual eye-tracking data, such as the thermal map and 3D gaze visualization, can be used to analyze the visual height and the area of concern of the subjects in the process of spatial perception.

Through integrating emotion recognition and eye-tracking, the designer can understand the key positions and time points of emotional arousal of participants in axial spatial roaming and analyze the tracking status of eye-tracking during this period. On the one hand, eye-tracking signals help designers to understand which visual elements cause emotional arousal when users have emotional changes during spatial perception. On the other hand, using emotion recognition and subjective survey can infer whether the spatial elements concerned by participants have positive or adverse effects. The combination of the two technologies can better meet the needs of spatial perception feedback.

7. Conclusion

This paper focuses on the research progress of the application of biofeedback technology in the design of virtual interactive building space. We found that the research combining emotion recognition and eye-tracking feedback in the field of building space is still in the primary stage. There is a lack of in-depth study to combine these two methods of evaluating architectural space. With the ISD being still in the design process, this gives us a great opportunity to use the technologies to determine if future users would prefer the design. And when the building is built in two years, we would be able to gather another set of data and evaluate if the current understanding really reflects the users' needs, and if the integration of the two technologies is feasible.

Acknowledgements

This work is partially supported by the National Social Science Fund Later Stage Funding Project [grant numbers 19FXWB026] and the Guangdong Science and Technology Project [grant numbers 2017A020220011]. Thanks to the "Kingfar Research Support Program" of Kingfar International Inc for supporting this study and providing the necessary equipment.

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HIGAME+

Planting as a medium to connect IOT objects in different environments to emotionally interact with elderly people alone

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Abstract. Elderly living alone have less chance to communicate with their families, so they tend to feel lonely and lack well-being. This study uses gardening activities which is familiar to elderly as the behavioral medium. Make elderly people living alone and their children living in other places through the Internet of Things system to connect space off-site to emotional interaction. Connect children of elderly 'mobile phone apps to HiGame+ potted plants in the home environment of the elderly, so that family members can care and accompany the plants in the homes of the elderly without space restrictions. At the same time, the potted objects will also record the long-term behaviors of the elderly, and will be transformed into the visualization of mood information to interact with children of elderly from other places to break the limit of spatial distance. Give elderly living alone to be emotionally connected and interactive, to increase their well-being.

Keywords. Elderly Living Alone; Emotional Interaction; Cross-Space Interaction; Internet of Things; Plant Care.

1. Background

Due to advances in technology, how to use interactive design to help specific ethnic groups and address their needs has gradually been valued and considered. For the needs of the elderly, more and more related interactive designs combining various technologies have begun to appear. Among them, in order to develop more possibilities in response to the use of interactive design. The concept of the Internet of Things has been used in interactive design. The Internet of Things is an information carrier of the Internet, traditional telecommunications networks, etc. Allowing all ordinary objects that can perform independent functions to achieve interconnection and interconnection. Gubbi et. al (2013) pointed out that In response to the needs of elderly people living alone, the IoT is a very popular technology because it can solve the constraints of space and distance.

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However, when using these technologies for the elderly, it must be considered whether the IoT and other technologies are suitable for interacting with elderly that thinking and habits compared to the traditional. And whether there is the right objects and the technology in the interactive process suitable for their operation to solve and meet the real problem needs of the elderly. In this study, we will explore the appropriate interactive media and methods for emotional interaction between children living outside and elderly people living alone with the IoT. And compare the differences with other smart homes designed for elderly people living alone

1.1. INTERACTION DESIGN FOR ELDERLY

In the human-computer interaction of many products, the difficulties encountered by the elderly are not because they do not know how to use these interactive designs. Carmichael (1999) pointed out that it's because the designers of various services do not have enough thought to recognize these potential users their Limitations suffered. In recent years, quite a number of interactive system designs have been designed to improve the quality of life and well-being of the elderly. But Marin (2011) said that many of the interactive technologies used in it show that it will affect the health of the elderly. The application of these interactive technologies may not only improve the needs of the elderly, but also lead to unexpected negative effects. Especially the design of some devices to create a pleasant atmosphere with flashing lights and colors may be interesting for young users, but not so for the elderly.

1.2. SMART HOME FOR ELDERLY PEOPLE

The concept of smart home plays an important role in the environment in which people live, and Jiang (2004) said that it must be considered as a basis for future residential planning. Its related design and research focuses on making and connecting tangible household items that people are familiar with. Tang (2000) pointed out that with the rapid development of the IoT, there are more and more smart home IoT systems designed for elderly people living alone. The most common way is to integrate remote home care services with smart houses, so that elderly people living alone can live more independently.

Some research used the furniture in the homes of elderly people as the IoT medium to interact with. Tseng (2019) chose the chair that elderly has been in for the longest time as an object to connect with them in the smart home (Figure 1). Design an IoT smart chair with multiple sensors that can sense the physical condition of the elderly. Children of elderly can compare the long-term records of the elderly from the App system, and can obtain behavior data of the elderly, to understand the elderly's living habits and know whether their recent daily routine is normal, so as to improve the emotional interaction and parent-child relationship between the elderly and family members.

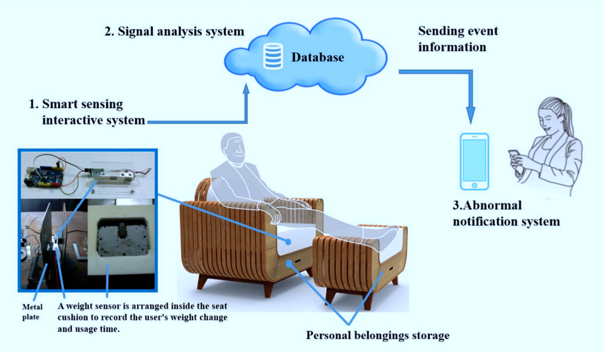

Figure 1. The concept of IoT chair in a smart home (Tseng 2019).

1.3. THE PROBLEM

The advancement of the IoT technology has shortened the distance between people, and the emergence of smart home related conceptual design has also assisted elderly people living alone to connect with the outside world at home. However, many smart homes on the market designed for elderly people who live alone rarely consider the emotional needs of elderly people. At the same time, they rarely consider the interaction mode that really fits the elderly and what they really wants.

Higher social technology use was associated with higher subjective well-being, and it was mediated by reduced loneliness. Chopik et. al (2016) pointed out that close relationships are a large determinant of well-being. But most designs for elderly people living alone are designed to help them to live independently without the assistance of their families. However, the more convenient and independent the home environment for the elderly, the less the relative family members will actually care for the elderly. A healthy elderly person needs not only health and safety precautions but also spiritual satisfaction and well-being in life, especially elderly living alone.

As mentioned in the literature, in the process of using smart home to interact with the elderly, the focus is on receiving data. Although it can help children grasp the health and living conditions of the elderly, and better understand the habits of the elderly. However, for the purpose of improving the emotional interaction between the elderly and their families, there are not many functions that can directly help and guide the elderly through the IoT, or objects that family members can interact with elderly. Elderly will experience less.

2. HiGame

2.1. HIGAME REACT TO THE PROBLEM AND CONTENT

In previous studies Wu et. al (2016) proposed a horticulture game design: HiGame system. That elderly people living alone and their children living in other places can use the Internet of Things to plant together. Connect the different places in the space to improve the emotional communication between the elderly living alone and their children. HiGame target is to increase the frequency of interaction to increase the well-being of the elderly. In the HiGame interactive planting research, we explored the psychological healing effect that horticultural planting behavior can bring to the elderly.

Therefore, in that research we chose to let children of elderly living in other places give instructions to the elderly who live alone to follow the instructions to perform actual plant care. Cooperate with each other to complete the planting of potted plants. And break through the space constraints to achieve the interaction between the elderly living alone and their children and emotional connections. In the interactive mode of the elderly, HiGame uses a single light to give different instructions to the elderly (Figure 2). So that the elderly can use the light as a medium to feel the care of the plants (also for the elderly) transmitted by their children.

Figure 2. The prototype of HiGame.

However, the research experiment found that the use of light alone for interactive presentation can make elderly people feel limited effects. And this interactive effect is not obvious for family's image of caring and elderly people's intuitive perception. In this interactive IoT system, the objects that children of elderly living in other localities can connect with the homes of elderly people are simple. What kind of interactive presentation can enable the elderly to receive interactive information more effectively, this could be studied more deeply.

2.2. FOUND SOLUTION

The focus of this research will be on the sensation of elderly. Strengthen the interactive presentation part of the elderly's interactive end. Changed the interaction mode of the elderly people, and focused on the experience of the elderly people in the interaction. In addition, the technology and details used for each functional object in this interaction will be explored in more depth. So that elderly people living alone can more easily receive the emotional interaction information transmitted by family members from other places to achieve the purpose of research: Solve the problem of spatial distance and improve the well-being of elderly people living alone.

In this research explore the design of multiple objects for emotional communication in smart spaces. And do user tests on the elderly to verify the actual effect of the design of this IoT interaction model on the elderly living alone. To know whether the elderly can feel the care and companionship of their children, and indeed can improve the emotional exchange between children live in other localities and elderly living alone, in order to improve their problems about the lack of well-being due to living alone.

3. Literature Review

3.1. SENSATION OF ELDERLY IN INTERACTION DESIGN

The correct design of the visual components is an important factor in the design of Interaction design for the elderly. When designing the visual display for the elderly, simplicity is the key. Too many colors and movements will make the elderly confused and frustrated. And the interaction with objects familiar to the elderly can strengthen the elderly's visual experience and reduce their misunderstanding.

About sound feedback to elderly, it is necessary to ensure that the volume is loud enough for the elderly users and is a sound they can recognize. Elderly often don't know what to do, especially when they encounter unrecognizable voice. This sense of helplessness often undermines their confidence in interaction, which leads to fear of making mistakes and inhibits their ability to Interact. (Williams, Alam, Ahamed, & Chu, 2013)

3.2. ACHIEVING EMOTIONAL INTERACTION IN DIFFERENT SPACES WITH THE INTERNET OF THINGS

Spatial distance has become a major obstacle to emotional communication. In order to solve the limitation of space on interaction, in recent years, more and more researches have been done on putting objects and IoT network to design various relationships and regular interactions.

Social networks can connect users in different spaces through the IoT. Jiang et al. (2004) mentioned that the concept of the Social Internet of Things (SIoT) has gradually been formalized, and as a social network, each of these objects in this system needs to be able to establish emotional relationships with others. And according to different users and different emotional needs, the corresponding will be different and appropriate objects to make different. The users of the space can use the objects and methods they accept to do emotional communication that connects the space to other places.

3.3. OUR APROCH

In this study, we used the plant care behavior that familiar to the elderly as an interactive presentation method for the interaction presentation of the elderly. And adding simple natural sound effects to enhance the elderly's perception. Reducing the use of excessive or complex sound and light effects. In the most comfortable way for the elderly, to help them receive and feel the emotional interaction from their children in other localities more smoothly.

HiGame+ sets the Internet of Things objects connected with the elderly living alone from a single potted object to multiple related objects that take care of potted plants. Compared with HiGame potted plants, in order to achieve more experience receiving for the elderly in the interactive experience part, in addition to the interactive prompts for lights, there are more interactive effects for the family to automatically take care of the plants, and sound prompts to attract other seniors It can also enable them to receive and interact with hearing and enhance their feelings.

4. The system: HiGame+

The gardening tools used in the planting process set by HiGame are inherited in this study, several key objects were connected to the IoT, and became a part of the IoT system connected to elderly people living alone in this study (Figure 3).

A waterer device is designed above the potted plant, which contains a servomotor that can remotely control watering. The drainage hole at the bottom of the pot is also equipped with an IoT motor to control the drainage of plants. In addition, a new LED plant light fixture object has been added to provide remote control of the plant's lighting function to supplement the lack of sunlight due to the pot plants being placed in the home. A horn device is also added inside the potted plant. When family members control the objects remotely, the horn will emit sound effects corresponding to the event to give the elderly more experience.

In the HiGame+ pot, there are soil moisture sensors, photoresistance, and pressure sensors that sense the state of the plants, so as to grasp the status of the pot plants and transmit the real-time sensed plant demand to the app of the elderly family members. Enabling them to give plants remote care instructions as needed. In addition, an ultrasonic sensor that records the behavior of the elderly is placed in the pot to record the daily behavior of the elderly and return it to the remote family of elderly.

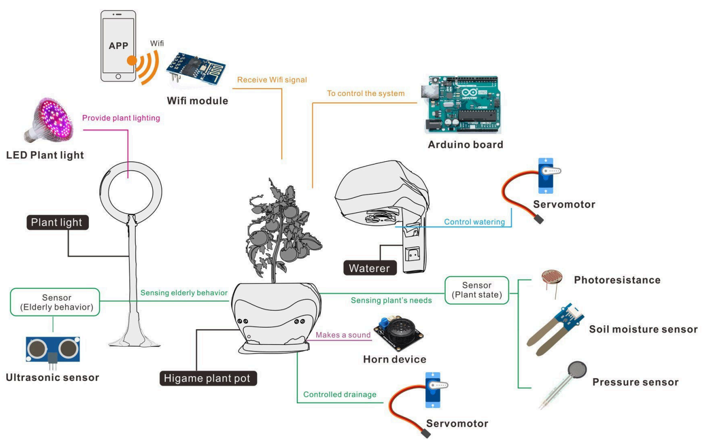

Figure 3. Technical Description of HiGame+.

4.1. CONNECT DIFFERENT ENVIRONMENTS THROUGH THE INTERNET OF THINGS TO ACHIEVE LONG-DISTANCE EMOTIONAL INTERACTION

Through the design of the emotional interactive potted plant system, the IoT is used to connect the elderly's home environment with families and children in the field. The real plant and the IoT interactive plant pot which are set in Elderly's home is the connection medium for the elderly. Around this plant representing the elderly is an IoT environment contains light and water .

The connection medium for family members living in other places is the App. Through the App, family members and children who doesn't live together with elderly can connect with the environment of the elderly's home no matter when and where they are. Let elderly people still feel even when they are at home The environment of this home is accompanied and cared for by the children, which affects the mood of the elderly. The elderly's reaction behavior will also be recorded and converted into emotion information and transmitted to remote family members to emotional interact with them(Figure 4).

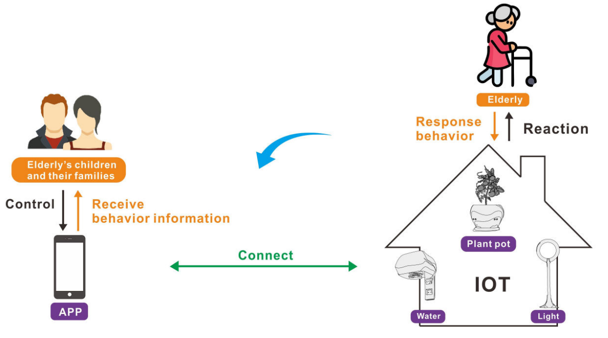

Figure 4. The relationship between the IOT, users and the environment.

In this cross-space emotional interaction process, the elderly do not need to take care of this interactive potted plant in person. They only need to ob-serve and feel the growth of the potted plant and the operation of the Internet of Things system around the potted plant, and they will feel the care of the home and the care of them from their children living outside.

The way the elderly respond interactively is that sensors in the IoT will record long-term viewing and activity behaviors of the elderly. Slow sensing will be used to convert the elderly's behavioral data into emotional feedback through the App system, and visualize to let elderly's long-term mood inter-act with children living in other places.

Children of elderly people who live in various other places are all the member of this family IoT system. When the potted plants in the elderly's home are in demand, these family members will be notified in the app on their mobile phones. Then they have to follow the plant requirements notified by the App, remote control to give the plants the necessary care instructions, or go back to the home of the elderly to personally solve the problem of potted plants. From this behavior, family members can feel more emotional connection with their parents even if they do not live together. At the same time, during the cooperation process of family members, they can be more attentive and closer to each other.

In the App, family members also receive information on the recent mood of the elderly, and can use this information to decide that whether they need to care more about the elderly recently or to accompany them more often, etc.

4.2. INTERACTIVE RELATIONSHIP OF CO-PLANTING BEHAVIOR IN DIFFERENT SPACES

The growth of a plant symbolizes long-term accumulation of time and care.Its current state is not caused by just a moment. Its final result can show the relationship about a long time between the caregiver and it. Therefore, this study uses planting as a behavior to let elderly living alone and his family members doing emotional interaction across space. The potted plant in this study is equivalent represents the elderly living alone in the home. Its cumulative growth will show the long-term relationship between family members and the elderly, so that this invisible family state can be visualized through plant growth and displayed in the eyes of family members.

This study divides the planting behaviors that family members need to assist into three parts:

- All family members need to go home together to do it, including platform and harvesting. it symbolizes that the whole family starts together and then ends it together.
- Family members according to the plant demand sensed by the potted plant IoT system in the elderly's home every day, to using their apps to remotely control the IoT object in the home of the elderly. In order to take care of the basic daily needs of potted plants, including watering, irradiation, and plant drainage.
- Remote control cannot solve some conditions and needs of potted plants, including weeding and fertilizing. Family members in the field will be notified when these conditions happened. And they have to go back to home of the elderly to deal with these needs of the potted plants.

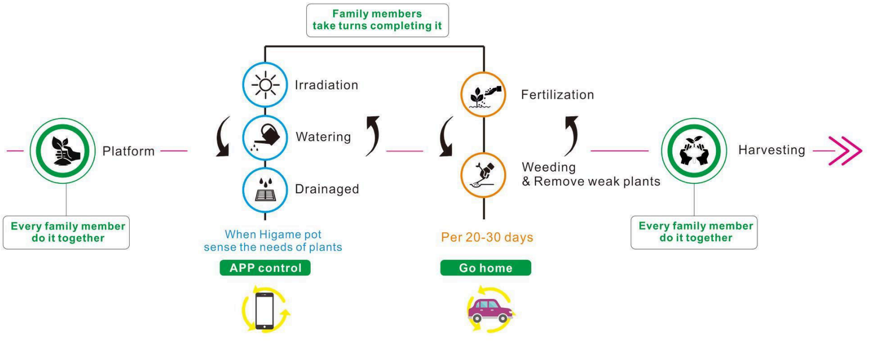

Figure 5. Activities of taking care of plants.

5. Discussion and Conclusions

In the context of simulation, we found a few elderly people who are currently living alone and are 65 years of age or older and give them a test (Figure 6). According to the results of the questionnaire survey, when the elderly know that this interaction will be controlled by children of them. More than half of the subject can feel the children's concern from afar and feel like being accompanied. They expressed that if having HiGame+ to interact with them at home can reduce their loneliness of living alone.

Figure 6. User test of HiGame+.

According to the literature, close relationships are a large determinant of well-being. Most of the elderly subject thinks that the presentation of this interaction makes them feel close relationships, and felt healing and pleasing to their sensory acceptance. About added a voice prompt, it really made it easier for some of the elderly with poor vision to receive interactive messages.

In this study, a interactive mechanism was designed and produced for testing. After testing, this design can indeed reduce the loneliness of elderly living alone. In the follow-up studies, we will further explore and study how long-term behavioral data of elderly that collected through HiGame+ interactive mechanism can transformed and visualized. To interact with children of elderly live in other places. And design other interactive modes that have a more significant effect on the elderly living alone.

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GENERATIVE HOUSING COMMUNITIES

Design of Participatory Spaces in Public Housing Using Network Configurational Theories

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Abstract. This research-by-design project explores how public housing estates can accommodate social diversity and the appropriation of shared spaces, using qualitative and quantitative analysis of circulation networks. A case study housing estate in Hong Kong was analysed through field observations of movements and activities and as a site for the speculative re-design of shared spaces. Generative design processes were developed based on several parameters, including shortest paths, visibility integration and connectivity integration (Hillier & Hanson, 1984). Additional tools were developed to combine these techniques with optimisation of sunlight access, maximisation of views for residential towers and the provision of permeability of ground level building volumes. The project demonstrates how flexibility of use and social engagement can constitute a platform for self-organisation, similar to Jane Jacobs' notion of vibrant streets leading to active and progressive communities. It shows how computational design and configurational theories can promote a bottom-up approach for generating new types of residential environments that support participatory and diverse communities, rather than a conventional top-down approach that is perceived to embody mechanisms of social regimentation.

Keywords. Urban Planning and Design; Network Configuration; Community Space and Social Interaction; Hong Kong Public Housing.

1. Introduction

John Turner stated in his book 'Freedom to build; dweller control of the housing process' that "housing should be treated as a process to human ends rather than as a packaged product, that decision-making power must give to the hands of the users themselves". A top-down approach to housing is insufficient to fulfil residents' needs (Turner and Fichter, 1972). According to Mercer, one of the world's largest human resource consulting firms, Hong Kong ranks 71 on the Quality of Living Index 2019, a decreasing position that is impacted by the high cost of housing and limited amount of public space (Mercer, 2019). Due to the

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 283-292.

strong emphasis on efficiency within Hong Kong's culture of governance, its public housing program is characterised by standardization and repetition. As a result, the architectural design and urban planning of Hong Kong's public housing estates can be perceived to embody mechanisms of social regimentation, rather than the ability to incorporate changes within society, such as changes in family structure and new modes of living and working as part of the emergence of a post-industrial society.

Jane Jacobs argued that ”in real life, only diverse surroundings have the practical power of inducing a natural, continuing flow of life and use” (Jacobs, 1961, p101). She argued that successful city spaces are activated through social and economic diversity, not superficial architectural variety. A multitude of interactions between different types of local stakeholders and visitors within urban spaces significantly improves residents' quality of life, increasing opportunities for social and economic prosperity. If everyone in the community takes responsibility for safety, social and cultural life, a ”feeling or the public identity of people, a web of public respect and trust, and a resource in time of personal or neighbourhood need” is created (Jacobs, 1961, p56). Jan Gehl argued that 'pedestrianism' should be integrated into city policy to develop lively and healthy cities, as well as strengthen the function of city spaces to contribute towards social sustainability and an open and democratic society (Gehl, 2010, p21).

2. Hong Kong Public Housing Estates

In Hong Kong, a public housing programme has been evolving since 1953 when a large fire at a squatter site made thousands of people homeless. A number of 'resettlement estates' was built quickly to house the affected and also to facilitate a large-scale squatter areas clearance program. As Hong Kong has a very limited amount of flat land available for urban development, public housing is still often used as compensation for residents affected by an ongoing densification of urban areas in the territory. Due to the need for a cost effective and efficient use of available land and public resources, public housing is characterised by 'standard types', repetitive high-rise slab blocks or towers arranged in dense patterns with limited public spaces or greenery in between.

The urban design of public housing estates is strongly influenced by Modernist ideas such as Le Corbusier's 'Ville Radieuse' (Radiant City) and the urban studies undertaken by the Congrès International d'Architecture Moderne (CIAM). Their 1933 'Athens Charter' promoted the concept of 'The Functional City', in which land planning would be based upon function-based zones, including living, working, recreation and circulation. Modern techniques should be used to construct high-rise apartment buildings, with in-between spaces reserved for large green parks (Gold, 1998). In Hong Kong, due to the limited available land, the in-between space between public housing towers has been minimised which affects the privacy, views and sunlight access for the apartments as well as for the public spaces within estates. Additionally, there is a mismatch between the planning and design of public spaces planning and their capacity to fulfil local needs, as very often these spaces are designed 'top-down' by the authorities who apply standardised guidelines and prioritise costs efficiency (Au, 2015).

3. Public Spaces within Public Housing

As apartments in Hong Kong are notoriously small, shared spaces around residential buildings are used as an extension of the domestic sphere. As an increasing number of people are no longer in conventional family structures or regular types of employment, shared spaces are even more important to accommodate social support, networking and collaboration. Yet the amount of open space in Hong Kong is 2.7 m2 average per person, which is less than half of the space in other Asian metropolises such as Tokyo, Shanghai and Singapore. Commercial facilities and spaces such as indoor markets, shops, coffee shops and restaurants play an important role in the social and economic needs of low income or 'non-standard' residents, yet many retail spaces in public housing estates are being privatised since 1993 (Li, 2003).

The Housing Authority and Hong Kong Government have formulated guidelines for the planning of estate facilities to contribute to well-being (HKPSG 2018). However, these guidelines are aimed at a linear top-down design process where decisions are made with limited input from local communities and the designs are considered to be fixed upon completion. This paper argues for the adoption of a more 'open-ended' view towards community spaces, allowing them to be flexible to appropriation and change over time as decided by residents. As Hong Kong's society is already seeing significant changes in the make-up of family structures, job nature and a higher demand for individuality, the design of public housing should incorporate facilities to support societal changes well into the distant future.

4. Case Study: Wo Che Estate

Wo Che Estate in Shatin, New Territories, is one of many typical estates which planning is based on the repetition of standard building types, and clear division of different programs. Built in 1977, it consists of thirteen residential blocks, accommodating around 19,000 residents. The overall circulation system separates pedestrians and vehicles at different levels, using elevated walkways and footbridges to connect all residential blocks, shopping malls, parks and a nearby metro (MTR) station at the upper ground level. As shown in Figure 1, the density of circulation movements gradually increases in the direction towards the MTR station, where there is a single route connecting the station and the estate for residents undertaking their daily commute. The main footbridges are designed as efficient point-to-point connections, which do not support alternative usage activities over time. The vertical circulation in residential buildings is organised through centralized lift cores as is typical for housing in Hong Kong, with entrance lobbies creating an abrupt division between public and semi-private circulation space. There is one shopping mall within the estate which imposes further limitation on the flexibility of movement and limits the residents' daily shopping choices.

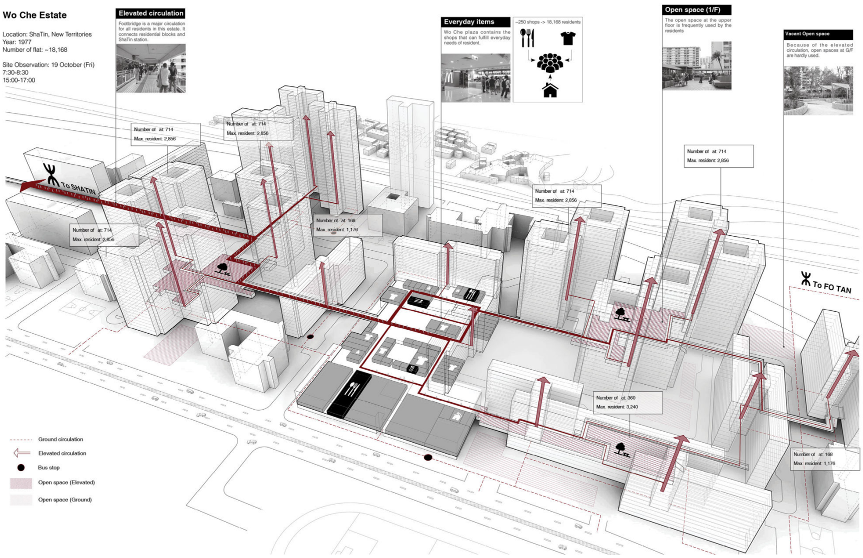

Figure 1. Configurational analysis of the circulation network in Wo Che Estate.

Figure 2 shows the daily routine of a resident traveling from his flat to the MTR station. It describes how the circulation network is controlling the resident's choices and their social encounters with other in this housing community. The intensity of usage of open spaces along the path is analysed and represented with a dark to light orange colour range, showing how residents mostly sit along central circulation and the planned sitting areas. The remaining parts of the spaces are hardly used as gathering space, as they are 'dead-end' spaces without connectivity to other programs or destinations. The field observations on site make clear that the layout of public spaces and circulation has very limited capacity to support social diversity and diverse activities organised spontaneously by local residents.

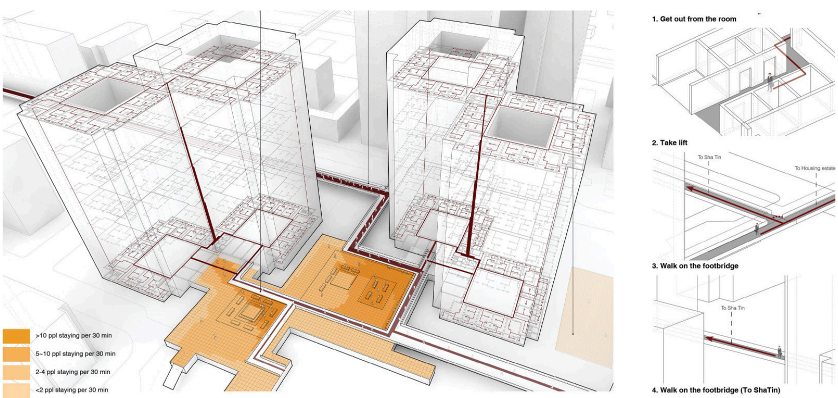

Figure 2. Configurational analysis of open spaces and daily routine in Wo Che Estate.

5. Generative Design Process for Housing Communities

In connection with the analysis of an existing housing estate in Hong Kong, this research-by-design project explores how a computational design approach can create a more participatory and open-ended urban environment that focuses on multiple choices of pathways and appropriation of shared spaces. The site of the Wo Che Estate was used to speculate on a comprehensive redevelopment, with a focus on improving the social performance of shared spaces. A computational design process was developed into two parts: the formation of the pathway system and the distribution of solids and voids.

Conventionally, efficient and centralised pathways connecting residential buildings to major surrounding destinations such as shopping malls and public transport nodes are used in the design Hong Kong housing estates. This research project explored strategies for creating multiple pathways with a certain redundancy in circulation options and public space provision, to facilitate different movement and activity distribution scenarios. For the Wo Che Estate site, a regular grid (10x10m) was used to divide the site (300x300m), to test various pathway systems that connect to access points to the surroundings by generating shortest paths between them. Six access points set for the site were determined based on surrounding connections and destinations. One set of shortest paths was generated by linking these access points from one point to every other point, and total six sets of shortest paths sets were generated by repeating this step for each point. By overlapping all sets of shortest paths (Figure 3), a multiple-choice pathway system was then formed within site, where ‘integration’ was also incorporated in the design process to control the width of each pathway. Breaking with conventional housing design guidelines in Hong Kong, the project conceived circulation systems not only to accommodate pedestrian connections, but also as systems to create opportunities and spaces for social engagement.

As stated by Hillier (1996), there is a relation between the spatial configuration and the likelihood of encounters called ‘natural movement’, which is the proportion of movement determined by the structure of the urban grid itself. Based on the configurational theories developed by the Space Syntax Group, ‘integration’ is a normalised measure of distance from any a space of origin to all others in a system as well as a predictor of movement patterns, both pedestrian and vehicular (Hillier & Hanson, 1984). To evaluate the pathway systems in our generative design process, the network integration was calculated and visualised ranging from the most integrated (red) to the most segregated (blue). In the generative process, the integration values informed the width of pathways, so that more integrated pathways would also be wider to accommodate a higher movement density and larger scale activities (Figure 3).

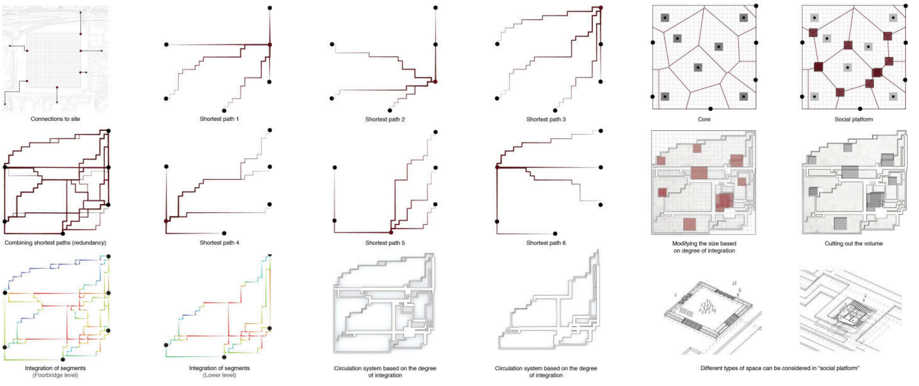

Figure 3. Shortest paths, integration, Voronoi analysis and addition of social platforms.

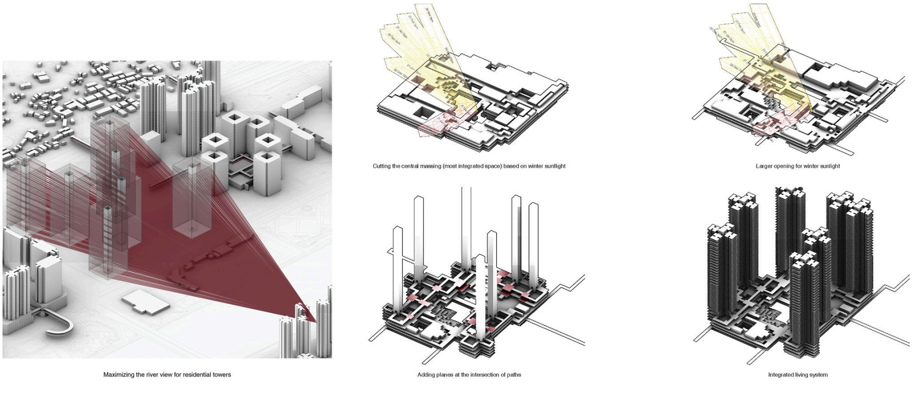

Figure 4. Maximisation of views, optimisation of sunlight access, platforms and towers.

Subsequently, the location of each residential tower was determined based on the principle of maximisation of views for each tower (Figure 4). This was achieved through a customised algorithm that projects viewing line vectors from each building façade and minimises the amount of intersections with other buildings through an Evolutionary Solver (Galapagos in Rhino/Grasshopper). Standardised tower volumes were used based on the latest standard type of public housing named 'New Harmony'. After fixing the position of the towers, 'social platforms' were introduced into the network system to combine circulation space with social activity spaces. A Voronoi algorithm was used to determine the minimal distance needed to reach each residential core and the value of network integration was associated with the size of the platforms. To optimise sunlight access for the most integrated space (as shown in red in Figure 3), winter sunlight vectors calculated at 21 December were used as projection lines from the social platforms, creating cuts through the podium building volumes to increase the sunlight access and permeability of the open spaces at different levels (Figure 4).

After testing and combining these different generative design steps into an integrated digital workflow, different options were tested and refined. Figure 5 shows the final design iteration chosen for refinement and visualisation, demonstrating the methodology and visualising a new living environment that includes multiple-choice pathways and different types of social space.

The developed case study design show how the configuration of the pathways is informed by the idea of network integration and natural movement. The clustering of public spaces is also visible, showing how more integrated paths result in larger open spaces for extensive group activities, and segregated paths are more suitable for private and small group activities. Similar to the idea of sitting described by William Whyte (1980), different choices of using public spaces with different privacy characteristics are available, such as connected or separated plazas for groups or individuals. The arrangement of private and public space in relation to configurational theories shows how a diversified social environment allows for participation by different types of people, such as extrovert and introvert residents. Multiple choices of shared spaces are not only providing physical comfort, but also achieve socially comfortable spaces for everyone in the community.

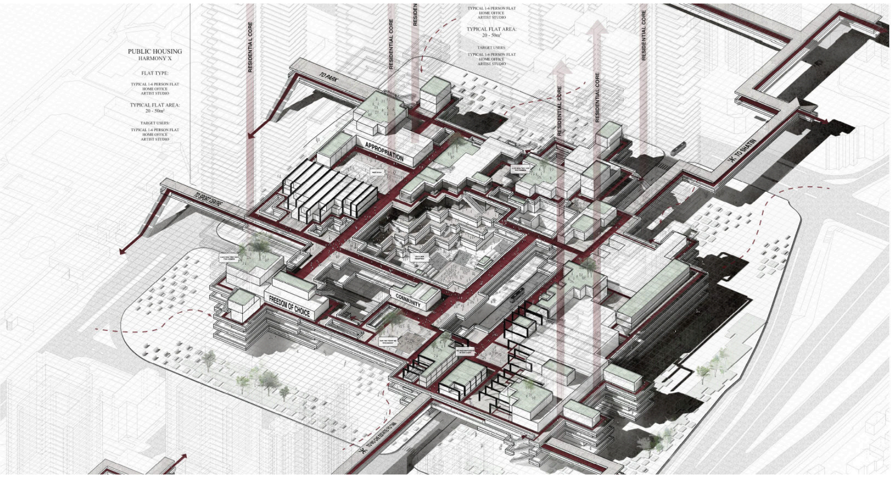

Figure 5. Multiple choices of pathway system and shared spaces.

6. Evaluation

The final design iteration was evaluated for its possibilities to generate different activity patterns in different situations, in order to contribute to the active and progressive community as argued for by Jane Jacobs (1961). Different patterns of usage were studied based on the idea of 'natural movement', which posits that more integrated streets, which are likely to be more accessible from other streets, will draw more pedestrians. Using data and principles found in the earlier testing of network configurations and in our field observations, the activity patterns under different situations at the same pathway system were generated and visualised.

The analyses were performed using techniques developed by Space Syntax - DepthmapX, a software that helps to analyse the connectivity integration and visibility integration (figure 6, bottom right). Through the accurate mapping and drawing a set of intersecting lines through all the spaces of the urban grid (Hillier & Hanson, 1984), the plan of the pathway system was converted into an axial map. Every segment in the axial map showed how integrated a street is, which allowed us to generate a connectivity integration diagram. Also, the urban networks set up in DepthmapX were evaluated for their inter-visibility connections, which were used to generate the visibility graphs. The distribution of integration values from the diagrams allowed us to understand the level of social interaction in certain spaces and the properties of the overall system, so that issues of publicness and privacy in public spaces, for extrovert and introvert people or activities could be considered.

Figure 6 shows three different usage scenarios including normal use, lunchtime peak time, and a large festival on a public holiday. The first situation shows a distribution of pedestrian movements predicted by the idea of integration: more integrated streets that are represented by wider arrows. Less accessible spaces are represented by narrower arrows and are mostly dead-end spaces (pocket spaces separate from the primary access to the MTR station). The central series of stepped public spaces is the most integrated space, so it could serve as a communal plaza and amphitheatre. The massing that surrounds this open space is suitable to house retail shops and markets which need high visibility and traffic (Figure 7).

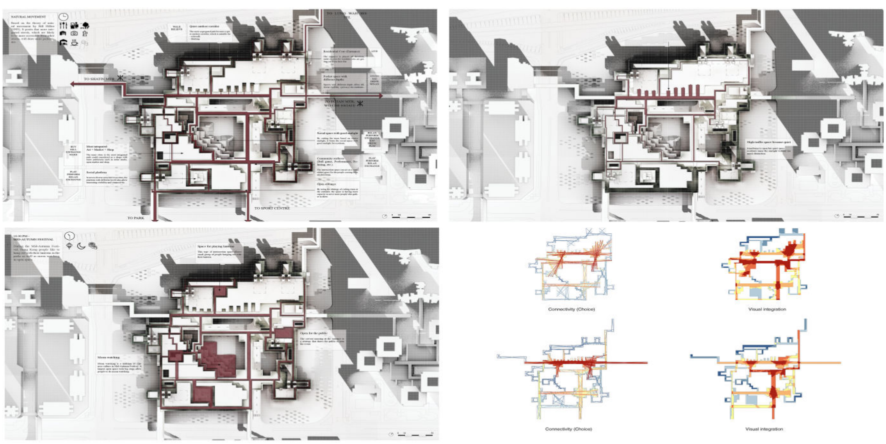

Figure 6. Different usage situations: normal (top left), lunch time (top right), Mid-Autumn Festival (bottom left) and visibility and connectivity integration analysis (bottom right).

During lunchtime, the movement density is different and pocket spaces are showing high activity levels as they are suitable for café and restaurants (figure 6, top right). The outer narrow pathways that surround the podium remain quiet and private, showing a hierarchy of privacy and choice of different character circulation spaces under these circumstances. During the large-scale festival such as the Chinese Mid-Autumn Festival, all large social platforms are being occupied as a shared-space for activities such as moon-watching and the lighting of lanterns, as part of the Chinese cultural traditions. Some private pathways connected to the social platforms have become denser and the proportion of private space is reduced in this situation, as the whole system is turned into 'festival mode' (Figure 6, bottom left).

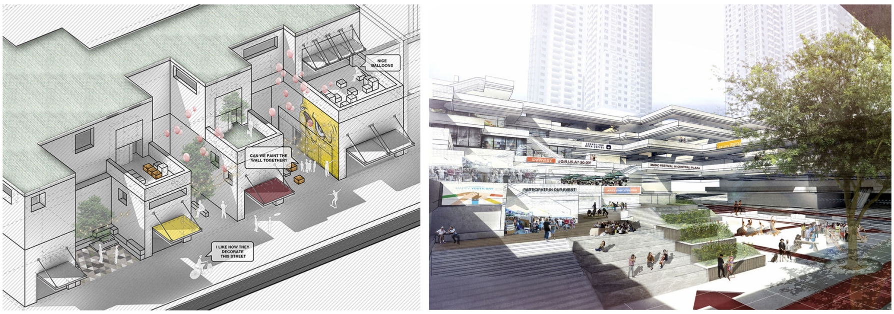

Figure 7. Pocket spaces (left) and central open space (right).

The playing out of three scenarios show how the same network can provide freedom of choice for residents using different shared spaces and pathways to their destination over time. This methodology also provides data useful for the planning of different programs in a proposal, planning different types of commercial or community facilities in relation to public spaces and circulation. The project demonstrates the possibility of linking generative design, social sciences, configurational theories and environmental factors with a specific socio-economic agenda.

7. Conclusions

This research and design project demonstrates how generative tools can help develop an alternative approach to housing estate design. The computational workflows enabled the incorporation of greater organisational complexity than standardised repetitive housing solutions. By introducing the multiple choices pathway and shared spaces based on the idea of social differentiation approach, the urban environments that are generated could increase the range of lifestyle choices for residents and provide social, economic diversity to the future housing estates in Hong Kong.

Rather than focusing on a single housing estate, the methodology has potential to be employed in design at other sites in Hong Kong, setting a new standard for the evaluation of estate circulation spaces and the incorporation of social flexibility and participation. The methodology has the potential to extend beyond a linear workflow and allow residents, designers and developers to participate in the design process and negotiate their different priorities through its parametric workflow. The incorporation of redundant circulation and unprogrammed public space could allow for permanent qualities of flexibility that would invite resident to appropriate spaces for spontaneous or planned activities of wide-ranging nature. Against the backdrop of increased integration of digital sensor-based monitoring systems, it can be further speculated that a real-time site space management system could be integrated into estates that would offer a feedback loop between usage patterns and estate design. This would allow the living environments to continuously evolve overtime, informed directly by the changes of everyday life.

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TECHNOLOGIES AND TECHNIQUES FOR COLLABORATIVE ROBOTICS IN ARCHITECTURE

- establishing a framework for human-robotic design exploration

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Abstract. This study investigates the technological and methodological challenges in establishing an indeterministic approach to robotic fabrication that allows for a collaborative and creative design/fabrication process. The research objective enquires into how robotic processes in architecture can move from deterministic fabrication processes towards explorative and indeterministic design processes. To address this research objective, the study specifically explores how an architect and a robot can engage in a process of co-creation and co-evolution, that is enabled by a collaborative robotic arm equipped with an electric gripper and a web camera. Through a case-based experiment, of designing and constructing an adjustable façade system consisting of parallel wood lamellas, designer and robotic system co-create by means of interactive processes. The study will present and discuss the technological implementations used to construct the interactive robotic-based design process, with emphasis on the integration of visual analysis features in Grasshopper and on the benefits of establishing a state machine for interactive and creative robotic control in architecture.

Keywords. Design cognition; Digital fabrication; Construction; Human-computer interaction.

1. Introduction

The background for this work is the capacity for Industrial robotic arms to engage and change the way architects explore and fabricate novel structures and material compositions. Also, the advancement of computational design processes and CAD-related technologies have made possible the modelling, analysis and simulation of complex performance-driven constructs. The recent development of robotic arms, with their versatile and highly customizable setup, has made the fabrication of these architectural constructs feasible. In the most exceptional cases, the robotic arm is such a well-integrated aspect of the design exploration that one cannot separate the resulting design from its means of fabrication. The use of industrial robots has become a *"transformational technology in architecture"* (Daas and Wit, 2018). Despite these advancements, in

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 293-302.

the majority of robotic-driven architectural projects, the robot, however complex tasks its performing, is following the deterministic set of commands given by the architect through a file-to-factory procedure (Pigram, Maxwell and Mcgee, 2016). This pre-planned procedure precludes the explorative element from the robotic fabrication process, as the architect has no option of intervening by re-directing or altering the fabrication process. This places the architect in the role of disengaged spectator. To successfully integrate robotic-driven design exploration the fabrication process needs to allow for human intervention and support an indeterministic search of the problem-solution space. This issue is discussed by Bryan Lawson in his seminal work on design thinking (Lawson, 2005) and later by Mary-Lou Maher who suggested a cognitive model for co-evolutionary design featuring two parallel search spaces; the problem space and the solution space (Maher, 1994). The work of Kees Dorst and Nigel Cross has also supported Maher's co-evolution model and use it to explain the behaviour found in their protocol studies of experienced designers regarding the nature of creativity in design (Dorst and Cross, 2001).

Therefore, this study investigates the technological and methodological challenges in establishing a framework for robot-based design exploration that allows for a collaborative and creative fabrication-driven design process. By taking advantage of existing methods and technological advancements in the field of computational design and architectural robotics, the study aims to establish and showcase suitable methods and procedures for connecting these fragments into a framework for design exploration with collaborative robotics.

Previous work within the field of interactive robotic-driven processes in the architectural domain already exists. Through their 'Mixed Reality Modeling' project, Johns et al. (Johns, Kilian and Foley, 2014) showcased an iterative process of robotic heat-gun melting of wax. Seeking to include "human in the loop modifications" their proposed design process allowed the designer to either manually remove wax from the physical object or to spray paint the object and thereby directly inform the robot where to perform the heat-gun treatment. The relevance of feedback loops has also been discussed by Dubor et al. (Dubor et al., 2016) who by exploring a series of case studies propose a framework for human interaction and machine response. In their paper, they conclude that 'collaboration between robots and human can enhance creativity and innovation by supporting designer and researcher while exploring complex material systems.' (Dubor et al., 2016). Similar work has been conducted by Moorman et al. (Moorman, Sabin and Liu, 2016) through the construction of a framework for dynamic robotic fabrication. Their proposed RoboSense framework seeks to promote a feedback-oriented design process where the robot shifts from being an executor of explicit commands to an "actor in a dynamic and reciprocal relationship with its fabrication environment" (Moorman, Sabin and Liu, 2016).

The projects referenced above presents exciting advancements in the construction of technological and methodological frameworks for robotic interaction in a design content and how these fabrication processes can support design exploration. At the same time, it is essential to recognize that all of the above projects work with either purely interactive processes or re-active processes, as in the wine pouring case study in the RoboSense project. To obtain a collaborative process the robot needs to perform in a way that exceeds what can be anticipated by the designer - a robotic agent that contributes with actions and intentions that assist the human designer in exploring unknown areas and connections between a given problem-solution space.

In the field of architectural robotics, a growing range of technologies and methods are emerging, of which some hold great potential for supporting a framework for collaborative human-robot design exploration. As displayed in the diagram in Figure 1, the construction of a framework for collaborative robotic design processes requires certain key elements. While some are well described, and standard in the field of computational architecture and robot-based design, others need to be adopted from other research fields. Another important aspect for a proposed framework is the option of parallel exploration of the physical design object and its digital twin, which demands that the physical object (or system) can be reproduced for further exploration in a CAD environment.

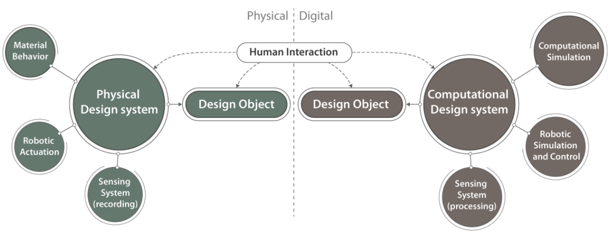

Figure 1. Framework for collaborative human-robot design exploration.

This study aims to utilize and explore the missing links needed to connect these fragments into a combined framework for design exploration with collaborative robotics. Therefore it is helpful to briefly look at the existing work for each of the key elements displayed in Figure 1.

Most of the elements needed to construct a collaborative framework already exist; however, a method for connecting and controlling all the sequential processes needs to be defined. As the behaviour of each key element is likely to pass through a series of clearly defined steps, triggered by input from either the internal processes of the system or from external user input, the concept of state machines are interesting. A state machine can be defined *"by identifying what states the system can be in, what inputs or events trigger state transitions, and how the system will behave in each state"* (Wright, 2005) and can be used to control the behaviour of simple systems, as in the example in Figure 2, or very complex UI systems. As GH is based on dataflow programming, suitable methods will have to be investigated to 'break' this flow and construct a customizable state machine.

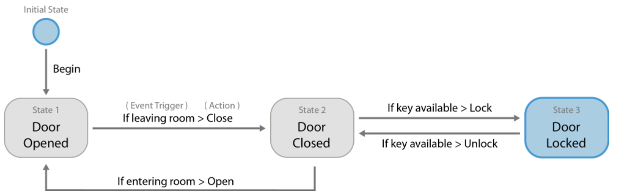

Figure 2. Example of a State Machine Diagram, with the key concepts ‘State’, ‘Event’, ‘Action’ and ‘Transition’.

The paper will present and discuss the implementations of existing technologies and methods to construct a new framework that supports a collaborative robotic-based design exploration. The paper will elaborate on the integration of visual analysis features in GH and on the benefits and challenges of establishing a state machine for controlling sub-routines. By presenting a design example, the paper will showcase the collaborative design process made possible by utilizing the proposed explorative framework.

2. Methods

To investigate the technologies and techniques needed to support a collaborative robotic-based design process, the study applied a research-by-design strategy (Hauberg, 2011). The strategy relies on physical and digital prototyping for uncovering possible solutions and allows for a continuous and parallel process of designing the framework and designing with the framework. The design process thereby informs the development of the framework and vice versa.

2.1. THE PHYSICAL DESIGN SYSTEM

To facilitate continuous investigation and development of suitable methods and techniques for robotic-based design exploration, a bespoke physical design system is developed during the study. This material-based system is developed on the criteria that both designer and robot should be capable of manipulating and changing, in a reversible manner, the system’s inherent design variables. These geometric configurations also have to permit both analogue qualitative user-driven design evaluations and numeric-based performance-driven computational simulations. To meet these criteria, a façade element consisting of twenty-four identical wood lamellas within a steel frame was designed and constructed (see Figure 3). Each lamella was constrained to a pre-made groove in the bottom rail, allowing for 90-degree stepwise rotation, and fixed in a rotatable acrylic disc within the top rail, allowing for 45-degree stepwise rotations. Reconfiguration of the lamellas’ bottom parts was restricted to manual user interaction. In contrast, the top parts could be rotated through a collaborative process with a robot performing the rotational movement of the lamella and a human user removing and inserting locking pins to fixate the lamella.

On the robotic side, the physical design system consisted of a UR10 robotic arm from Universal Robots equipped with a RG6 electric gripper from OnRobot onto which Logitech’s Brio 4K Ultra HD webcam was mounted. To enable user input, two simple push-buttons were connected to the digital inputs in the control box of the UR10.

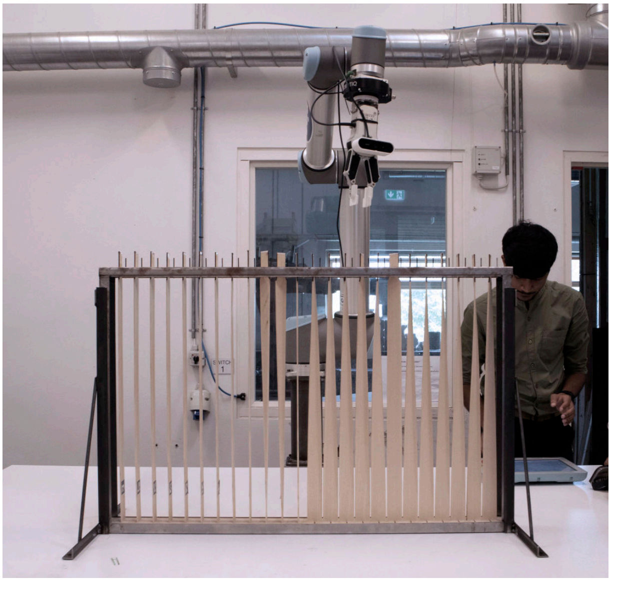

Figure 3. The physical design system consist of 24 wood lamellas mounted in a steel frame. Variations caused by rotation of individual elements creates potential for directed views and intentional blocking of sunlight.

2.2. THE COMPUTATIONAL DESIGN SYSTEM

The study utilized the Rhino-Grasshopper environment for developing a computational design framework integrating the following five sub-systems. A ‘Computational Design System’ containing the generation and geometric-driven manipulation of the virtual façade system. An ‘Environmental Simulation’ that calculates the sun shading and view-blocking performance of the virtual façade system. A ‘Robotic Simulation and Control System’ that based on availability, ease of use and utility used Vicente Soler’s (UCL Bartlett) Robots for generating target planes, simulating the robotic movements and streaming code to the robot. A ‘Visual Analysis System’ containing custom components that utilize computer vision libraries from OpenCV for tracking the position of the physical wood lamellas. A ‘State Machine’ which, based on components from the MetaHopper add-on by Andrew Heumann, handles the transitions between predetermined states and triggers actions in the order they need to be executed.

3. Results

3.1. COMPUTATIONAL FRAMEWORK FOR COLLABORATIVE DESIGN EXPLORATION

The study resulted in a collaborative framework that integrates visual analysis methods and a state machine to successfully allow for human-robot design exploration of a material system. The computational design framework allows for an interactive design exploration where a human agent, guided by design intentions regarding obstruction of desired view lines and sun shading, can manually alter the rotation of the wood lamellas. Subsequently, the robotic agent can be initiated and via the mounted camera register the current rotation for each lamella. This information allows the computational design model to perform environmental simulation based on a series of alternative lamella configuration and suggest a new and improved version by robotic rotation of the wood lamellas. As visualised in the flow chart in Figure 4, the framework allows interactions by the human designer (cyan coloured circles in the flow chart) to occur both during the physical material-based design exploration and the robotic fabrication process.

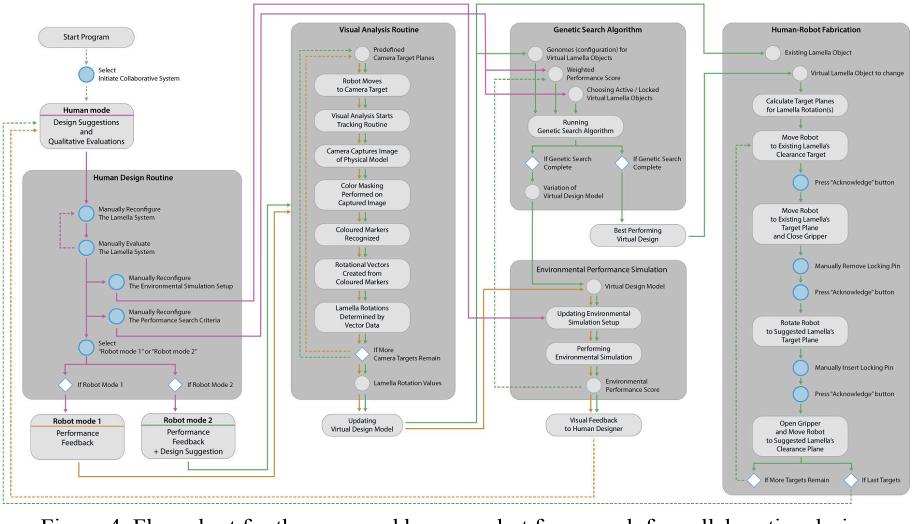

Figure 4. Flow chart for the proposed human-robot framework for collaborative design exploration. The cyan-coloured circles represent human actions during the design process while the three types of colored flow-lines refer to processes within the 'Human mode' (pink), 'Robot mode 1' (orange), and 'Robot mode 2' (green).

The main result of the study is the design of the collaborative framework in its entirety and the design process it supports. However, two aspects were crucial for successfully achieving this objective; the integration of visual analysis features in GH and the introduction of a state machine for controlling the interactive robotic processes.

3.2. VISUAL ANALYSIS IN GH

Integration of visual analysis was achieved by implementing functions from the OpenCV library into custom GH-components, thereby enabling tracking of individual lamella positions. As the standard python component in GH does not allow the use of libraries like OpenCV and NumPy, the custom VA-components were instead build using GH Python Remote by Digital Structures. The VA-components allowed two types of tracking; registration of ArUco markers and recognition of custom coloured markers. The ArUco marker, developed by Rafael Muñoz and Sergio Garrido (Garrido-Jurado et al., 2014), is a synthetic square marker identifiable by an inner binary matrix surrounded by a black border (OpenCV - Open Source Computer Vision, 2019). By attaching ArUco markers on each lamella the visual system, using the cv2.aruco module in the OpenCV library, was able to distinguish between the 0- or 90-degree rotation allowed for the bottom part of the lamella system. Custom red and cyan colour markers were applied to the top of each lamella, and by colour recognition, the VA-system could calculate the individual rotation vectors. The VA-process for tracking the custom markers consisted of a set of discrete steps, starting with the capture of two images containing the twelve wood lamella for the left and right side, respectively. As can be seen from the diagram and the pictures in Figure 5, the captured images are cropped to the boundary zone of the lamella ruling out any unwanted artefacts and allowing for efficient computation of the lamella rotation angles. Next, two image masks are created based on the predefined red and cyan colour in HSV colour mode. These masks are used to subtract the background leaving only red and cyan colour allowing a calculation of the contour for each coloured area and a subsequent approximation of the outline of these regions. A boundary rectangle for each coloured region serves to locate the individual centroids and from these establish the two-point vectors (with direction from red-centroid to cyan-centroid) that informs about the rotation of the wood lamella. Based on the bottom and top vector the twisting of each lamella was determined and the digital version of the design system could be updated so as to mirror its physical "twin". Each of the GH components developed for visual analysis were designed with an input field for activation of the internal logic and an output field with a boolean value flagging its successful completion - simple features that were crucial for integration of a state machine.

3.3. STATE MACHINE IN GH

Construction of a custom state machine inside GH was achieved through custom python components and use of components from the MetaHopper add-on, as shown in Figure 6. The 'SetObj' component from MetaHopper allowed the framework to use the Boolean value from selected components to control the value of standard GH-buttons, in other words getting a 'True/False' output from one component would 'Push/Release' another GH-button. The state machine allowed control and activation of sequential stages in the established human-robot design process.

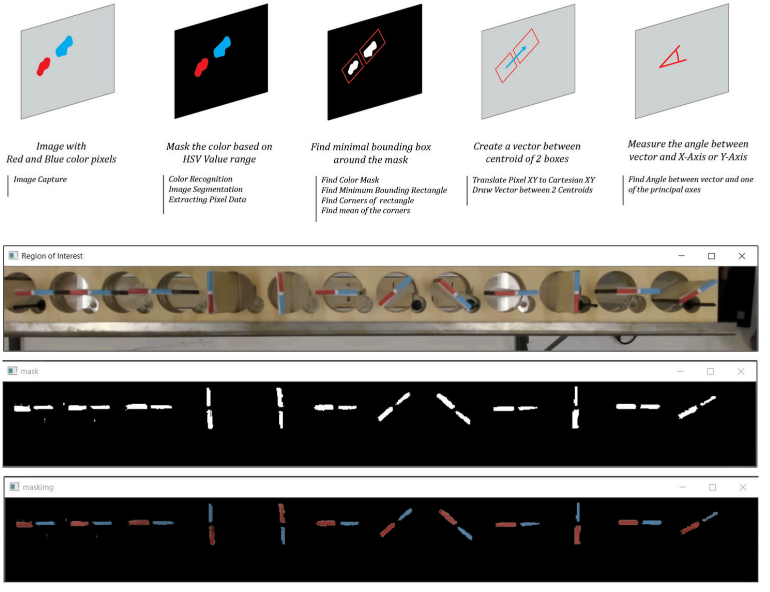

Figure 5. Top: Diagram of the visual analysis process from image data to rotational data. Bottom: Example of the visual analysis routine performed on the top side of the wood lamellas by using OpenCV in Python. The first picture shows the cropped image recorded by the robot-mounted webcam. The second picture shows the masking out of all unwanted colours. The third picture shows the result of applying the mask to the cropped image. .

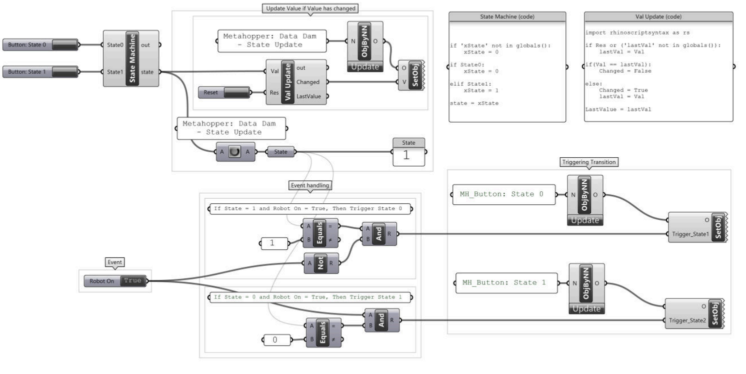

Figure 6. Example of a simple State Machine in Grasshopper. The Grasshopper definition uses custom python components and MetaHopper components to change and keep track of states. The State Machine integrated in the proposed framework is an expansion of this setup.

4. Discussion

Following a research-by-design approach, this study has investigated and established a framework that allows a designer to engage directly with a physical design object, while in succession obtaining new design suggestion from a robotic system. The development process and the final result reveals essential aspects of human-robot design exploration.

The camera used to capture the coloured markers and the ArUco markers has an automatic focus feature which often affects the image capturing process and results in blurry photos with a negative effect on the colour detection procedure. During the prototyping process, this was resolved by inserting a time delay (approx. 2 seconds) between robot (and camera) arriving at capture position and the actual capturing process. Another challenge, well-known in the field of visual analysis, is the importance of lighting conditions. The colour detection algorithm used in the framework takes in the absolute HSV values from the colour system and detects accordingly within a given range the varying hue, saturation and value. In the physical setup, due to the presence of a skylight in the indoor environment, the ambient light varied by a visible spectrum to cause significant error in the colour detection. This issue can be mitigated using complete artificial light or by minimizing the effect of varying coloured light in the system.

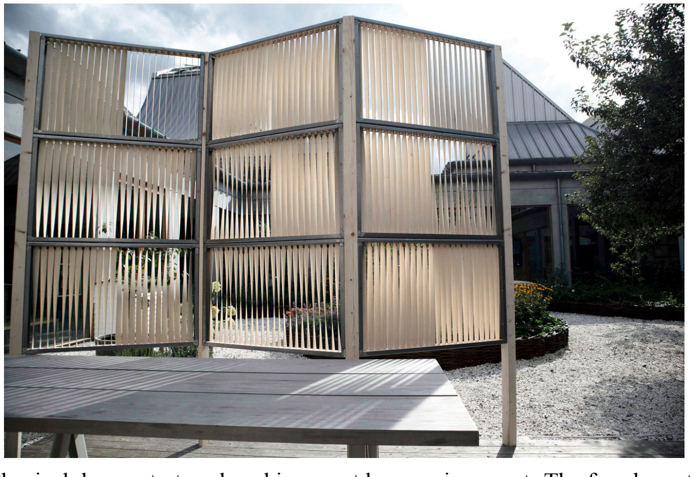

Figure 7. Physical demonstrator placed in an outdoor environment. The façade system clearly displays its environmental performance towards shading the sun and directing views.

When taking part in a creative and collaborative design process, the experience of time and the maintenance of creative flow is essential. An important aspect of successful collaborative work is knowing the intention of the co-workers - a challenging aspect when working with robots. Not knowing what goes on "behind the scenes" during ex the time-span of computational performance search, which often took 30-90 seconds, leaves the designer in a state of passive waiting. Initial experiments show a significant difference in running the collaborative process with or without the opportunity to see GH-based visualisations of the computational performance search. Through parallel design and evaluation of the framework, it was evident that the additional time used to ex resolve the issue of automatic focus, as mentioned above, could be solved through technological changes/upgrades. Optimising the algorithms used in the framework is another area for optimisation. Many of the computational processes run in a series, and the initiation of a task is often dependent on the completion of previous tasks. In some cases, it would be more efficient to employ multiprocessing to ex. move the robot between the image capture targets, while simultaneously running the image analysis on previously captured images - the proposed framework currently waits for each image to be captured and processed before moving the robot to the next target position.

The study has sought to carry out foundational work on which to base applied research. The paper has focused on the technological and system-oriented aspects of collaborative human-robot design exploration and shown that the proposed framework can support such processes. For future work it will be important to investigate to what extent this robotic-based approach will affect the creative design process and if a fruitful “dialogue” can be established between a holistic-driven human designer and a performance-driven solution-proposing robot.

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DATA-DRIVEN EMBODIED CARBON EVALUATION OF EARLY BUILDING DESIGN ITERATIONS

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Abstract. In the early design phases, Life Cycle Assessment can assist project stakeholders in making informed decisions on choosing structural systems and materials with an awareness of environmental sustainability through their embodied carbon content; yet embodied carbon is difficult to quantify without detailed design information in the early design stages. In response, this paper proposes a novel data-driven tool, prior to the definition of floor plan layouts to perform embodied carbon evaluation of existing building designs based on a Bayesian Neural Network (BNN) regression. The BNN is built from data drawn from existing floor plans of residential buildings, and predicts material volume and embodied carbon from generic design parameters typical in the early design stage. Users will be able to interact with the tool in Grasshopper or as an online resource, input generic design parameters, and obtain comparative visualizations based on the choice of a construction system and its environmental sustainability in a 'shoebox' interface - a simplified three-dimensional representation of a building's primary spatial units generated with the tool.

Keywords. Regression; Bayesian Neural Network; High-Rise Residential Buildings.

1. Introduction

Human activities have grossly influenced the Earth's climatic conditions. The construction and operations of buildings can account for up to 36 percent of global energy use and 39 percent of energy-related carbon dioxide emissions annually (Dean et al. 2017). Together with rapid urban growth driving up demand for residential apartments, improving building design for maximised environmental sustainability has become more important than ever.

To support this endeavour, Life Cycle Assessment (LCA) is typically adopted as a methodology to evaluate the impact of embodied and operational carbon in buildings (ISO 2006). For which, the impact of embodied carbon is typically

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quantified in a metric known as Global Warming Potential (GWP) - a measure of the greenhouse gas (GHG) emissions for the manufacturing of building materials. The process of LCA is usually applied to late stages of design, where the building information is well advanced and there is little possibility to make improvements due to larger sunk costs incurred. Quantifying the impact of embodied carbon (GWP) within a building in the early stages would allow designers to plan for and minimize the subsequent environmental impact of building designs. However, GWP is difficult to quantify in the early design stages due to uncertain information regarding the design project and the resulting material volumes required.

This paper proposes the development of an LCA-based tool to address the challenge of quantifying GWP without a floor plan design in the early LCA stage. More specifically, we focus at the stage 2 - Concept Design of RIBA Plan of Work 2013 (Sinclair 2013), where the material and construction systems are not yet defined. The approach presented builds up further on previous attempts (Meex et al 2018).

As a case study, construction systems such as hybrid concrete-timber systems are explored in this research to assess the potential reduction in GWP due to the supplementation of carbon-intensive concrete with a more sustainable material like timber. A predictive model that maps generic design parameters to eventual LCA results were built using data from existing building projects in a Bayesian Neural Network regression framework. Our proposed model implicitly relates the basic building dimensions, to kinds of spaces (circulation/served/serving), inner/outer enclosures, ratio of support and infill components, to the eventual probabilistic material volumes and embodied carbon estimations. In the resulting tool, the user will be able to input initial client-driven parameters, visualize and evaluate the LCA results based on different construction systems and choices of infill systems.

2. Background

LCA provides a quantitative assessment of the upstream and downstream burdens throughout the life cycle of the building. There are three levels of LCA with varying levels of detail to cater for different stages of design: screening LCA, simplified LCA and complete LCA (EeBGuide 2014). In practice, LCA is typically conducted near the completion of the building project, where changes are more difficult to be made and at a high cost (Treloar et al. 2000). Following the logic of the MacLeamy curve (Macleamy 2004), the ability to 'optimize' the resulting embodied carbon of the building and reduced the cost of changes is the highest in the earliest stages of design.

Only a few LCA tools for early stage evaluations are currently available. Screening or simplified LCA tools such as CAALA (Meex et al. 2018), aid in the initial phases of building design. VPL-based tools like Bombyx (Basic et al 2019) and Integrated Design Model (Otovic et al 2016) aim to provide design guidance based on simplified building information as input and intuitive carbon evaluation as output. These tools, as opposed to complete LCA tools, focus on few prime building elements, user-specific life cycle stages, and cover a reduced number of impact categories. However, such tools do still require an existing design to obtain

LCA results, which is why they are only suitable for planners who already possess a certain level of expertise. Our proposed framework allows users to evaluate and formulate immediate conclusions to influence design decisions with only generic, quantitative parameters. Furthermore, the tool builds upon the common graphical representation of GWP data with the comparison of two or more design variants. Through highlighting the best performing and worst performing design variants, users will be aware of the scope for more sustainable design.

To overcome the lack of design information and expertise in the earliest design stages, predictive models are developed to assist users in quantifying embodied carbon (Victoria et al. 2018), operational carbon (Ferlito et al. 2015), and costing (Liu et al. 2013) throughout the lifespan of the building to improve environmental and cost efficiency. These predictive models are typically built on linear regression approaches that map a few inputs to the desired output, allowing users to explore the relationship between basic inputs and outputs without the need for an existing design (Victoria et al. 2018, Ferlito et al. 2015). However, such research has mostly been focused on predicting operational carbon (Gadezi et al. 2016) rather than embodied carbon (Victoria et al. 2018). For this paper we assume the following set of generic quantitative parameters that help to determine the total amount of all surfaces in a typical residential building: footprint area, depth, and width of the building, the number of units required in the building, building height and typical floor height, and structural/material choices.

The main contribution of this paper is a software tool that would be shared as an online resource to predict GWP evaluation for early design iterations of residential buildings. The software inputs the generic residential design parameters, and outputs a 'shoebox' representing the typical resulting architectural primary spatial units, and a breakdown of material quantities and GWP of the said representation. Figure 1 illustrates how the coupling of LCA with predictive modeling facilitates the ability to compare the impact of different quantitative design variants, as an alternative to the standard screening process where a floor plan design has to be generated before LCA can be conducted. This paper discusses the various steps to construct the predictive tool, which are data collection, data modeling, and visualization of the building 'shoebox'. The following sections describe each of the components illustrated in figure 1.

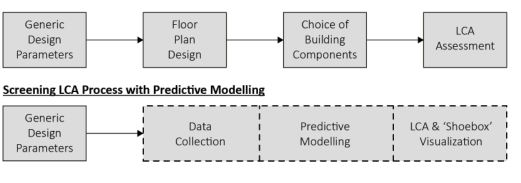

Figure 1. Proposed improved simplified LCA process with predictive modelling .

3. Data Collection

Data from numerous built projects with information on building parameters, material volume and GWP information of materials would be required to build a reliable predictive model. Industry Foundation Classes (IFC) files that commonly used in Building Information Modeling (BIM) programs are an excellent source of information. Such files include information on spatial elements, material quantities, and building shapes that could be automatically transcribed into a digital database. For a preliminary study, we manually collected information from case studies of built construction as illustrated in Floor Plan Manual Housing (Heckmann and Schneider 2018) and Manual of Multi-Storey Timber Construction (Kaufmann et al. 2018). State-of-the-art timber construction systems were compiled on top of other conventional systems for multi-storey apartment buildings as timber has substantial impact on lowering GWP. 17 case studies with two forms of construction system - Shear Wall and Column Beam systems and the concomitant material combinations implemented in these systems were studied. The data extraction process is shown in figure 2. In this process basic building dimensions, spatial areas (circulation/served/serving), inner/outer enclosures, ratio of support and infill components are measured and consolidated to prepare for the modelling process. Specifically, superstructure, structural (support systems) and non-load bearing elements (infill systems) were considered, as shown in table 1. The choices for both infill types provided to the users were adopted from Quartz dataset (Quartz,). The thicknesses of the respective structural walls were assumed to be consistent throughout the building.

Figure 2. Data extraction process: selection of case studies, translation and data entry. .

Due to the uncertainty of the service lifetime and end-of-life process, the scope of the LCA study is kept with the cradle-to-gate boundary, denoting the embodied carbon captured in raw material extraction, transportation, and manufacturing process of the building products. This boundary does not include the impact of transportation to the construction site. The LCA database is sourced from Quartz and GWP is adopted as an indicator for the measurement of the embodied carbon factor (Quartz). The functional unit will be $KgCO_2eq\ per\ m^2$ with m^2 representing the gross floor area of the building.

Table 1. Building elements and respective materials accounted for embodied carbon in the case studies .

Type of System	Type of Building Component	Material
Support Systems - Shear Wall System (Superstructure structural)	Vertical load-bearing element 1	Concrete
	Vertical load-bearing element 2	Concrete
	Horizontal structure (Slab or frame)	Concrete, CLT, Glulam
Support Systems - Column Beam System (Superstructure structural)	Vertical load-bearing element 1	Concrete
	Vertical load-bearing element 2	Glulam, Steel
	Horizontal structure (Slab or frame)	Concrete, CLT, Glulam
Infill Systems (Superstructure non-structural)	Partitions	Drywall, Timber frame wall, Wet wall
	Frames	Panel, Glazing, Door, Window

4. Modelling Process

The goal of the modeling process is to predict the material volume for different inputs, before calculating the total GWP. A typical approach to prediction is a regression approach, which involves finding a mathematical function to map inputs to outputs (Friedman et. al, 2001). In our process, the inputs refer to generic quantitative building parameters (figure 3), and the outputs refer to the different material volumes and building areas mentioned in figure 4. Input data can be categorized into unit level and building level information:

1. Unit level inputs influence the size and programmatic constraints of one apartment unit in the building: Number of served spaces for living or sleeping, and serving spaces like corridors, wet cells (bathrooms or kitchen), and storage are required.
2. The building level inputs will influence mainly the material volumes of support (load-bearing) and infill (non-load-bearing) systems. Eight different structural systems with different material combinations are determined and embedded, and the users have a choice of the two types of infill system: partitions and frames that they would implement in the design with three options each.

There are several considerations when choosing the regression model for this particular use case:

1. The model should be able to act as a non-linear regressor - The interactions between inputs and outputs are non-linear. i.e. the number of rooms and the material volume needed for their enclosures is not simply a linear relationship.
2. The model should be able to gauge uncertainty of an output - For the model to be used as a decision-making tool, understanding the model uncertainty will add another dimension to obtain the optimal choice. Instead of a deterministic approach where model parameters have just a single value, models could take a stochastic approach and consider model parameters as having a probabilistic distribution with a range of values.
3. The model should be able to handle categorical and continuous variables - Certain inputs like construction and material systems are categorical (takes a fixed number of possible values) while building floor area is continuous (infinite number of values between any two values).

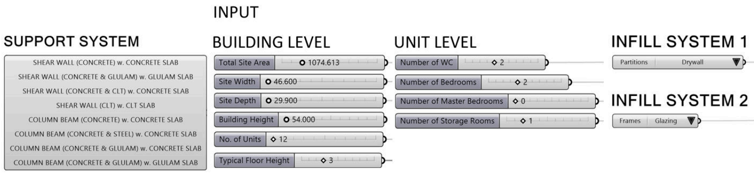

Figure 3. User input for both building and unit level in grasshopper.

One of the regression methods that fulfill those criteria is a Bayesian Neural Network (BNN), as proposed by (Gal et. al., 2016). By incorporating “stochastic dropout” within a neural network structure, a BNN is able to capture the uncertain spread of GWP resulting from generic design parameters across multiple building projects. Also, BNN regression approaches are able to scale with more input data due to its ability to detect all possible interactions between the input generic quantitative parameters and output GWP, as compared to more traditional regression methods like linear regression (Tu 1996). We assume that the building database available for modeling will grow in the future.

Data regarding generic quantitative parameters, eventual GWP were collated from 17 buildings in Section 3 (Data Collection), forming 17 data vectors. The first 14 data vectors were used for training the BNN, before the last three, which were extracted from a floor plan that is structurally verified, were used for validation. We utilized two BNNs for prediction, the building topology related information and construction system related information. The structure of BNN and their inputs and outputs are shown in figure 4. Categorical features in the data, like the ‘type of construction system’, ‘material for construction’, ‘sub-material for construction’ and ‘floor slab material’ exist as text. To allow the BNN to understand such forms of data, categorical data are converted to a mathematical vector, in a process known as “One-Hot Encoding.”

The building topological model statistically relates the basic building parameters to the functional spaces of a building, from which the ratio of circulation, served, and serving space of a building could be calculated. Similarly, the construction system model statistically relates the basic building dimensions, to the material volume required of the support and infill systems within a building, via an implicit understanding of the inner/outer enclosures of different areas within a building. The eventual GWP of the building is calculated from a multiplication of the material volumes with a material database.

Due to the presence of non-linear relationship between inputs and outputs, BNN should be more accurate than Linear Regression in modeling GWP. To compare the accuracy of the two types of regression approaches, the BNNs were benchmarked against the more commonly used Linear Regression method (Gadezi et al. 2016, Victoria et al. 2018), by calculating the Mean Absolute Percentage Error (MAPE) of the predictions made on the three validation data points, and evaluating the Cosine Similarity. In Figure 5, we show that for all the prediction outputs, the MAPE for linear regression is much higher than that of the BNNs.

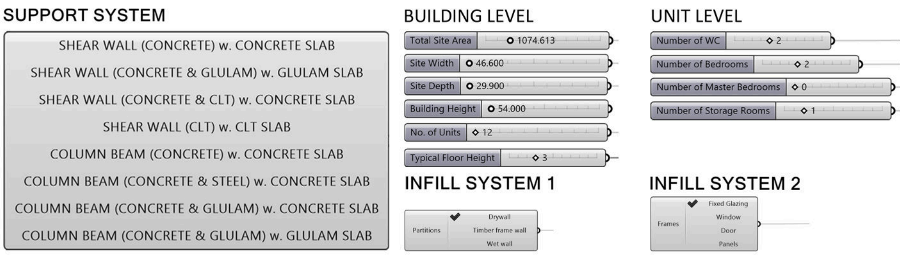

Figure 4. BNN Structure and Outputs .

For Cosine Similarity, the closer the values to 1, the better the performance. BNNs achieve an averaged Cosine Similarity score of 0.9893 across the three validation data points, compared to that of 0.9393 for the LR. As seen from the inhouse benchmarking test, BNN has better accuracy compared to linear regression and is able to provide an uncertainty indication when data is sparse. To provide a link to the visualization tool in Grasshopper, the trained BNN models are uploaded to the web and queried through a customized Python script in Grasshopper. Users without knowledge of Grasshopper will still be able to access the tool as an online resource.

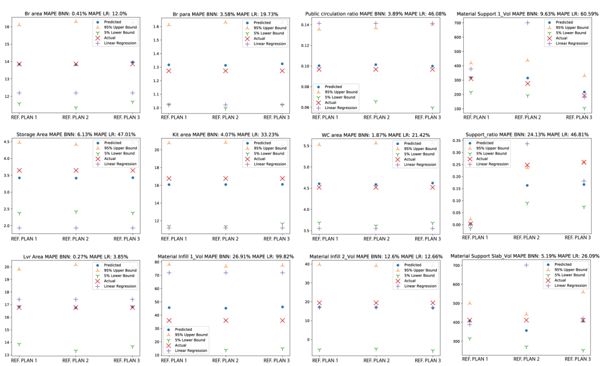

Figure 5. Error Comparison between BNN and Linear Regression for different projects .

5. Visualization in Tool

The tool provides a guided interface for users to input basic design parameters, as shown in figure 3, within Grasshopper or as an online resource. In return, the user will receive a ‘shoebox’ model generated from the input parameters, and a radar chart showing the different GWPs of different construction systems applied to the ‘shoebox’ model. The break-down of the different materials and their volume used in different construction systems are shown in a bar chart diagram in figure 6. In the background of the visualization tool, the basic design parameters will be passed to the BNNs and two types of outputs are produced: building topology related and construction system related output.

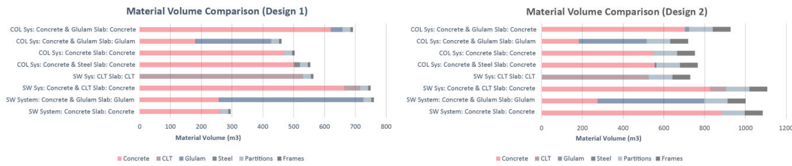

Figure 6. Bar chart shows a breakdown of the material combinations adopted in each identified construction system for both design variants. .

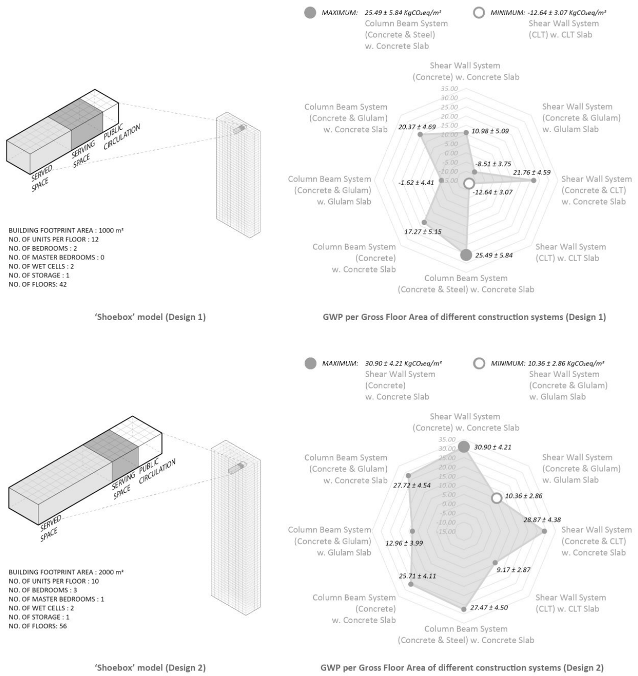

Figure 7. A'shoebox' model is generated from two different input parameters, and a radar chart showing the different GWPs of different construction systems.

The 'shoebox' model, a three-dimensional representation of a building's primary spatial units, arises from the building topology related outputs of the BNN models. These outputs consist of the area of wet cells, bedrooms, master bedrooms, storage, living room, kitchen, and public circulation ratio. Multiplied by the number of each type of unit, these areas are tabulated into three essential spatial entities: served, and serving spaces within the unit, and unitized public circulation area, according to the definition by Louis Kahn (Sutanudjaja and Khan 2013). Wet cells, storage and kitchen are considered serving spaces while bedrooms, master bedrooms, and living rooms are considered served spaces. The 'shoebox' showcases the implicit relation of the three essential spaces in affecting the material volume required for different construction systems, via the change in basic design parameters. Figure 7 shows the 'shoebox' visualization of two design variants with different inputs. Specifically for served space, an increase in the number of rooms in a unit would result in an increase in the number of enclosures, hence increasing in GWP value as illustrated in design 2.

The radar chart (figure 7) and the bar chart (figure 6) diagram are results of the construction system related output of the BNNs. The construction system consists of two types, shear wall or column beam system respectively, both with different material combinations, for a total of 8 different combinations. For the basic inputs given in figure 3, the eight different construction system combinations are tried to obtain eight different combinations of material volumes together with their uncertainty values. GWP values per gross floor area of the building are calculated according to the corresponding material volumes. Figure 7 shows two design variants with different building footprint and apartment units. The left image illustrates the three ratios of the spaces generated from the building topology related output. The right image demonstrates the different GWP values of different systems, denoting the maximum and minimum values.

6. Conclusion and Future Work

A predictive tool was developed to evaluate embodied carbon for early design iterations for residential buildings based on generic quantitative design parameters. Planners and designers can access the tool in Grasshopper or as an online resource, enter the relevant building information and obtain preliminary evaluations on different construction systems and material combinations in a simple visualization tool, represented in a 'shoebox'. Since the predictive model is based on a Bayesian Neural Network, uncertainties could be measured, giving the users an extra dimension to ponder upon while making decisions with the tool. Also, more complex, non-linear interactions between input values and output values could be captured, as shown when the Bayesian Neural Network outperforms the Linear Regression method in our validation process.

A limitation of the current stage is that it is only drawing information from a small dataset, with 17 distinct residential building projects and limited material choices and construction systems. In order to further support the development of the tool, an open source database on building projects should be developed and training of the predictive model made into a web application. Users will be able to upload IFC files of recent building projects, that could be parsed and archived into the database. This will allow the tool to keep up-to-date with construction technology, and to scale beyond predicting GWP for residential building types with limited materials, to predicting additional LCA factors for a multitude of building types, with more detailed construction materials. Various stakeholders, from planners to experts to developers and policymakers could then select projects for the predictive module to reference, and download a customized predictive tool for their use case.

Nevertheless, this study underlines the potential role of data science in simplifying the LCA process.

Acknowledgements: The presented work is part of the research project 'Next Residential High-rise' funded by the SUTD-MIT International Design Centre (Project No. IDG21800103). Aspects relating to the component volume and GWP calculations were supported by Arup through a collaboration based on the Arup Global Research Challenge 2019. We would like to thank Zackary Xuereb Conti, Ray Cheng, Jun Wen Loo (all researchers at SUTD), Colin Yip, Xavier Zhou, Shiu Chern Ong (all Arup Singapore Pte Ltd) for their support.

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AUGMENTED REALITY-BASED COLLABORATION

ARgan, a bamboo art installation case study

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Abstract. ARgan is a geometrically complex bamboo sculpture that relied on Mixed Reality (MR) for its joint creation by multiple sculptors and used latest Augmented Reality (AR) technology to guide manual fabrication actions. It was built at the Chinese University of Hong Kong in the fall of 2019 by thirty participants of a design-and-build workshop on the integration of AR in construction. As part of its construction workflow, holographic setups were created on multiple devices, including a series of Microsoft HoloLenses and several handheld Smartphones, all linked simultaneously to a single digital base model to interactively guide the manufacturing process. This paper critically evaluates the experience of extending recent AR and MR tool developments towards applications that centre on creative collaborative production. Using ARgan as a demonstrator project, its developed workflow is assessed on its ability to transform a geometrically complex digitally drafted design to its final physically built form, highlighting the necessary strategic integration of variability as an opportunity to relax notions on design precision and exact control. The paper concludes with a plea for digital technology's ability to stimulate dialogue and collaboration in creative production and augment craftsmanship, thus providing greater agency and more diverse design output.

Keywords. Augmented-Reality; Mixed-Reality; Post-digital; High-tech vs low-tech; Bamboo.

1. Introduction

Augmented Reality (AR) and Mixed Reality (MR) technology are rapidly advancing. Software packages, like Vuforia for Unity, AR-Kit for Apple and AR-Core for Android, as well as the Fologram plugin for Rhino, make it increasingly easy to build applications or stream digital content to constantly advancing hardware, like Smartphones with depth sensors and Smart Glasses, like the Microsoft HoloLens, which allow for a more submersive AR experience. In addition to the gaming and advertising industry, architects and engineers are increasingly finding use in applying this technology within their field (Chi et Al., 2013). There, AR has been proposed to facilitate information extraction from building information models to improve the efficiency and effectiveness of

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 313-322.

workers' tasks (Chu et Al., 2018). Usage examples can be found on construction sites in the form of Smart Helmets and Tablets, primarily for helping engineers to make more accurate and rapid judgments for construction review tasks (Ren et Al., 2017). User experiences for AR systems in industrial settings are also well accepted and have demonstrated their potential to reduce errors in assembly and improve the quality of the maintenance work (Aromaa et al. 2018). Use of AR as a holographic aid in fabrication and construction is also increasingly visible, for example in projects like the Steampunk, designed and built in Tallinn by SoomeenHahm Design, Igor Pantic and Fologram.

This indicates that AR and MR technology are on their way to play an increasingly important role in today's 'post-digital' architectural context, which' aim is to *"[...] addresses the humanisation of digital technologies through interplay between digital and analogue cultural and material systems, between virtual and physical reality, between high-tech and high-touch experiences, between the local and the global"* and which is typified by using alternative notational systems in implementation methods that allow for increased participation, interaction, and collaboration (Crolla, 2018). We foresee AR/MR to become far more effective in this 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. Instead of reducing the onsite need for human labour skill by shifting construction complexity to automated pre-manufacturing and reducing construction to the basic assembly of advanced kits-of-parts, AR/MR enhances human onsite agency and increases labour forces' capacity to participate in complex building processes.

This paper argues for this position using the developed workflows and experiences from building the demonstrator project ARgan. ARgan is a geometrically complex bamboo sculpture, built at the Chinese University of Hong Kong in the fall of 2019. It is a case study on how recent AR/MR tool developments can be extended towards applications centring on creative collaborative production, as it relied on Mixed Reality (MR) for its simultaneous joint creation by a large group of sculptors (see Fig. 1). Virtual digital information was holographically overlaid onto the field of vision of the sculptors to guide their manual actions during crucial steps of the production process using multiple Microsoft HoloLenses and several handheld Smartphones. The types of overlaid information ranged from direct instructions on connections of the primary structural bamboo framework to visualisations of dynamic flow patterns used for surface densification.

The paper concludes with a plea for digital technology's ability to stimulate dialogue and collaboration in creative production and augment craftsmanship, thus providing greater agency and more diverse design output.

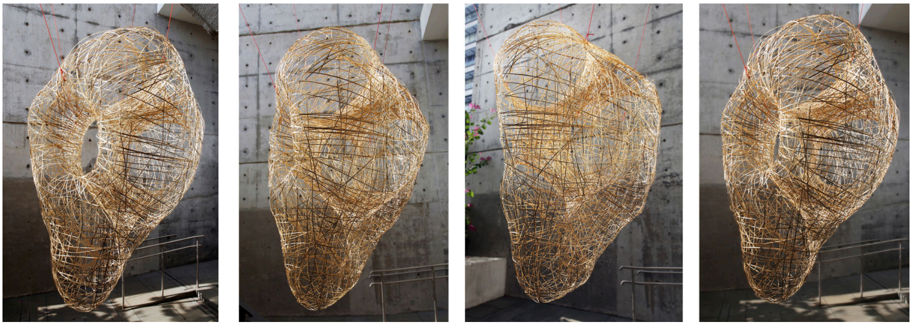

Figure 1. ARgan, Bamboo sculpture (Chinese University of Hong Kong, 2019).

2. BACKGROUND

Mixed Reality (MR), as defined by P. Milgram and H. Colquhoun, creates environments wherein real and virtual objects are displayed together (Milgram & Colquhoun, 1999). As stated by X. Wang, *"Augmented Reality (AR) can create an augmented workspace by inserting the virtual space in which users store and interact with digital contents into the physical space where people work"* (Wang, 2009). *"By exploiting people's visual and spatial skills, AR brings virtual information into the user's real-world view rather than pushing the user into a completely computer-generated virtual world,"* commonly referred to as Virtual Reality (VR) (Wang, 2006). VR and AR can be positioned at opposite ends of the spectrum, with VR placing the user in a completely computer-generated virtual world and AR being a system that blends computer-generated 3D models together with the physical context, preserving the user's awareness and ability to interact with the real world (Jahn et al., 2018).

While the potential of AR is currently widely discussed in the research community, its technological integration and implementation into architectural design seems slow. This is at least partially because of a lack of powerful, easily accessible and flexible tools. This bottleneck was recently opened-up with hardware products like e.g. Microsoft´s 2015 HoloLens, an AR headset whose original applications were envisioned to be largely within the gaming and entertainment industry. The second-generation HoloLens, promised to be available to the public in early 2020, is instead presented as a tool applicable in engineering, construction, and design. Similar to smartphones launched in 2007, innovative open-ended hardware was produced first, requiring several years of application development for the technology to maximise its true potential. This study set out to explore the potential and latent opportunities for AR/MR integration in the construction of non-standard architecture with a focus on building contexts with limited means and resources for computer-numerically-controlled (CNC) or robotic fabrication.

3. DESIGN AND FABRICATION

ARgan is a freeform, amorphous, doubly curved shell surface, made from bent, interconnected bamboo splits that were either mechanically fixed with metal wire or woven into one another. Its design started with the digital modelling of a base shape, which was a freely formed, continuous SubD surface, modelled in McNeel's Rhinoceros® (v.7 WIP) software (see Fig. 2). To test the ability of AR/MR setups to assist in the construction of non-standard form, the base shape was designed to be highly irregular. Internal voids were embedded in the shape to increase surface double curvature for buckling resistance.

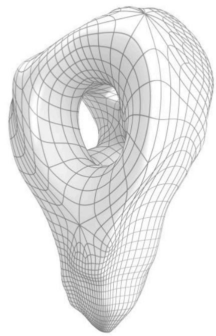

Figure 2. SubD model of base shape.

Using Anemone, a recursive looping add-on for Rhino's procedural modelling plug-in Grasshopper, an agent-based particle flow system was setup that generated flow patterns across the base shape (see Fig. 3). These flow patterns were to be used as visual guides for the densification and stiffening of the base shape with woven bamboo splits (see below). Short lines, freely placed near the base shape, were used as input parameters to direct flow patterns. These short lines, each with specific orientation and weighting value, were detected by randomly placed particles that travelled across the base shape, adapting their direction in response. The lines could easily be tweaked at will in reaction to observed emerging flow patterns. Two sets of particles would flow in perpendicular directions (see red and blue lines in Fig. 3), becoming the guides for two perpendicular directions of bamboo splits, which would give the doubly curved base surface bi-directional strength and increased buckling resistance.

The construction strategy consisted of splitting the base shape up into four main components for simultaneous fabrication by four teams (see Fig. 4). A base grid from split bamboos defined their doubly curved shape. The annotation and fabrication system for this base grid involved digital unrolling of all members, including their intersection points, which could then be straightforwardly pre-drilled and re-joined (see Fig. 4, step 1 and 2). This base grid was then to be densified with additional bamboo splits according to the generated flow patterns (step 3). The base components would then be connected (step 4 and 5) before being subjected to a final round of densification (step 6). Each of these steps was relied on AR/MR to ease production. The sculpture's design was not scale-specific. A holographic setup was used to test overall component dimensions ahead of time in response to the available workspace (see Fig. 5).

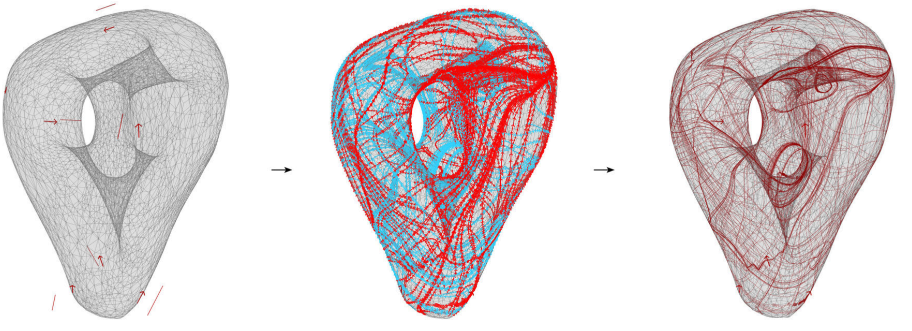

Figure 3. Agented-based system defines flow patterns in response to simple input parameters.

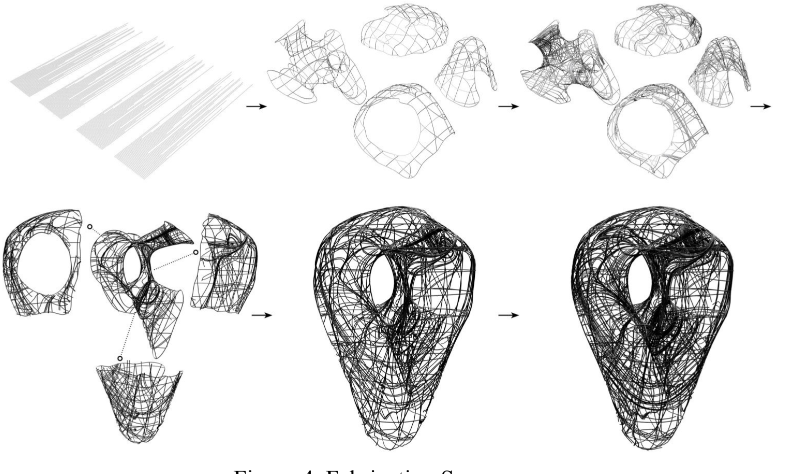

Figure 4. Fabrication Sequence.

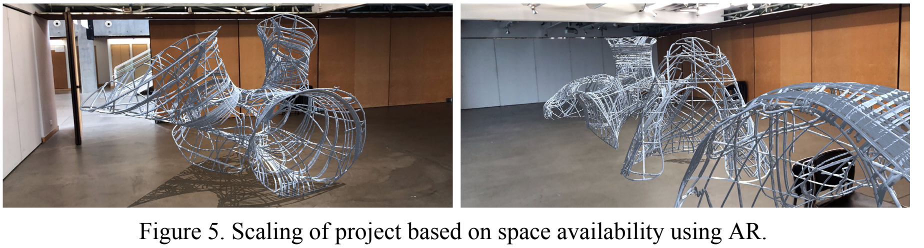

Figure 5. Scaling of project based on space availability using AR.

4. FABRICATION

The first fabrication step involved manual marking and pre-drilling of unrolled bamboo splits. An AR setup was created that removed need for printed drawings or other notational systems (see Fig. 6): Using both handheld Smartphones and HoloLenses, each team could map individual member number labelling and intersection point data from the digital file directly onto the materials.

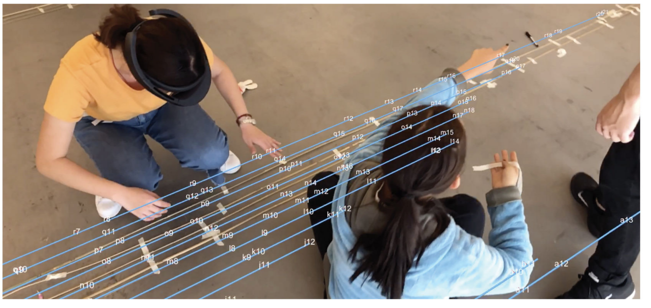

Figure 6. Pre-drilling of unrolled bamboo splits following AR information.

The pre-drilled split assembly used an AR/MR setup that visualised in three-dimensional space where members were to be placed and interconnected (see Fig. 7). Splits were suspended from the ceiling and interconnected one at a time until a stable base shape was achieved. The digital information overlay used colourfully contrasting markers and annotations to guide where the next assembly action was needed. These guides could only be followed loosely, as variations in material behaviour or inaccuracies from craftsmanship made precise physical replication of the digital model impossible. This was anticipated, and a loose following of the predefined system logic was sufficient for the project to proceed.

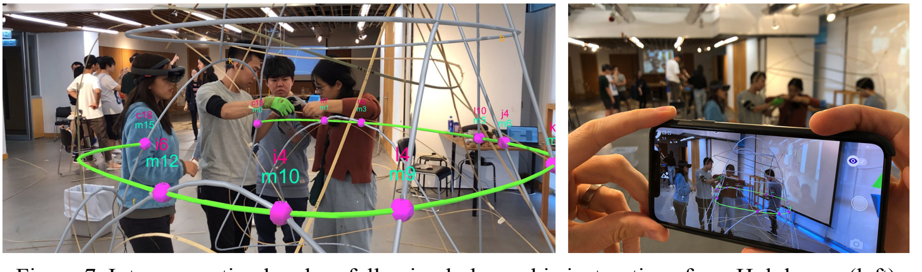

Figure 7. Interconnecting bamboo following holographic instructions from Hololenses (left) and Smartphones (right).

The AR/MR interface was designed with virtual holographic control buttons, overlaid onto the user's field of view, that allowed cycling through the installation sequence (see Fig. 8). Using simple pre-programmed hand gestures, the sculptors could move back and forth through the member series to install, amend and finalise the construction of the components.

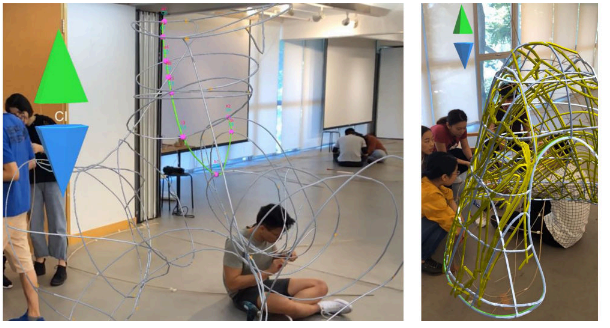

Figure 8. Holographic buttons allow user interaction through hand gestures.

Once the components' base grids were completed, the holographic setup would move on to visualise the flow patterns generated by the particle flow system (see Fig. 9). This information was then used as a rough directional guide for densification of the base grid with bamboo splits that were woven through the structure following the two perpendicular directions defined by the patterns. No exact instructions were given: personal judgement was used to decide when levels of densification resulted in sufficient surface strength and stiffness.

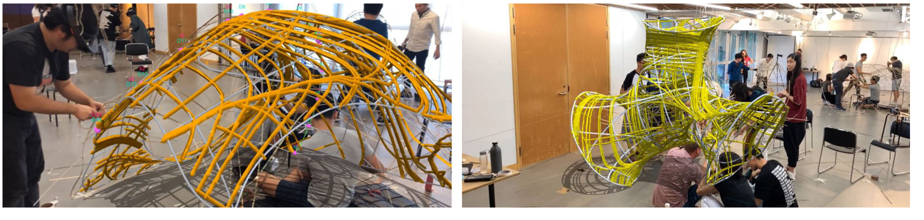

Figure 9. Densification of components guided by holographically overlaid flow patterns.

With all base shape components completed, the next step involved their interconnection into the final sculpture (see Fig. 10). A holographic setup was again used to guide this action. This process was straightforward, since all open edges were of a sufficiently accurate length to match up, and their inherent floppiness allowed for easy deforming during fixing. Once interconnected, the surface continuity gave the whole a greater stiffness. Like with the densification of the individual components, a virtual overlay of the flow pattern over the complete shape guided further densification, with added members spanning across the component seams, further increasing surface smoothness and continuity (see Fig. 11 and 12). In total, five Microsoft HoloLenses were simultaneously used, together with over a dozen handheld Smartphone devices, all reading from the same digital model.

Figure 10. Assembly of components into final structure.

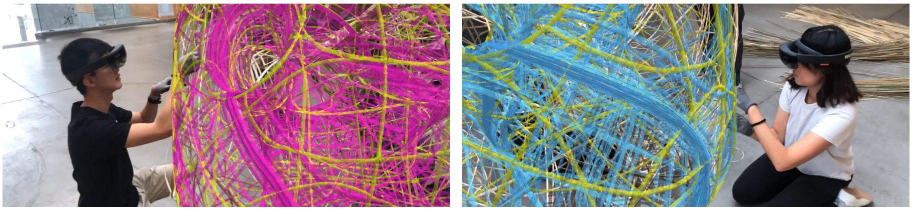

Figure 11. Densification of final assembly following holographically overlaid flow patterns.

5. DISCUSSION

The design and construction of ARgan successfully demonstrates recent developments in AR/MR technology's effectiveness at lowering construction complexities for certain freeform structures. Without needing elaborate traditional annotation methods or drawings to translate design fabrication information from building information models to site, AR/MR hardware devices, like HoloLenses and Smartphones, allow procedural control opportunities to be brought directly into the world of even low-tech construction.

The project illustrates this point so clearly only because its materialisation was conceived from the start to not rely on hyper-precision: Rather than attempting to create exact real-world carbon copies of digitally designed three-dimensional shapes, the strategy was to engage sculptors to respond where possible to holographic guidelines rather than precise instructions. This resulted in more realistic material accuracy expectations, allowing intuitive response to natural material behaviours in the bamboo splits or to follow personal instincts when defining certain characteristics of the project. This redefinition of precision requirements guaranteed the system's robustness and gave the authors agency to advance despite inevitably high allowances in material behaviour or craftsmanship. This approach diametrically apposes the precision aims frequently lauded in research on robotic or CNC fabrication. Yet, precisely this counter-narrative is what seems necessary today to further productively facilitate technology translation and integration beyond the academic lab into the world of praxis.

Figure 12. Completed final structure.

The workshop organised to build the ARgan revealed several important aspects related to the current state and possible future directions of AR/MR technology integration into architecture. First and foremost, it highlighted that the threshold for designers to engage with this technology has dropped to a point where anyone with a basic introduction to procedural design can easily incorporate it in their workflow. Today's available hard- and software have removed most critical hurdles and allow for immediate technology translation into existing project applications, increasing agency in contexts previously secluded from technology integration. This, in return, points out that current main research challenges lie in the conceptual rethinking of workflow integration of specific materials and forms of craftsmanship. Each material and trade come with their own idiosyncrasies requiring specific types and modes of production data extraction from design information models. This will be further facilitated by additional upcoming features in both software and hardware, like the increased numbers of hand gestures made possible in the second HoloLens generation, promising potential for great future impact.

6. CONCLUSION

Advances in AR/MR hardware and software technology promise to play an increasingly important role in today's 'post-digital' architectural context, which aims to increase the impact from digital technology through its integration into praxis. As the technologies enable augmentation of onsite skill through the direct visual overlay of specific holographic instructions onto manual actions, advantages of computational design and design production control can now be introduced in contexts that were, up until recently, largely excluded from such advancements. This will enlarge local design production opportunity spaces and will give greater flexibility and agency to local communities, especially construction industries that largely rely on manual labour. However, as ARgan demonstrates, common notions on building accuracy, tolerance and allowance may need recalibrating, as the hyper precision made possible through traditional

CNC or robotic fabrication setups at this point does not seem commensurate to what is possible with augmented manual production. Further AR-driven design and construction related research, tailored to specific materials and craftsmanship, is needed to identify how these technologies can positively affect local construction solution spaces. With the arrival of easily accessible AR/MR technology, opportunities present themselves for increased productive dialogue and collaboration between designers and craftsmen, providing greater local agency and prospects for more diverse design output.

ACKNOWLEDGEMENTS

This workshop was supported by a grant from the Construction Innovation and Technology Fund (CITF), titled: "Augmented Reality in Construction" (ID 3200), and was organised in collaboration with Fologram. The workshop and construction team included Kristof Crolla, Garvin Goepel, Nick van den Berg, Cameron Newnham, Canossa Chan, Izk K Chan, Kam Wo Chan, Peter Chan, Tsz Sun Ovan Chan, Wang Fung Chan, Hoi Yan Cheung, Dominic Co, Shasha Du, Chun Hin Jacky Fong, Mengdi Guo, Kunning Hao, Chung Hei Ho, Kevin Ka Ho Ho, Maximilian Wolfgang Hoeppler, Jason Hu, Shing Fung Adwin Keung, Ho Yu Lam, Yip Fay Lau, Ho Wai Ian Leung, Siying Li, Shuk Man Lo, Wing Sze Ngan, Long Wun Adabelle Poon, Ling Sum Evangeline So, Wenyan Xue, Linlan Zeng.

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AUTOMATED GRADING OF PARAMETRIC MODELLING ASSIGNMENTS

A Spatial Computational Thinking Course

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Abstract. This paper describes the implementation and deployment of an automated grader used to facilitate the teaching of a spatial computational thinking course on the online education platform, edX. Over the period of a course on the platform, more than 3000 assignments were graded. As an evaluation of the grader, examples of assignments and statistical results are presented and discussed.

Keywords. Automated Assessment; Parametric Modelling; MOOC.

1. Introduction

The rise of the web provides people new ways to interact and learn. In recent years, Massive Open Online Courses (MOOCs) have allowed students to receive a quality education through the web. Some institutes have since taken up a "flipped classroom" approach in their pedagogy, where curricular content was taught outside the formal system and in affiliated online systems. Industry professionals alike make use of such platforms to keep themselves updated with the relevant skills. In the spatial discipline, Spatial Computational Thinking is increasingly being recognised as a fundamental skill. This paper describes the application of an automated online grader used to facilitate the teaching of Spatial Computation principles on a MOOC.

The use of a web-based grader is common in online learning platforms for learning programming. Numerous studies have highlighted the advantages of automated formative assessment (Lewis & Davies 2004, Douce et al. 2005, Nicol & Macfarlane-Dick 2007, Baranaa & Marchisioa 2016). Automated formative assessment provides a system where students can conveniently test their understanding of taught concepts, which is synchronous with the pedagogical objectives of a MOOC.

Approaches for assessing programming assignments may be summarised into two categories: dynamic analysis and static analysis (Ala-Mutka 2005). A submitted file is executed in a dynamically assessed assignment and not executed in a statically assessed assignment. The former checks for functionality and

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 323-332.

efficiency of the code while the latter checks for programming styles and design. Numerous systems for automating assessment have been developed for learning textual programming languages. One of the earliest systems was the AGSICP for Cobol Programming (Aaronson 1973). More recently, two popular systems are Web-Cat and Stepic.

For parametric modelling, no automated assessment approaches have been developed. In general, the approach could be similar to existing approaches using automated assessment for learning textual programming languages. However, for parametric modelling, the output of the program may be a complex 3D model. A more advanced approach is therefore needed for assessing the validity of such models.

The paper describes the development of an automated grader for parametric modelling assignments. The contents of this paper are organised as follows. Section 2 sets the premise the grader was designed for. Section 3 describes our implementation of a grader for parametric modelling assignments. Section 4 provides an example of how the grader is used in a MOOC. Finally, Section 5 concludes the paper.

2. Context

The Automated Grader was used in a second-year module, "Spatial Computational Thinking" at the National University of Singapore. The module consisted of 150 students, most of whom did not have prior scripting or programming knowledge. The module focused on the development of algorithms for generating complex, parametric 3D models. It was taught on the edX MOOC platform using videos and online exercises. The modelling assessments were all performed in the web-based parametric modelling tool developed by the authors (reference removed). The Automated Grader was developed on the Amazon Web Services (AWS) infrastructure, allowing large numbers of assignments to be graded in parallel.

For each assignment, the instructors created a detailed problem description on the edX platform, and a model representing the correct answer was uploaded to the Amazon Simple Storage System (S3) object storage. Students then performed the modelling assignment and uploaded their models through the edX platform. In the edX platform, the student models were added to a grading queue, from which the AWS server would fetch the models and grade them using an AWS Lambda function, returning the grade and any feedback to the edX server. Within a maximum of 20 to 30 seconds, students would see the grade and feedback displayed on their browser.

The modelling assignments increased in complexity as the semester progressed. At the start of the semester, the assignments started quite simple. As the students learnt new concepts and techniques, the assignments also grew in complexity.

The automated grading process meant that these assignments could not be open-ended. Each student was expected to submit a model that, given certain inputs (such as parameter values), produced 'correct' outputs. The way that the models were implemented could still differ from one student to the next. However, the outputs were required to be the same for all students. This, of course, meant that individual creative freedom was quite limited. In order to overcome this limitation, the final assignment of the semester was open-ended and was manually graded. Nevertheless, it is noted that automated grading freed up a significant amount of time that allowed instructors to spend more time helping students with their final assignments.

3. 3D Model Grader

The grader was designed to be an extension of a web-based parametric modelling tool developed by the authors. A similar approach could be developed for other existing parametric tools. However, for commercial software issues with commercial licenses would have to be resolved if parallel execution of the grader would be required.

Each parametric model has a set of input parameters. Setting the values for these parameters and executing the model will result in a 3D geometric output, which we refer to as the *output model*. Each assignment was accompanied by an answer model and a number of input parameter sets. The grading process then consisted of the following steps:

- The parameters in the parametric answer model were compared to the parametric submitted model. If the submitted model had missing parameters, the grader would exit and assign a zero grade.

For each set of input parameters:

- The parametric answer model and parametric submitted model were both executed, thereby producing two output models: the submitted output model and the answer output model. These two output models were compared to one another, and a grade was calculated.

3.1. MODEL NORMALIZATION

One complication that had to be addressed was the normalization of the output models. The ordering of the geometric objects and entities in an output model should not impact the correctness of the model. For example, the answer output model may contain two polygons. If the submitted output model contains the same two polygons, it should be marked as correct, irrespective of the polygon ordering. The same applies to the ordering of other geometric entities, including vertices. Thus, in order to be able to compare models, they first needed to be normalized, so that the model representation could be guaranteed to be deterministic.

The normalization process consisted of two stages. First, the vertex order within individual objects was normalized. Second, the order of the objects in the model was normalized.

For the normalization of vertex ordering, a few different rules were applied. For open polylines, they were modified in order to guarantee that the coordinate values for the start vertex were always less than the end vertex. For polygons and closed polylines, they were modified in order to guarantee that the first vertex was always the vertex with the lowest coordinate values. For polygons with holes, additional rules developed.

For the normalisation of object ordering, a *fingerprint* was generated for each object in the model. The fingerprints were generated from the data constituting that object, including the coordinates of the vertices. (For the fingerprinting process, all numerical values were rounded to 8 significant digits. This accounted for rounding errors that could result from different computing hardware and operating systems.) For entities that were not exact clones, each fingerprint was guaranteed to differ. The normalisation process then sorted all entities according to their fingerprints.

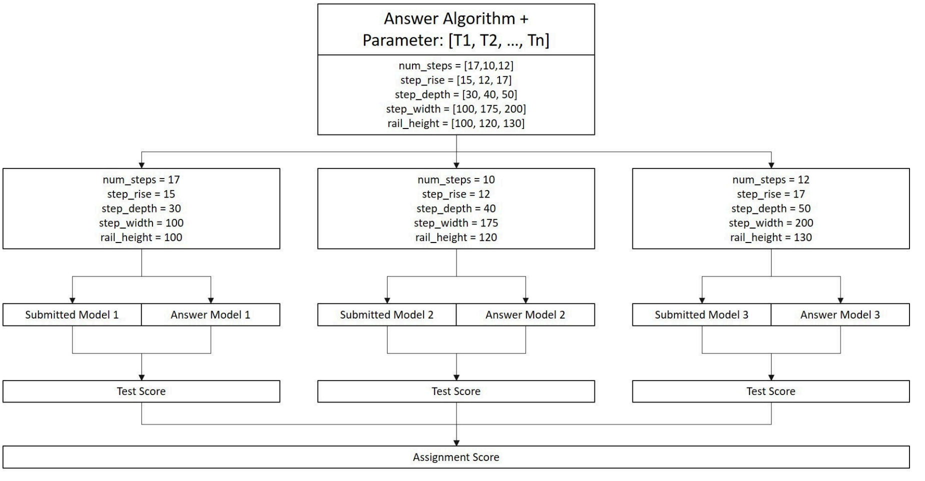

Figure 1. Schematic flow of information in an assessment with five parameters and three tests.

3.2. MODEL SCORING

In each test, the object (points, polyline, and polygons) in the answer output model were matched against the objects in the submitted output model. If a match was found, then the score was incremented by 1. The matching process required an exact match between objects, using the same fingerprinting process as was used for model normalization. To encourage efficient solutions, extra objects found in the submitted output model result in 1 mark being deducted (equation 1).

$$E_{type} = (n_{congruent} - a) \tag{1}$$

where:	E_{type}	=	Score for Entity Type (point, polygon, or polyline)
	$n_{congruent}$	=	Number of entities (of type) generated in the submitted model which are congruent to the ones generated in the answer model
	a	=	1 or 0; 1 mark is deducted if extra entities were created for an entity type

Figure 2. equation 1.

$$S_{test} = (\sum E_{type} + A_{equal})/(N_{entities} + N_{attributes}) \tag{2}$$

where:	S_{test}	=	Score for a test
	E_{type}	=	Score determined by equation (1)
	A_{equal}	=	Number of attributes in the submitted model which are equal to the ones in the answer model
	$N_{entities}$	=	Number of entities in the answer model
	$N_{attributes}$	=	Number of attributes in the answer model

Figure 3. equation 2.

$$S_{final} = \bar{S}_{test} \tag{3}$$

Figure 4. equation 3.

The score awarded to each test is the fractional result from the sum of all the number of congruent points, polylines, polygons, and model attributes in the submitted model against the total number of entities and attributes in the answer model (equation 2). The final grade given to an assessment is determined by the average of the test scores (equation 3). For example, consider an answer generated model has 10 polygons. If only 8 of those polygons can be matched against entities in the submission generated model, then the grade would be 8/10, or 0.8. An example breakdown of the grading is detailed in Section 4.1.

3.3. GRADER FEEDBACK

Feedback messages highlight to the students how marks were lost and allow them to rectify and receive a better grade in their subsequent tries. Such information returned from an automated assessment is essential in the facilitation of a self-paced course. The key feedback messages are listed as follows:

- Entities could not be found
- Extra Entities
- Model Attribute not found

- Incorrect model attribute value
- Missing start node parameters

In the web parametric modeller the authors have created, entities may be assigned with attributes. Attributes define the types of data that may be attached to entities in the entire model. They exist in key-value pairs in which the user can specify data to be stored under a name key. Materials are assigned to entities through the use of attributes. The materials of a submitted model may also be checked.

A submitted model with missing entities translates to a parametric model with wrong procedures. A submitted model with extra entities would be another with redundant procedures. In addition, the grader was able to pick up translational and directional errors in the geometries which would be highlighted to the student in the returned feedback.

4. Spatial Computational Thinking

The learning outcome of the course was to gain theoretical knowledge and practical skills in applying spatial computational thinking as a way of generating 3D models, building upon elementary critical and logical thinking aptitude. The key concepts tested and the weekly assignments are listed as follows:

- W1 - Variables and Operators: Hello World (Console-Based).
- W2 - Lists, Control Flow, and Functions: Printed Hash Checkerboard (Console-Based)
- W3 - Entities and Attributes: Debugging Generated Geometry (Static Geometry)
- W4 - (break)
- W5 - Rendering and Geometric Constraints: Windows (Parametric Geometry)
- W6 - Search Spaces, Vectors, and Planes: Parametric Stairs (Parametric Geometry)
- W7 - Loop Updates and Transformations: Parametric Stair Runs (Parametric Geometry)
- W8 - Vector Arithmetic and Graphing Polylines: Solar-Responsive Roof (Parametric Geometry)

To familiarise the students with procedural thinking, the earlier assignments were simple 1-part tasks. In the later weeks when more complex concepts were introduced, each assignment was broken up into smaller steps to guide the students into creating the final model while building up their capacity to deconstruct a spatial problem.

The assignment for Week 1 was a simple 1-part task that required the students to submit a file with a single parameter. The console should print "Hello __parameter_value__" when executed. In Week 2, the students were given another 1-part task which required them to submit a file with a single parameter that defined the size of a printed checkerboard. The students were first introduced to geometry in Week 3. For their assignment, they were given a file that generated an extruded model and they were tasked with changing the arguments and values in the procedures to achieve another extruded result.

The assignment for Week 5 was a 3-part task that broke the creation of a window into the creation of a polygon, the creation of a grid of panes, and finally the extrusion of the frame. In Week 6, the students created a flight of stairs. They were first tasked with creating a staggered polyline that was then translated to the profile of the stairs. Next, they were required to create the volume of the stairs. Finally, the railings are created. This 4-part task will be discussed in detail in Section 4.1. The students were tasked with another stairs assignment in Week 7. In this 4-part assignment, the students first had to create a run of steps on a plane. Next, the last step was modified into a landing. Then, they were required to create runs of steps one after another. The model was required to be able to change direction based on a parameter. Finally, the number of steps in each run was made variable by a parameter. The final assignment in Week 8 looked at the creation of a parametric solar roof that reacted to the direction of the incoming sun rays. The assignment was broken down into three parts. The first required the students to create a series of arches. Next, the students created a barrel vault. Finally, glass panels with varied sizes were installed on the vault. Panels with direct exposure to the incoming rays were smaller in size.

4.1. PARAMETRIC STAIR WITH RAILING

The parametric stair model served as an introductory modelling task to more advanced concepts like transformations with vectors and planes. As an example of a typical submission to the automated grader, the task featured in the course has been chosen to be described in detail.

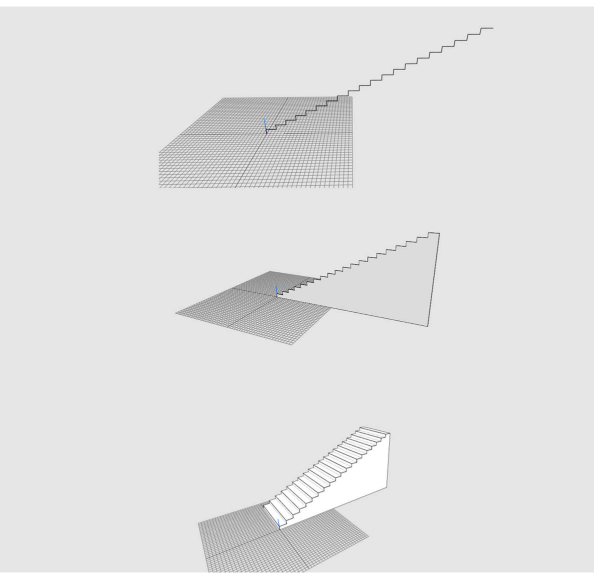

Figure 5. The 4 parts of the assignment (Tasks 1 to 3). Example of an erroneous submission in Task 4.

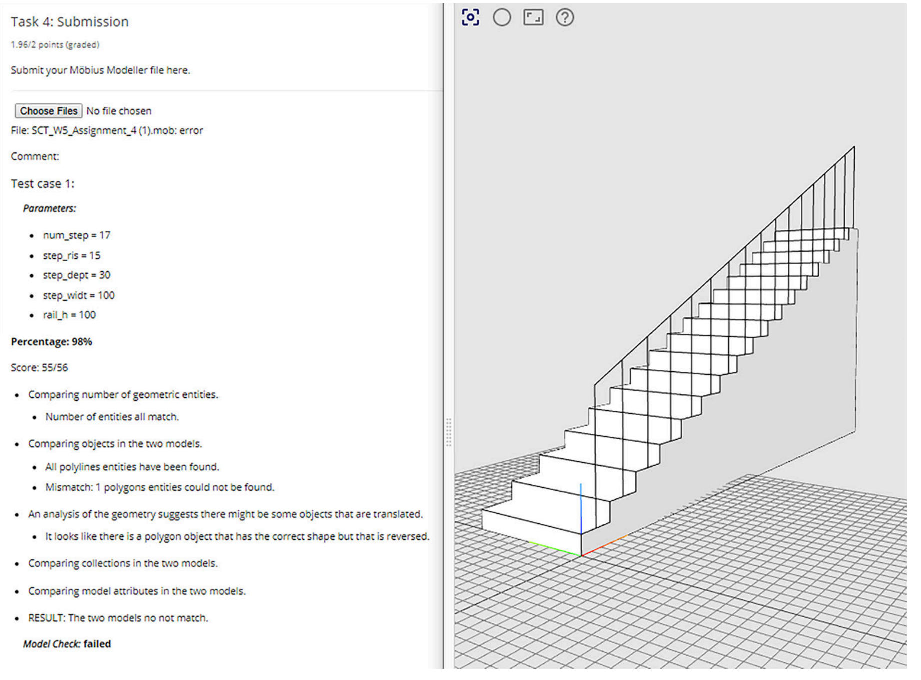

Figure 6. The 4 parts of the assignment (Task 4). An example of an erroneous submission.

This assignment was divided into four parts (Figure 5 and 6). First, the students were tasked to create a staggered polyline which would translate to the profile of the stair. Step depth, height, and number were set as parameters. Next, the cross-section polygon was extruded in the direction of its normal based on another parameter. Finally, the polyline rails were added. The height of the rails was also defined by another parameter.

Following the submission through edX, the model was run through three tests and each generated model was positionally compared to the one generated by the answer algorithm (Figure 1). The fractional score calculated from the average of the three tests was returned to edX, where the final grade was converted into the edX weighted grade.

Figure 6 also shows the most commonly detected error for the task. A polygon with a reversed list of positions was determined to have its normal pointed in the opposite direction and was treated as a different polygon. As seen in the figure, the face opposite to its normal is rendered with a darker shade in the viewer. With 1 polygon missing in a model with 56 entities, a score of 55/56, or 0.98, was given for the first test. Similarly, the submission generated model was scored 34/35, and 40/41 in its next two tests respectively. The task was awarded a final score of 0.98.

4.2. RESULTS

Amazon CloudWatch was set up to log all submission processes. Over the period of the course, over 3000 submissions were registered. The authors used the collected information to make incremental improvements to the grader feedback. Negative scoring of extra entities was introduced in Week 6, along with detailed suggestions for missing entities. A gradual decrease in the number of submissions with extra entities over the subsequent weeks can be seen in the data (Figure 6). This suggests an improved quality in the submissions.

	w5	w6	w7	w8	total
entities could not be found	144	192	224	209	769
reversed	-	66	20	15	-
translated	-	3	93	97	-
extra entities	0	199	148	88	435
model attribute not found	28	7	0	18	53
wrong model attribute value	25	3	0	7	35
missing start node parameters	18	24	40	29	111
Total Erroneous Submissions	215	425	412	351	1403
Total Submissions	528	857	846	920	3151

Figure 7. Frequency of Errors for Parametric Geometry Assignments.

In general, the automated grader achieved the desired results. It gave students immediate feedback on their parametric modelling assignments, allowing them to learn at their own pace. However, feedback from students also highlighted that they often did not understand why a model was being marked as incorrect. For example, for the common error of the reversed polygon mentioned above, the grader only reports that one of the polygons is incorrect. It does not explain why it is incorrect.

In order to tackle this issue, a set of additional checking algorithms were implemented to detect common errors. For example, if a student model was missing a polygon, the algorithm would check if the reversed polygon was present. If it was present, it could then feedback to the student that the polygon was reversed. Many other checks were performed, for example, polygons that were correct in shape and orientation, but that were placed in the wrong location (often due to some small offset). However, as models became larger, this checking process got increasingly complex and slow to execute. In the end, the decision was taken to reverted back to simpler checks that were faster to execute. Nevertheless, in order to achieve the pedagogical objectives, it is important that students are able to understand why their models are being graded as incorrect. Our investigations into this are ongoing.

5. Conclusions

Our ongoing research aims to investigate the extent to which the visual programming language can support computational thinking concepts required for constructing complex parametric models. This research paper focuses on an extension of our web-based parametric modeller for automated assessment of parametric modelling assignments, and a framework using modern cloud technologies which may be replicated on other web-based parametric modelling systems.

The grader is being further developed and improved. Three key areas are being worked on. First, the grader currently only gives textual feedback to the students. We are investigating approaches whereby the grader might be capable of giving visual feedback. Second, the grader currently requires all students to be given the same problem, which causes problems with plagiarism. We are investigating approaches whereby questions can be randomized so that each student will receive a variant of the question, which will require a slightly different answer. Third, the grader is currently only grading the geometric output model that is generated. We are investigating how the grader could support performative grading. For example, the assignment may be to create a space with certain daylight and solar radiation requirements. In such a case, students will be able to submit different models, and as long as the model meets the performative requirements, the model will be marked as correct.

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CODESIGNING WITH BLOCKCHAIN FOR SYNERGETIC LANDSCAPES

The CoCreation of Blockchain Circular Economy through Systemic Design

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Abstract. The paper is exploring methodology within the work in progress research by design through teaching project called 'Synergetic Landscapes'. It discusses codesign and cocreation processes that are crossing the academia, NGOs and applied practice within so called 'real life codesign laboratory' (Davidová, Pánek, & Pánková, 2018). This laboratory performs in real time and real life environment. The work investigates synergised bio-digital (living, non-living, physical, analogue, digital and virtual) prototypical interventions in urban environment that are linked to circular economy and life cycles systems running on blockchain. It represents a holistic systemic interactive and performing approach to design processes that involve living, habitational and edible, social and reproductive, circular and token economic systems. Those together are to cogenerate synergetic landscapes.

Keywords. Codesign; blockchain; systemic design; prototyping; bio-digital design.

1. Introduction

'The design of connections between places, communities, and nature is widespread, and accelerating (Thackara, 2015). These new undertakings may be diverse, but a green thread connects them: the understanding that caring for the health of a place and of the persons who inhabit it are parts of one story. With this care for place as their frame, communities are connecting the "what is" with the "what if?" across a range of activities, including regional food hubs, High Nature Value farming, fibershed and grain chains, biorefining, forest and watershed recovery, land-based learning, code clubs, and the maker movement.' (Thackara, 2019)

This paper reports on current work in progress (WIP) on the Synergetic Landscapes Masters in Architectural Design postgraduate unit B research by design studio of the Welsh school of Architecture that takes part in Cardiff

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 333-342.

University's Community Gateway project (Cardiff University, 2019). The focus here is on the context for the research on how blockchain offers a novel methodology for understanding and 'enacting' codesign through prototyping within cross-species coliving in urban environment (see Figure 1). Blockchain presents challenges to preconceptions of organisational and hierarchical structures. Since its inception blockchain has had negative associations with the crypto-currency Bitcoin being used on the dark web for anonymously buying drugs and other illicit trading. However, the idea behind blockchain, which we will unpack in section 2, is more altruistic. Blockchain is not inherently 'evil' as is often the presumption, rather it presents a novel way to rethink trust, power, oversight and control within systems. In our work we will deploy it in codesign settings to explore opportunities for new inter-species relations.

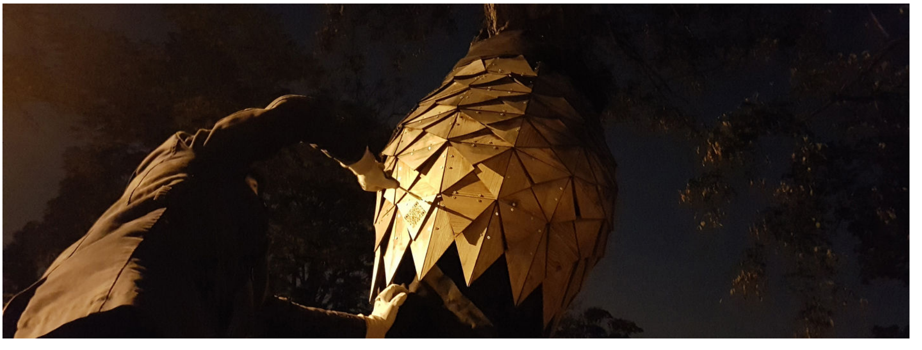

Figure 1. TreeHugger: The Ecosystemic Prototypical Urban Intervention with engraved QR code leading to site with its DIY recipe (Davidová, 2019; Davidová & Prokop, 2018; Davidová & Zímová, 2018).

The world today faces an Anthropocene Extinction, or 6th Mass Extinction (Dirzo et al., 2014). The reported declines are suspected to be caused mainly by human land use. I.e. locally, farming practices can affect arthropods directly by application of insecticides, mowing or soil disturbance, or indirectly via changes in plant communities through the application of herbicides or fertilizers. Forestry practices can also affect local arthropod communities via changes in tree species composition or forest structure. In addition, local arthropod populations can be affected by land use in the surrounding landscape; for example, through the drift and transport of pesticides and nitrogen by air or water, through the effects of habitat loss on meta-communities or by hampering dispersal (Seibold et al., 2019). Various environmental ecologists show that many species are adapting for life within the cities (Nemeth & Brumm, 2009). Therefore, the previously anthropocentrically-developed cities need to adapt for cross-species coliving conditions (Davidová & Raková, 2018) unless we are not to face full deadly biodiversity loss.

As humans have equal-neither privileged nor pejorative-roles within the overall ecosystem and biosphere (Boehnert, 2015), human world citizens must pursue their active equal role within the cocreation of biosphere (Davidová & Zímová, 2018). The World Economic Forum has recognised that blockchain, crypto-currency and the 'token economy' provide a means for 21st century communities and distributed organisation to reclaim power and enact their values in a way not possible through 20th century centralised banking, industrial and commerce models (World Economic Forum, 2018). This research extends existing research (systemic approach to architectural performance and rethinking the blockchain) and explores how these methodologies, technologies and concepts might empower communities, reconfigure ecosystems of people/plants/animals/things to create sustainable ecosystems of commerce and exchange. These ecosystems of exchange are based around things people and others value (water quality, sustainability) rather than the (monetary) value or things.

2. Project Description

In this section we briefly contextualise the current work by discussing previous iterations, the current project and its specific aims. It goes on to contextualise blockchain and its role in helping to explore new inter-species relationships.

2.1. HISTORY

The project is relating two separate existing researches: a) Systemic Approach to Architectural Performance (SAAP); b) rethinking relational conventions through blockchain. To both fields, codesign and cocreation processes are central driving tools.

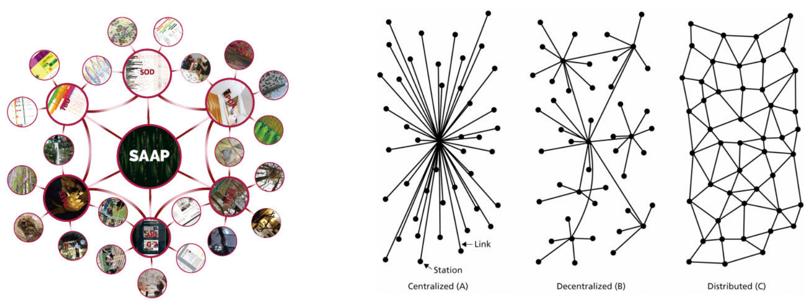

Figure 2. From left to right a) Synergised integrated process-based fields of SAAP (diagram: Davidová 2019) b) Centralized, decentralized and distributed networks. diagram (Baran, 1964).

SAAP is the fusion of process based fields formerly initiated by the integration of Systems Oriented Design and Performance Oriented Architecture (see Figure 2). SAAP involves Time Based EcoSystemic CoDesign and CoLiving, which is performed by both biotic and abiotic agents, including humans. It is 'Time Based Design' (Sevaldson, 2004, 2005), which merges and develops methodological processes and the result's performance evolving in time. While doing that, it generates theory through experimental practice. It is based in (eco) systemic interventions that therefore co- and re-design the initial system by its coperformance and coliving. These interventions are fusing the natural, edible, social and cultural environments of a variety of species, including humans, with abiotic agency (Davidová & Raková, 2018). For example, the TreeHugger wood responsive insect hotel (see Figure 1) interacts with larger ecosystemic network, being codesigned by the community, whilst being a product of material science research. It is offering diverse habitation as well as it is being feeder for bats and birds and advertising recipes for its iterations (Davidová, 2019; Davidová & Prokop, 2018). All those processes are codesigned in real time. In a novel approach we relate non-monetary system of values in blockchain to investigate cross-species and cross-matter circular economies that explore bottom up system that can mitigate variety of kinds of scarcity.

To understand the value of blockchain in this context is it best to return to its origins. It was a response to the 2008 financial crisis, caused by a combination of bank risk-taking and limited oversight. Under the pseudonym 'Satoshi Nakamoto' a group published a white paper proposing a new system for peer-to-peer transfer of funds that does not need a third party-a bank-to verify a ledger of transactions (Nakamoto, 2008). Bitcoin was the test currency and blockchain the technology on which it was built. Making the digital ledger of bitcoin transactions public enabled a level of oversight not previously possible. Simultaneously, it enabled computational checking that the ledger was not being tampered with. In removing the need for a banking or financial institute to 'check' it removes the power asymmetry between the bank its customers. It also removes structures and agents that enable and reward risk-taking; which becomes possible when a few individuals have insight, control and access to a substantial pool of resources aggregated from a large pool of individuals.

As our understanding of blockchain grows so too does our understanding of its implication. Artists Rethinking the blockchain provide a more speculative and theoretical perspective on DLT (Catlow, Garrett, Jones, & Skinner, 2017). A coffee machine is given a bitcoin 'wallet,' and instructions for buying coffee. It is also paying users of the machine who cleans it (Tallyn, Pschetz, Gianni, Speed, & Elsden, 2018). It is no longer just people that have the capability to trade, and the rationale for decisions on the purchase of coffee beans are encoded into the coffee machines programming. The power of decision making is also taken from the hands of individuals. Elsewhere Distributed Autonomous Organisations (DAOs) are emerging. These organisations are using these traits of blockchain to eliminate organisations hierarchy and power structures, increase transparency and reduce bureaucracy (Norta, 2015, 2016). This technology is being touted as fundamentally transformative, and as such it compels an exploration of existing structures and how they may be rethought. In this case it provokes the question of what are the opportunities for new forms of relationships between human and non-human?

Much of the history of civilisation is based on organising in centralised and decentralised systems (Figure 2). A library, government or place of work all organise people in one of these two ways. In 1964, with specific regards to communication, Baran hypothesised the problematic of these two systems and the opportunities that a distributed system might present (Baran, 1964). We now recognise this as the fundamental principle on which the internet is based, and how this system of communication can be powerfully transformative. Blockchain has presented us with the ability to ask what if other things, such as banking, could be structured differently to mitigate these problems. This project asks what if our relationship with other species could be reorganised to be more transparent, trusting and resilient.

2.2. PROJECT AMBITIONS

The WIP project discusses prototyping within the collaborative Synergetic Landscapes unit. This unit is to investigate the synergy of 'non-anthropocentric architecture' (Hensel, 2013), codesign across human and non-human communities and its linkage to emerging technologies. It is testing on how the emerging technologies (blockchain, reading and prototyping devices) and innovative approaches to life and business (circular economy, platform and token economies) help us rethink established forms of exchange and value with regards to sustainability and cultural landscape ecosystems. By doing that, the unit aims to investigate the possibilities of integration of decision-making on landscapes from the 'bottom up' on a community level within a recently deprived community of Grangetown, Cardiff, Wales, UK.

3. A Methodology

This core section explores the problematic of the designer (singular), as well as the opportunities presented by codesign and how blockchain presented a novel working method to advance current discourse on codesign.

The project presents an opportunity to challenge the trope of the individual creative designer. It extends the narrative to question the agency which humans have to 'design' for and control other species. This trope is one we teach and aspire to, and it is reinforced in the design media and in education. Design schools are replete with textbooks and lectures on Vitruvius, Mies van der Rohe and Hadid. Yet the modern age of design as a complex inter-disciplinary process is well recognised and documented in current (Apple) and historical (Bell Labs) cases (Gertner, 2012; Isaacson, 2011). Moreover, while codesign is currently in vogue in many circles, reconciling the ideology of the collective and the individual designer, it is not without challenges. A reasonably well documented example is Erskine's Byker Wall, often celebrated as a successful codesigned project. It is most often referred to as Erskine's Byker Wall; prefaced with the Architect's name the project is evidence of our fascination and comfort with the myth of the 'individual' designer. In many ways the project was a failure. Firstly, Byker was a 17,000 strong community and only 46 households were picked to engage with the architect in what was then known as 'public participation.' In a thoughtful critique of the project by Anna Minton the power dynamics and asymmetries of both the design and political processes are brought to centre stage (Minton, 2015).

The problematics of power geometries has been well reviewed by Doreen Massey (Massey, 2013). Within digital systems this is also cause for concern, as the designers of the systems are the agents with real power, with users relinquishing it for gains in convenience and efficiency (Haraway, 1991). Returning to our project the opportunities presented by blockchain are to remove or redesign these power structures to reduce the asymmetry that Haraway and Massey posit as inherent in such systems of organisation. Such approaches are specifically needed in excluded communities like Grangetown in cities like Cardiff that largely suffer by productive generation unemployment and homelessness. In addition, other species have been by now excluded from participation in any capacity beyond optimisation for domestication or industrial farming.

3.1. DESIGN (AND VALUE)

'If the Anthropocene proves more a fleeting geopolitical instant than a slow geological era - waves of apes maniacally excavating ancient carbon and drawing loops on maps - then whatever comes 'next' would be formed not by the same Anthropos but by something literally post-, un-, in-'human', for better or worse. So too the cities. '(Bratton, 2019).

Figure 3. Diagram showing the relationship between the collective and the individual and between the mapping and the prototyping (diagram: Davidová 2019).

The holistic team-built WIP project is exploring possibilities of cities' transition towards Post-Anthropocene for cross-species bio-digital coliving. This is approached through codesign and full-scale prototyping in the complexity of real life and real time in so called 'real life codesign laboratory' (Davidová et al., 2018). It is investigating prototyping of materialised ecosystemic interventions for cross-species habitable and edible cultural landscape ecotop. The project will test its linking through QR codes to their online recipes for DIY. This is to investigate if such action can support local- and visiting- makers' communities (empowering people by skills, tools sharing and open access designs). Therefore also, if it can grow a number of its own iterations. Subsequently, such prototypes and recipes will investigate how they can be networked to a blockchain system of values investigating its use for socially and environmentally sustainable circular economy. Or generally, it will investigate on how to develop new structures for social/economic exchange 21st century models.

The methodology is grounded in Research by Design (Morrison & Sevaldson, 2010; Sevaldson, 2010). This means that the unit generates theory through experimental practice of designing and its outputs implementation into-, observation of- and reflection on- the real-life codesign laboratory. The designing is approached through combining codesign (Sanders & Stappers, 2008) with individual design in Systems Oriented Design (SOD) (Sevaldson, 2013) and full-scale prototyping (Hensel & Menges, 2006). Such combination is a driving methodology in Systemic Approach to Architectural Performance (SAAP) (Davidová, 2017, 2018). The students are developing collaborative teamworking skills while holding their specific roles within the team. This is approached through collaborative visual complexity mapping tool of SOD, so called gigamapping (Sevaldson, 2018). The students‘ roles are based on their research interest within the unit's team project. Therefore, each individual student is deeply developing her/his research interest into an expertise and learn how to relate such to other team members' expertise within a framework of one complex collaborative holistic project. After the initial collective project of several interventions that will be prototyped in real life, each individual student will develop her/his expertise and its relations to others into a design thesis. This will be informed by real life observations and improvements (see Figure 3).

3.2. CODESIGN THROUGH GIGAMAPPING AND PROTOTYPES WITH BLOCKCHAIN

This project is exploring several layers of codesign. The processes also involve the cocreative planning for the initial generative interventions as well as codesigning them in real life through interaction and DIY. They address the urgent questions in Systems Oriented Design on needs of representing the participants that wouldn't be heard otherwise (Sevaldson, 2018). The first stage mainly involves people, the people that represent certain human or nonhuman social groups involved. The second stage involves the overall environment. What are the implications for a bird or a tree having a 'wallet' and trading power? What behaviour would manifest where human and non-human interactions and exchanges were recorded in an immutable DLT? Can Mamuna get the code and the material to reiterate the ecosystemic prototype she likes in her front garden, because she has been volunteering on community gardening that coproduces food for homeless people? Can the pollinators get paid for doing their job for coproducing the food for the community garden? And what about the plants? Etc...

This all has started with the codesign gigamapping workshops (see Figure 4), where the local community with its youngest, various stakeholders and specifically, local NGOs play critical role. One layer already incorporated in that is interaction with concepts provoked by blockchain next to the future DIY generated from the first-generation intervened prototypes. The background rich community has been updating the integration of Muslim religion into blockchain concept which is offering many solutions to that social group. I.e. in Muslim religion, there is no possibility of interest payment. Therefore, one needs to gather community together to buy a house or open a café. They all provide a service to each other and must operate without the bank. With blockchain, there is no bank and it can well accommodate such system. One needs no money for buying coffee in Ali’s shop. You can earn your tokens for taking care of Grange Garden. By doing that, you have raised Ali’s café income. Therefore, he is glad to award you with the best and ethical coffee (see Figure 4). Also, many other social groups can get integrated through blockchain though they might not well fit into the 20th century economic model and by it ruled society.

Figure 4. From left to right: a) Gigamapping codesign workshop with the community; b) A cafe owner draws a concept of the possibility of serving coffee to those that cannot afford it. (photos: Davidová 2019).

The second fully focused on blockchain workshop will also cover format targeted at non-technical people. The format will build on work started by the Design Informatics Research Centre at the University of Edinburgh and developed upon by the ’Chip of the New Block(Chain) research project at the University of Auckland. The workshops are comprised of three distinct parts, a presentation, a trading game and an ideation session. First, in a short presentation we introduce in very general terms blockchain. Second, participants build a blockchain. Using Lego to represent bitcoin they buy and sell trading cards and build the blocks onto a Lego blockchain. This creates a permanent record of the transactions that everyone can see, helping to create a tangible point of reference. Third, an ideation session is facilitated by the organisers. Here the participants are encouraged to consider what opportunities this technology might present. The session ends with a design exercise to propose a new concept in how blockchain might reorganise an existing situation and what benefits might be gained.

The third stage of codesign will already stimulate the cocreation through real life prototypical interventions of token systems within the ‘real life codesign laboratory’, both the analogue and its cross-related virtual ones. Such observations will be generically cocreated by its communal environment as well as updated by the initial authors for their master dissertations.

4. Conclusion

This work in progress discusses some of the factors being explored by the authors about design in the 21st century in search for balance and equity across diverse species and social groups in Post-Anthropocene. What the Post-Anthropocene could mean? What if beehives have a crypto-currency wallet and money where you had to pay the hive to harvest its honey? What if the hive paid locals who maintained flowerbeds? As bee’s reside within a certain radius of the hive, what if their 'money' could only be spent within certain proximity of the hive? These concepts all become plausible with programmable crypto-currency. We are designing within and with inter-species and inter-communities' architecture with the concept of circular economy. Can we assign 'value' to other species and their presence in the build environment? Can we design systems that encourage and support interspecies existence? The work seeks for tools for participation of those who typically can't rise their voice to codesign social, environmental and economic systems from the 'bottom up'. How can the power asymmetry between human and non-human species be reduced? How would we as a species feel about a redesign and reduction of our power, control and oversight of our environment? The paper documents a Systems Oriented Design methodology, informed by- and informing- blockchain, that is typically seen as evil, for a possible collaborative design approach. This work contributes to the body of knowledge by providing an approach that allows researchers to explore a novel collaborative design methodologies as well as speculate on design in a Post-Anthropocene world.

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INTEGRATING DESIGN STUDIO TEACHING WITH COMPUTATION AND ROBOTICS IN HONG KONG

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Abstract. There is a persistent need among Hong Kong Architecture students to develop greater aptitude for critical and design thinking. The mechanics of criticality entail observation, reflection and the development of a knowledgeable response. This important process aligns with a tool-based iterative design research approach, where a cycle of action, observation, reflection, and reaction can take place. In order to complement fundamentals in architectural design, a focus on tools and tool-making approaches toward the development of a critical architectural proposal needs to be incorporated into core curriculum. Through the integration of robotics, automation and computational design approaches into the design studio environment, tool making for producing architectural media (drawings and models) can most effectively be explored. With an emphasis on design and programming tools for component fabrication and assembly, students can develop their own criterion for evaluation as a knowledge-based response to their investigations and proposed architectural systems.

1. Introduction

Universities in Hong Kong have broadly expanded their support of technology integration into teaching at the undergraduate and graduate level. Support schemes like the Teaching Development and Language Enhancement Grant at The Chinese University of Hong Kong specifically target the adoption of robotics and innovative tools into teaching. Additionally, some pilot programmes at the high school level have advanced their Science, Technology, Engineering and Mathematics (STEM) initiatives with the use of robotics in order to provide students with unique learning experiences and a more hands-on approach to problem solving and design thinking (Geng et al, 2019). However, within architecture programmes, technological tools such as laser cutters and 3D printers are often regarded as final output devices, rather than as vehicles for exploration and the focal point for a design studio.

This study examines the introduction and integration of automated robotic technology into the design studio environment - with a focus on having students conduct action-based research for an architectural proposal. A series of workshops were conducted within the context of design studio, to break down student fears of the equipment, teach fundamental robotics and computational literacy, and for integration into design projects. Students were evaluated based on their capacity to

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 343-350.

independently develop unique responses to equipment limits in the production of architectural design materials. Students calibrated the degree of challenge within their proposed systems based on design, material and equipment limits.

Students in Hong Kong are typically exposed to a one-way transmission of knowledge from their instructors, resulting in a passive learning condition (K. Yan et al.). The results of this study indicate the capacity for Hong Kong architectural students to establish a critical position on architectural design as channeled through tool focused exploration and problem-solving. Success in this space will improve their preparedness toward the development and sharing of a critical design position for evaluation by peers, critics and reviewers.

2. Background

Most graduate level architecture studios in Hong Kong revolve around the final design of a building. This is also reflected in the distribution and allocation of grading weights attached to the final review typically ranging between 50 - 70% of the overall final grade. Students are introduced to a site and programme typology which is then researched extensively in order to establish historical references and context. They may conduct multiple site visits in order to survey the local community and re-affirm the need for an architectural proposal. Case studies are also conducted in order to deepen student references with those programmatic associations. Students consolidate their findings and deploy into an architectural proposal based on a programmatic matrix associated with space allocation (nearly always in plan) and some basic circulation and floor area ratio (FAR) suggestions. Using drawings, models, and diagrams, they present the extent of their activities during the studio in a final presentation as evidence of completed work.

The collection of successful experiences with technology and computing has been shown to have a direct link to student perceptions of that technology's usefulness (Lai et al, 2012). Most studio participants at the graduate level in Hong Kong have little experience engaging in a technology-based design studio. The majority have experience with a technology or coding primer from their undergraduate studies. However, corresponding studios fail to integrate and support technological approaches into their pedagogical approach. This creates a situation whereby students aren't fully adopting and exploring those rudiments of computation and linguistics and absorbing them into their design toolkit (Gerber et al. 2013).

A recent survey of architecture, engineering, and construction professionals listed programming as the second most important ability students need but ranked it near the bottom of those abilities (9th out of 10) in terms of student competence (Gerber et al. 2013). Even with this in mind, students typically regard their studio design projects primarily as exercises in programmatic massing configurations, leaving the tectonics, qualitative spatial configurations, material assemblies and realities of fabrication as derivative.

3. Studio approach

A graduate studio was set up to directly tackle the fears and aversion toward technology that is currently experienced by incoming students. The studio, which had run through three full term iterations, set a goal of introducing action-based research cycles to incoming graduate level students. A series of weekly assignments were developed to build confidence in technical and analytical capacity, with an expectation that knowledge gained from each activity would be incorporated into future iterations. By emphasizing the application of knowledge gained through these experiences to further problem-solving situations, they become more effective in their design proposals (Fung & Liang, 2019.)

Equal emphasis was placed on the specific technical activities carried out against the qualitative outcomes. For example, a hand drawing was presented by participants as a technical exercise whereby they would illustrate in detail the mechanics behind their final output (make and model of the pencil, tooth of the paper used, how they controlled the writing device with their bodies etc.) Simultaneously, the students were prompted into describing the qualitative aspects of their work, highlighting both moments of their perceived success and failure. These moments would become the focal point of the next production activity, with added complexity, dimension, change in tool type etc. and would link a fundamental relationship between design decision making and technical knowledge and virtuosity with a specific tool.

Figure 1. Studio Workshop, 2019. Hong Kong.

This teaching setup put students into a continuous 'work in progress' cycle, whereby they could focus clearly on opportunities to advance their work through a technical lens. Each subsequent iteration would add and integrate digital technology, computation, CNC fabrication tools and multi-axis robotics in order to build up confidence and awareness of technological possibilities and limits. The broad series of outputs were as follows: 1) Hand Drawing; 2) Digital Drawing; 3) Surface Model; 4) Volumetric Model; 5) Full Scale Casting; 6) Surface Assembly; 7) Architectural Proposal.

4. Hardware Overview

In order to further support the studio, a grant to purchase small scale collaborative robotic arms was secured along with a series of workshop-based tutorials on how to access the equipment control systems with a python application programming interface (API). Students were encouraged to explore the capabilities and limitations of the equipment and make use of the technology. The equipment selected was deliberately small enough for direct integration into the studio environment without the need for a supporting technician, while producing standard sized models, drawings and assemblies (Fig. 1). More critical is the scalability of control systems developed - ensuring that similar student designs could be scaled into a genuine construction context.

Two types of desktop sized selective compliance assembly robotic arms (SCARA) were provided to the students at a ratio of two students per machine. Their overall reach was up to 450mm along with an extension rail providing an additional 1000mm in the XY direction - large enough for a wide variety of design studio activities. Repeatability and accuracy were also rated at 0.2mm - allowing for high levels of precision within the setup. Exercises and assignments were given to explore the possibilities and limitations of the equipment with different end effectors.

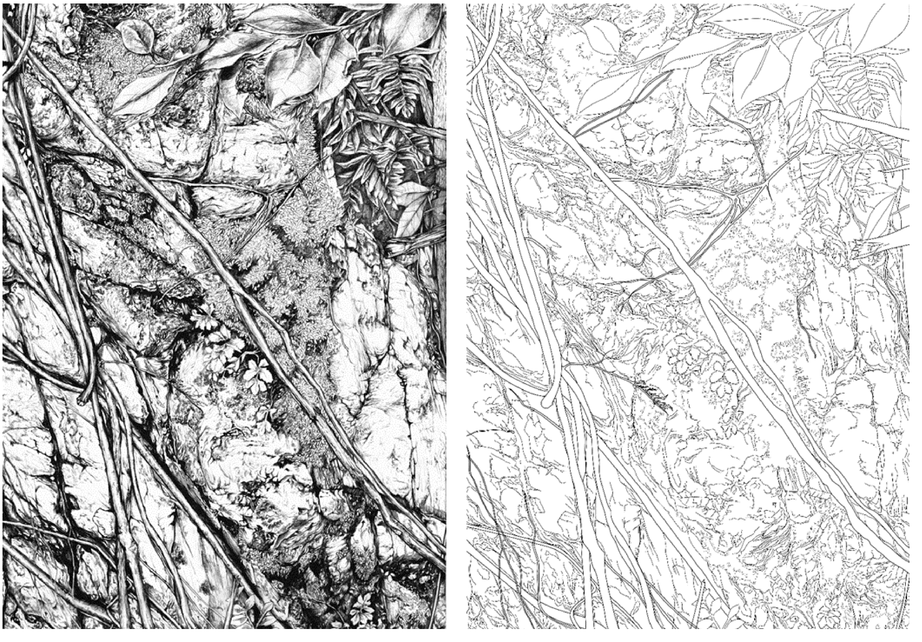

Figure 2. Hand Drawing (left), Vector drawing (right). Adwin KEUNG. 2019. Hong Kong.

Early assignments made use of the pen plotting and laser etching end effectors. This was an ideal entry point for students to gain exposure to developing control systems for CNC equipment (Fig. 2). This required the student development and creation of design vectors and immediate coordination with the limits of the robotics setup. Students were provoked into exploring different media in order to develop a body of shared knowledge specific to the type of tool and medium being explored. Although students had extensive experience using laser cutters, those devices were always separate to the studio environment and treated as final output equipment. In this context however, the direct placement of robotics into the studio encouraged an increased number of trials and experimentation alongside the studio ethos. This also ensured that students took direct control and responsibility for each motorized movement.

Subsequent assignments made use of a filament-based 3D printing end effector. Given the relatively large printable area capacity of the equipment, students were able to program full scale design components for either models or formwork for casting with either plaster or cement. This series of exercises was an ideal step for the development of a tectonic and component-based approach toward a design proposal - connected to an ambidextrous tool situated within the studio space. This was likely the most familiar set of digital tool investigations, as students have extensive experience with conventional desktop 3D printers. However, the control mechanisms and context differ entirely, as the equipment is presented as a multi-functional robotic arm, requiring individual coding of the robotic movements and deployment of filament, rather than supplying a stereolithography file for processing by a turnkey solution.

Most pertinent to this studio was the use of grippers and vacuum end effectors for pick and place operations (Fig 3). These components were introduced for students to develop their own design based on the limits of robotic assembly proposed in previous assignments. Students were able to develop an original workflow that could assemble 1:100 scale custom “brick” components into their designed assemblies. This workflow included the capacity to design, develop and produce assembly components, and programme equipment to arrange into complex models.

Figure 3. 1:100 Scale Study Model. 2019. Hong Kong.

5. Control Systems Overview

The robotic equipment came with a proprietary software interface making the system very approachable, however not practical for architecture and design purposes. The tools had no natural link to the standard architectural software used by the students requiring them to export models into a proprietary file type for equipment processing. However, a Python API was available, allowing participants to access and control the robotics directly from any Python terminal. This was specifically useful for pick and place operations, as students could develop a series of instructions to be carried out by the robot for assembly. This could include a "pick up" location for materials (either from conveyor belt or a pallet arrangement), an area for applying an adhesive layer, a destination location and orientation somewhere within the assembly.

A custom Grasshopper node was developed in house and allowed users to easily pass data from their computational design models into the mechanical control systems. Adding this additional layer of connectivity allowed students to comprehend the direct relationship between design dependencies and subsequent/immediate actions to be carried out by the hardware.

6. Evaluation Criterion

The initial introduction for the adoption of robotics into design studio was met with general apprehension. At the start of the first workshop, students began to feel more comfortable and curious about the use of the equipment. The equipment size and lack of technician allowed the students to immediately gain confidence and approach the robotics as precision toys rather than more intimidating larger scale (and potentially dangerous) equipment. The workshop covered introductory use of the included end effectors. Once the first testing exercises were initiated, students began to experience a hands-on approach to the tools - with their first drawings and laser etches being executed without any mechanical failures. As these tests were not rooted in any of the broader studio agenda, the atmosphere was more relaxed.

A second more focused workshop expanded the types of robotic equipment to include linear railings and conveyor belts (dramatically increasing the potential design/production space). The main agenda was to introduce logistical workflows associated with a digital design model and its physical assembly execution by the robotic equipment. These steps require repetitive calibration and coordination processes between materials, digital design and real-world workspaces. Once students were familiar with these processes, they were able to explore their own design direction more freely.

A third workshop focused on the establishment of pick and place operations for equipment derived from computational solutions. This used grasshopper and python as a basis and platform for a carefully designed instruction set to be carried out by the robotic arm and gripper entailing locations for picking their developed design elements, the potential for adding an adhesive layer and a final resting place within he design model (location coordinates and a rotational vector).

Subsequent to the workshops, the equipment was integrated into the studio environment and incorporated into assignments and deliverables. The first eight weeks required students to develop an original masonry unit based on drawing, formwork and casting exercises, and ultimately assemble a collection of those units together to form a partition wall at a scale appropriate to the robotics tools. Based on first engineering principles, the structures were required to remain entirely in compression, which can only be effectively proven through their physical assembly. The high precision and speed of the devices allowed students to develop and experiment with complex arrangements of materials that adhere to stacking principles and witness their immediate assembly results for documentation and qualitative impact. Students were able to quickly provide metrics associated with their design iterations such as number of units, assembly times, mechanical failures, global and local structural failures, tolerance variations etc. They were further able to develop their own computationally driven analysis tools to aid in predicting design model failures.

With each of their investigations, students were required to reflect upon those moments of success and failure within each iteration and declare how they will alter their design trajectory. This was now their perceived moments of qualitative success conjoined with a buildup of technical knowledge to carry out a more acute design and assembly revision. This critical inflection drives each student and their projects further into specificity and the continuation of another attempted iteration. It also strengthens student confidence in their design and technical capacity toward production of design. At any given presentation, students could articulate a balance between technical investigations and the qualitative outcomes from those decisions - forming the basis of a design position based on action, observation and knowledge gained from the experience.

7. Findings & Results

The integration of small-scale robotics and computational control systems into design studio is a novel approach toward architectural teaching and learning in Hong Kong. By directly positioning technology inside the studio environment, students approach the equipment as an extension of their workstations. This greatly contrasts to conventional fabrication and robotics equipment typically situated in a separate laboratory with technicians and safety hazards. Critically, design and control systems developed by students naturally scale upward and integrate with more costly and industrial rated equipment. Incorporation of robotics to design studio, along with an iterative approach to exploration allows students to frame their work as an applied technology research endeavor. It increases student confidence and exposure to the equipment and repositions the design studio as a mini design laboratory.

Future workshops are planned and funded to incorporate sensor driven artificial intelligence systems and a higher ratio of machines to students. Additionally, participants will be invited from non-architectural backgrounds to broaden the tools-based approach toward teaching and learning activities.

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DIGITAL STUPEFACTION

Seduction and Complacency of Digital Techniques

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Abstract. Digital design techniques have saturated architectural discourse in the past forty-plus years from modelling to simulation and fabrication. Digital or Computational Design now forms part of the standard architectural curriculum, promising efficiency in modelling, design, advancing site analysis and ease of fabrication. Alongside these promises, we as educators begin to witness a new level of complacency governed by the use of the digital tools; we call this Digital Stupefaction. With the increasing 'smartness' of digital tools, what is the risk of shifting away from the focus of what students should/could know, and what information they embody? Is it still relevant to be able to draw on intrinsic background knowledge, or tacit knowledge in action, when everything can be analysed and verified on the fly (or even pre-selected via AI)? How can educators respond to these challenges by adjusting the way they deliver subjects associated with digital design?

Keywords. Digital; Education; Critical; Pedagogy; Knowledge.

1. Introduction

We are on the cusp of a new era of digitally-enabled design: Artificial Intelligence (AI) and Machine Learning (ML) will further our ability to automate design processes as they provide 'decision support' based on precedence and using supervised/non-supervised algorithms. With that development in mind, Digital Stupefaction presents itself as an ever more tangible threat to design education. Questions arise about the readiness of students (and the educators) to critically reflect on the 'digital' opportunities at hand, and the impact they have on their desired design process.

25 years ago, Tom Maver (1995) wrote his brief essay on the 7 deadly sins of CAAD. There, he warns about a number of cultural aspects to be considered in what we'd call Digital Architecture today, ending with his most striking critique: the lack of critique itself. 25 years on, we do not seem to have received his message. When scanning available literature on digital design, one will rather find critique on what hasn't been achieved yet, and little-to-no critique on the effects of what has been achieved. Some observers, who previously commented on the effects of 'the digital' on architectural education (Lawson 2002, Kvan

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 351-360.

et al. 2004), warn about potential pitfalls when digital tools and techniques get introduced to architectural education. Theodore (2010) laments the lack of embodiment of concepts and ideas, experienced by those who exclusively dwell in the digital realm. Today, the discourse has moved on from this rather binary way of comparing digital with non-digital approaches. Questions still remain about the appropriate positioning of digital (next to non-digital) tools in architectural design and fabrication processes in tertiary education. Based on the experience of the authors who have been teaching both technical, as well as design subjects in academia for the past 15 years, the increasing adoption of digital tools does not automatically lead to an increase in design quality. In some instances, the application of digital tools can be seen as detrimental to the quality of design output overall.

This paper reviews the symptoms of digital stupefaction across various domains of digital design. As a provocation, it examines why and how such symptoms emerge in digital architectural design education through specific case studies. As Willis and Woodward (2010) question the promises of digital fabrication, claiming 'there is nothing "automatic" about it'. We question digital tools and asked if the black-boxing of software and plug-ins aid or simulate design thinking? If not, what is the alternative? The paper concludes with a set of recommendations towards de-stupefaction of digital design in architecture education.

2. Background

Over the past four decades, Digital Design has become a pervasive addition to the tool palette of architects (Mark, Gross, and Goldschmidt 2008). Academia is playing an essential role in promoting design computation and digital approaches in order to expand the boundaries of architectural education. If enabling CAAD and design graphics were the predominant focus on digital tools in their early days, their application has expanded with the advent of computational analysis and simulation, object-oriented modelling (BIM), parametric design, virtual reality, and geospatial data (GIS). The more recent focus on design to fabrication, mixed reality and the potential to apply Machine Learning in design add to the range of design processes that can be supported by digital means.

2.1. WHAT IS DIGITAL STUPEFACTION?

Reasons for the use of digital tools and techniques vary greatly. They are applied to automate repetitive tasks, allow students to deal with complexity (inherent to calculus-intensive tasks), form-finding, visualises their designs, manipulate it via parametric information exchange, and test their ideas for constructability and fabrication, just to name a few.

The question emerges: Does the increased application of design computation processes and techniques potentially lead to a decrease in the quality inherent to architectural design education? Should the use of digital tools be blamed for de-skilling and de-sensitising architecture students to the point of stupefaction? The aim of the paper is to examine the potential adverse effects digital design can have on architectural education via a differentiated analysis of issues that have arisen over the past decades. We will focus on both the tools and knowledge related to computational design and how it has affected design education. The authors do not seek the blame in the use of digital tools as such but point out how misguided pedagogy and andragogy do not necessarily correspond well with the opportunities presented via design computation.

2.2. PEDAGOGY APPROACH

Digital design, by the nature of the media, requires an added layer of skill set before designing. Many authors have suggested that the need to acquire technical expertise with design is a constraint of the media (Salama 2008, Loh 2015, Loh 2018) and digital design requires a different pedagogical approach (Kvan et al. 2004, Oxman 2008). In our opinion, there is no single digital design educational approach, but instead, we consider that there are multiple approaches which are still evolving with emerging technology. In this paper, we are less concerned with modelling in the form of CAD but modelling with some technical skill in visual scripting, or using other programming languages or digital techniques. In other words, there is some form of specialised tool (software and hardware) that stands between the designer and the outcome.

3. Methodology

The argument formulated here is based on the authors' observation in teaching digital architecture design through studios, seminars and workshops in the UK, Europe and Australia. The combined teaching experience of both authors exceeds 30 years. Where literature is available, we use them as a counterpoint and reflect on the current model of teaching practice and its outcome.

Some observations emerge from a qualitative questionnaire conducted by the second author on the use of digital technology and media in teaching and learning. The anonymous and voluntary questionnaire administered as an online exercise using SurveyMonkey(TM) were answered by students from a master-level design studio and a 2nd-year subject titled Digital Design and Fabrication at the University of Melbourne. Both subjects take place over a semester or 12 weeks period. The questionnaire aimed to capture the students‘ perspective of learning using technology and understand their views on how digital technology has affected the students' design outcome and learning experience. The invitation to participate was sent between 2015 and 2018 to 116 students, of which 38 responded (approximately 33% response rate).

4. Observations

The observations presented in this section highlight the key challenges educators encounter in the engagement of their students with digital design processes. Some of these are not caused by the fact that the tools used are digital, but the bespoke opportunities they offer to students as part of their design workflow. First, we discuss cognitive barriers relating to a mismatch between a digital design approach taken by a user and his/her ability to comprehend its affordances. Second, we examine how tools can misguide learning through overcompensation and putting tools before techniques and ideas.

4.1. KNOWLEDGE AND ASSUMPTIONS

4.1.1. Comprehending the meaning behind the data

Educators face a challenge when introducing (for example) structural or environmental analyses as part of architecture students' design process. An ever-broadening range of tools allows students to interrogate their projects in endless ways, but students do not automatically understand the process of analysis and simulation itself. The selection of criteria to be analysed, or the fitness function associated with the results often remain elusive to students who feel they should use analysis because they were told to. This problem gets reinforced by the student's inability to interpret the meaning behind the numbers - the results they derive from the analysis. Everything can be analysed, but to what effect? It is easy to let the analysis drive the form-finding process but never actually achieve any definitive result. It is a problem associated with the early-use of generative algorithms, and the symptoms continue. In generative design, the emphasis of design decision is critical in selecting the desirable outcome to enable the generative nature of the process. As Frazer (2002) writes, 'Design must be creative - or it is mere imitation'. If there is no sense of hierarchy in the performance criteria, the danger is an undifferentiated design that seemingly satisfies every criterion without privileging a particular design idea or concept.

4.1.2. Limitations of digital embodiment

Tacit knowledge is the conversion of information through practice (Senett 2009, p50); Downton (2003, p62) calls it the *knowledge-how*. Its counterpoint is explicit knowledge which refers to knowledge that can be formally learned. A number of authors believe that the creation of new knowledge and learning comes in the interaction of the two systems of knowing (Papert 1988, Nonaka and Konno 1998, Ratto 2011, Sanders and Stappers 2014, Loh 2019). To exclude one from the other might lead to a dangerous territory in architectural design. It leads students astray to make an assumption that the proposed solution is feasible without testing. Qualities such as mass, friction, scale, textuality and acoustic are intrinsic in the tacit, yet they are often absent in the realm of the digital media.

The seemingly limitless opportunities inherent to computational tools allow users to generate topological experimentation with great freedom in geometric expressions. A broad range of software plugins and custom scripts are now available to students to expand on their morphological explorations and introduce highly formally driven building skins, structural systems or other geometric articulations. The tools for achieving such geometric differentiation are often extremely seductive as they promise to deliver unique results. What students struggle to realise is that they risk engaging with form, for the sake of it. The danger here results from selecting parameters that appear captivating, yet remain superficial as they are without material or structural consequences. Geometric expressions may well appear glorious on screen, but would not correspond well to fabrication logic or material performance if translated into an actual built proposal.

Tacit is not exclusively in the realm of physical making, but also apply to the use of a software as McCullough (1997) suggests. With increasing availability of open-source software and online forums, students often resort to *'borrowing'* script uploaded by others on the forum. While the open-source nature of these forums need to be respected, it is increasing more difficult to understand if a students actually understand the Grasshopper 3D definition used to generate the resulting form, let alone how it could be built physically.

A side-aspect of this problem is the availability of low-cost 3D printing options for generating physical models. Model-making and workshop spaces within academic institutions increasingly give way to '3D breeding farms'. There, the process if model-making becomes a black box where students submit their virtual models online to pick up the final result on the day of presentation. The convenience of the 3D printing solution, combined with the reliance on third parties to resolve any process-related issues, result in two problems. Firstly, a lack of criticality if 3D printing is the appropriate medium, and secondly a de-skilling of the student who will less likely be able to gain deeper insights into the tectonic and material characteristics of their design. The particular affordances and distinctive attributes of analogue, digital, and post-digital modelling have been discussed in a great level of detail in Homo Faber, Modelling, Identity, and the Post-Digital (Burry, Ostwald, Downton and Mina (eds.), 2010)

4.1.3. Confirmation Bias

Confirmation bias relates to the misguided use of computational simulation to confirm a designer's preconceived opinion. Design students are vulnerable to taking this approach when, instead of interpreting simulation outcomes to understand the performance of their design, they use the data to simply confirm what they hope the outcomes to be. In those instances where students prioritise form-making over open-ended form-finding processes, they will search for analysis outcomes that 'fit well' with their initial design ideas. The issues here are twofold. First, the pre-conception of the initial design ideas. An idea is a fluid notion; design intent is more static, although scholars have argued on the fluid nature of design intention (Malafouris 2016, Pacherie 2006). As Oxman (2008 p106) suggests, digital design theory has transformed the concept of form into the concept of formation. Hence, the non-static nature of the idea as a process of ideation. We will expand on this in section 4.2. Second, the black-box nature of plug-ins for tools such as Rhinoceros and Grasshopper 3D led to the window-dressing application of digital tools. While plug-ins make certain computational process more efficient for experienced users, they also removes the layer of understanding behind the objective, and logic instil in the plug-ins.

4.2. TOOLS

4.2.1. Tools before Idea

Oxman (2008, p101-102) proclaims that design is intrinsically related to its media. Just as the paper-based culture of design encourages immediacy of ideation through sketches, design ideation using digital tools and techniques has in the past 20 years been topological, performance, generative and sometimes materially driven as a bottom-up procedural thinking. Parametric modelling with its own set of shortcomings (Davis 2013, p39) such as front-loading of design criteria demands a fundamentally different way of conceiving ideas, less as a concept of form but more as a process-driven methodology.

An emerging symptom of digital stupefaction has been the placement of the design tool before ideation. Here, we are not concerned about the mimicry of a paper-based culture of ideation with digital technology. After all, if one can sketch or draw with pen and paper, then most millennials can draw with a stylus and a tablet. What is disturbing is the submission of ideation wholly to the tool with a lack of design intention from the designer. One cause of this issue occurs when a student is unable to match a design problem to an appropriate tool for resolving it. Another reason for putting the tool before the idea occurs in scenarios where a student feels obliged to use a digital tool or technique simply because it was suggested to do so as part of the course outline (but without truly understanding the motivations behind that suggestion).

When laser cutter machines are acquired by the various Fab Labs within schools of architecture, these model-making tools can condition the way student design. The constraints of the tool to produce 2-dimensional planar geometry could be misinterpreted as the only conceivable way of manipulating or conceiving a form. Volumetric forms and landscape-like geometry are often sectioned and stacked to produce awkward models without the consideration that a change in making-strategy can offer a better design solution, or might open-up new ideation potential.

4.2.2. Tool before techniques

An equally obvious symptom of digital stupefaction occurs where inappropriate techniques are applied to a tool to solve specific design problems. A typical example is the use of Panelling Tool (developed by Rajaa Issa for McNeel) to discretize a doubly curved surface. Most students understand the need to panelize a surface for buildability purposes. Recent build projects such as the doubly-curved metal cladding of Dongdaemun Plaza by Zaha Hadid Architects clearly demonstrated the principle in practice. However, when it comes to understanding the role between the tools and techniques, students are often confused. When panelling a free-form surface, students are quick to achieve the seductive results of the panelised surface. When asked to make a paper model using a laser cutter to produce the form, some students would continue to use the quad surface resulting from the grid of the panelling tool. The result is a paper model that does not join-together well as the standard paper can only produce developable surface.

The above identifies a lack of connection between the tool, technique, and the material. This complicated tripartite relationship requires a strategic understanding of design intentionality and how it relates to the tool, technique, and material (Pye 1968). While the lack of strategic thinking or design strategy often led to a manic adaptation of the tool to solve in-appropriate problems. Conversely, a lack of strategic thinking could also lead to complacency of the technique and rely on it to deliver a 'more or less' result without any material consequences or fabrication logic.

4.2.3. Overcompensation

As Mitchell (2009) reminds us: 'architect's tools aren't neutral ... availability invites use'. Tool affordances and biases go hand in hand with assumption and values affecting the way users interact with them. In the academic context, students may get seduced to extensive application of particular functions within a tool in order to compensate for a lack of design thinking. Observing student behaviour during design studio, one such occurrence relates to situations where students use Building Information Modelling to advance their projects and take advantage of limitless ways to represent their design on presentation panels. In most instances the choice of BIM tools for design results in a less than stellar outcome, and students mistake the fact that there is a lot on the panels as a qualitative characteristic. The root cause of this issue is not related to the tool being 'digital' or not, but to the selection of an appropriate tool in the first place. The problem gets exacerbated though by the lack of critical thought students apply when confusing quantity with quality.

5. Synthesis - Recommendations

All of the 'stupefaction symptoms' exemplified in this paper are surmountable. Educators play a pivotal role in anticipating where these negative symptoms are likely to occur, to then guide students and instil a sense of criticality towards the engagement with digital tools and associated processes. Based on their experience, educators will thereby aim to counteract potential pitfalls and establish a sense of responsibility among students to become invested in their design process and the selection of an associated tool ecology that balances both digital as well as non-digital approaches. Students need to learn to question their choices and the reasoning behind their design approach. At times this is easier said than done.

5.1. A COMPETING LEARNING ENVIRONMENT

Within the constraints of a semester-long design course, students' primary focus tends towards the production of a captivating design outcome, or the acquisition of a specific set of skills. In many instances, a strong reflection on process or tooling is not foregrounded when students conduct their research or when they advance their design thinking. Increasingly, the tendency is to teach software or skill within the subject with the aim to apply the skill set directly to the design task. Software skills should not focus on any specific tool only. It is the responsibility of the educator to help steer students in their selection of a tool ecology (both digital and analogue) that takes advantage of the best possible combination of applications to support their desired design process. Figure 1 depicts an example of a tool ecology.

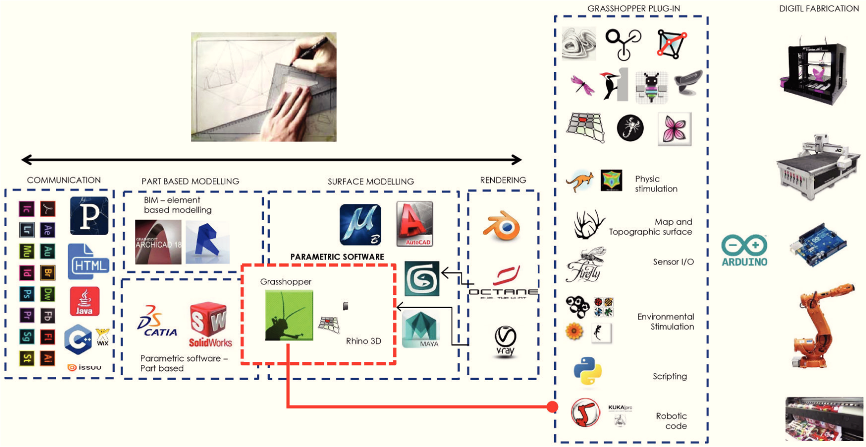

Figure 1. Example of a Tool Ecology for a Design Studio.

It is important to highlight that design education is iterative, and there is only so much students can learn within 12-week long semester or term. From the questionnaire, when students were asked how they find learning new technology (both tools and software) during their design course, 65% responded saying it is time-consuming but manageable; 30% responded saying that it makes their workflow easy and 5% responded that time is a critical factor to learn the software in order to deliver the design outcome.

5.2. POST-DIGITAL PEDAGOGY

A number of written feedback examples from students cause us to reflect on how we teach in a post-digital scenarios.

"It's difficult to engage with the newest technology and at the same time have a design process, site analysis and all other aspects of an architectural studio".

"Technology in the end becomes a representation tool. However, should there be more time, there maybe an opportunity for technology to also take up the role of giving design feedback"

"I found that there was a disconnection in understanding how the 3D simulation form output really worked spatially. As the iterative form output was the result of a set of parametric inputs, we were not the direct makers of the output, and thus had to inspect the resulting forms on a 2D screen environment."

These comments highlight three critical issues associated with the pedagogy of digital design. First, the notion that design is somewhat separated from the technology or media. If we are in a post-digital era where there is no longer any binary schism between digital and non-digital approaches in design, then has our teaching been too technique-focused in the last decade? With increased emphasis on digital processes, does this mean that by nature, other skill-sets will be less taught? This leads to question such as, what other design skills have we left out? A pen can capture shadow and light, can a VR model not do the same job? In our opinion, this is simply a bias or preference of design tools and the debate around digital versus the non-digital is counterproductive to the discussion of a post-digital pedagogy. Rather, the effort of educators should be focused on how to deal with shifting pedagogical model of the post-digital, as technology will continue to remain in the discipline of design.

Second, the representation in digital media is both abstract (in the form of diagrams and data analysis) as well as corporeal. The notion of feedback has been critical to computation logic, but it has rarely been exercised in teaching. It is therefore pivotal to instill in students a sense of criticality towards the quality of responses mediated via digital means. Figures 2 provide examples of engineers and software developers joining class in order to assist students in understanding both the meaning behind the data, and to explain the simulation processes applied by tools to derive meaningful output.

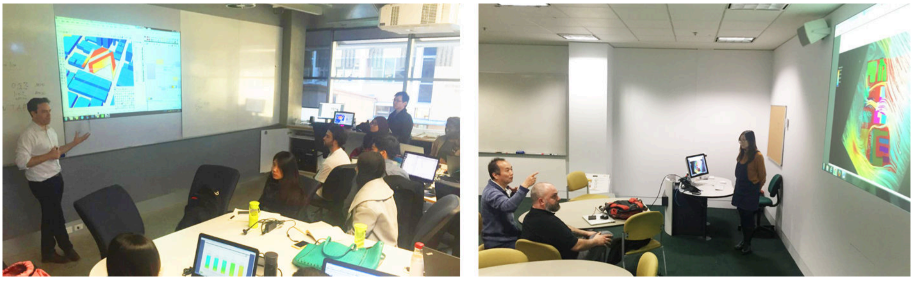

Figure 2. Expert input, explaining digital tools and techniques in the design studio.

Third, the disconnection between media, and design technique (and associated issues) could be the result of the way we teach technology as discrete units. Traditionally, design studios are run as iterative teaching environments, typically over 5 years of architecture education, supported by digital based communication subjects. If digital design teaching gets subsumed as part of the studio experience, it might assist in connecting the media with the design.

6. Conclusion

This paper attempts to summarise a series of observations we identified as Digital Stupefaction. It is broadly categorised into two areas. First, the cognitive barrier between the generated information and the students' ability to comprehend, make sense, or utilise the affordances of the techniques. Second, the technical barrier of the tool often results in students putting the constraints of the tool before the methods and at times, their conceptual thinking.

The increasing discretisation of technical learning with design techniques (and design sensibility) in the architectural curriculum has created an awkward disjunction between the understanding of digital affordances of tools and techniques with its application, interpretation and analysis. We called for educators to review how we teach digital design in an ever-evolving context of emerging technology. We may not be able to counteract stupefaction fully, but we can certainly minimise its impact on our student's learning by radically reconsider how we teach design.

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Robotics

DEVELOPMENT OF AN ANTHROPOMORPHIC END-EFFECTOR FOR COLLABORATIVE USE ON CONSTRUCTION SITES

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Abstract. This paper describes the design and development of anthropomorphic end effectors for collaborative robots for use in the construction industry. The research focuses on the form and function of the end effectors including an in-depth investigation of soft robotic techniques and sensor technologies. There is critical and legislative demand for automation in construction to meet increasing labour shortages, a growing population and ensure safe work environments. In an attempt to address these demands industry originally looked to replace human labour, however, in the last 5 years, the focus has shifted to human-machine collaboration, particularly collaborative robots. To ensure safety and increase productivity, end effectors also need to be well designed and collaborative. This research, its proposed hypothesis, methodology, implications, significance and evaluation are presented in the paper.

Keywords. End Effector; Construction Industry; Collaborative Robotics; Soft Robotics; Sensor Technology.

1. Introduction

The construction industry has not yet embraced digital technologies with skilled trades workers completing up to 80% of work on a construction site. Unfortunately, this reliance on human workers is causing the industry to face issues with productivity and safety on site. In Australia, the number of skilled trades workers has declined up to 45% since 2012, and with an increasing population of 1.6% per year (Australian Bureau of Statistics, 2019), it is clear that innovation is needed to maintain and increase productivity. This paper argues that a potential solution to the discussed labour shortages and productivity issues may exist in robots in construction (McKinsey, 2016).

Robots are successful in carrying out repetitive tasks with high accuracy, thus would be advantageous on-site for tasks that are repetitive and unsafe for human

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 363-373.

workers. Although considering the unstructured nature of construction, robots would need to be collaborative to work alongside tradespeople to ensure their safety. Precedents for implementation of robots can be seen in industry initiatives such as 'Industry 4.0' where the approach relies on a set of design principles, one being "technical assistance". Here robots assist by completing tasks that are unpleasant, too exhausting, or unsafe for humans to undertake (Rosenberg et al., 2015), thus improving the health of workers.

In comparison to industrial robots, collaborative robots offer the potential, as evaluated in previous research (Reinhardt et al., 2019) to work on construction sites as they designed to work alongside humans due to their lightweight structure and sensing abilities. Force-torque sensors allow the robot to sense, stop or move in the opposite direction upon collision, essential for collaborative work to reduce the risk for human coworkers. (Rosenberg et al., 2015). Although robots arms have been developed to be collaborative, end of arm tooling or end effectors have not been developed to be collaborative, which could cause hazards to workers. Further, with a limited range of end effectors currently available (with either gripping or vacuum functions) applications on construction sites are limited as most jobs cannot be completed by gripping or vacuuming. Existing end effectors can only grasp a small number of objects and if this object were to change, the whole end effector would need to be reprogrammed or replaced altogether. Traditionally the field of robotics explored rigid based materials systems, but the results can be complex and overly expensive with grippers costing up to 20% of the whole robotic system (Al-Ibadi, 2018). With the limitations in the current market, a solution would be to develop a soft anthropomorphic end effector suitable for construction, that not only reduces risk of injury but, that is capable of picking up a range of tools found on-site to be able to complete a pool of tasks, instead of a custom-built end effector for each task on-site, that would significantly increase the costs of implementing collaborative robotics, not providing a cost-effective solution. Hence when considering the construction industry and the needs for a collaborative, safe environment, not only does the robot needs to be intelligent but so does the end effector. This observation is backed up by Onrobot (2018) stating that:

" Since the increase in collaborative robots by a 23% growth between 2017 and 2018, the new World Robotics Report, published by the International Federation of Robotics, shows a huge demand for end-of-arm-tooling, (EoAT) especially in intelligent grippers that have "plugin and play" features."

With safety being the main topic within the field of collaborative robotics, this is essential for end effectors also. Further, end effector design needs to meet industry needs. For construction, in particular, it needs to be able to pick up a range of tools, that are all different in shape, size and weight and understand the surrounding environment including human co-workers through the use of sensor technology, The end effector also needs to be flexible for a range of tasks and low cost to purchase. Hence this paper explores the essential requirements of materials, actuation and sensors to ultimately understand how these particular needs could be met to aid collaborative robots onto construction sites.

2. Background

2.1. END EFFECTORS EXISTING COMMERCIALLY

Collaborative end effectors is a particularly new area of research and there are only a few end effectors currently on the commercial market that are developed for collaborative processes. An example of this is the "Co-act" series, which is a range of collaborative grippers designed by SCHUNK (2019). These grippers are modified versions of traditional two-finger parallel grippers that are built with soft protective housing, rounded edges and a range of sensors to be safe for human and robot interaction. These grippers include technology such as a camera, capacitive sensor systems, tactile sensor systems and optical feedback to deliver a safer environment for robot-human interaction. This sensor technology can be used to distinguish between the workpiece and human body parts, understand if a human is within close proximity and switch to safe mode. Tactile sensors let the gripper understand when it has an object gripped and determine the right force needed to grip certain objects (Robotic Industries Association, 2018). Although this gripper is collaborative it is limited in the range of tasks it can complete due to the limited range of two-finger grippers. In construction, a two-finger gripper may be able to pick up a tool such as a hammer or a power drill but it does not have the flexibility to manipulate or use the tool itself, thus this research project investigates anthropomorphic solutions that incorporate some of the interaction adaptability of the human hand with a range of different construction tools.

2.2. TOWARDS AN ANTHROPOMORPHIC END EFFECTOR

An anthropomorphic robotic hand is advantageous compared to simple grippers as it can complete a complex range of tasks that two-finger grippers could not, such as in-hand manipulation of objects. This intricate manipulation allows robots to grasp a whole range of objects ranging in size shape and texture. The human hand is a highly sophisticated tool that allows for efficient manipulation of everyday objects. (Armito, 2008). Considering that tools found on construction are designed for use via the human hand, this paper hypothesis that using anthropomorphism to design an end effector will give it an optimised gripping ability of these tools and help meet the needs of the construction industry. This use of anthropomorphic design will enable the use of a range of tools on-site, this could be a more cost-effective solution by reducing the need for a range of custom end-effectors to carry out specific tasks.

The human hand's compliant material forms around the shape of different objects increasing the grip (Deimel & Brock, 2016). This research explores soft robotic techniques to recreate this quality in a robotic hand. Soft Robots are inspired by biological systems, where robots are constructed from materials that are similar to living organisms instead of hard materials like traditional robots (Rus, 2015). The intended purpose of soft robots is to be flexible and adaptable to a range of unexpected environments. The organic movements that can be developed from a soft robot have the potential to reduce the amount of algorithmic complexity in programming and complete tasks that rigid robots are not capable of doing (Al-Ibadi, 2018). Soft robots aim to have integrated features in the material architecture to have embodied intelligence that could replace things like sensing, actuation and control that are all separate modular pieces of a rigid robot. Taking advantage of the material architecture could allow for a soft robot to mimic parts of the human body like hand movements but also maintain a safe interaction with humans, through reduced risk of injury from collision or pinch points, that would be typical of rigid components working in close range with human co-partners. (Rus, 2015).

3. Methodology

The research has adopted the action research framework, to which practical methodologies were applied by theoretical findings to best test and acknowledge the outcomes of the design stages. This method is characterised by an iterative process that tests materials, actuation and sensors to create a soft anthropomorphic end effector. The research allows for the tested and evaluated prototypes to inform each subsequent iteration and provide reasoning for future prototyping. This systematic study is carried out in an attempt to improve the research practise of this technology and provide a means for future own-practical actions, to where research is reflected and criticised upon for future action (Mcniff 2013). Yet further research is undertaken into soft robotics in order to arrive at solutions for anthropomorphic end effectors, thereby creating a cost-effective means of implementing collaborative robots onto a construction site. The research draws on a literature review of the current anthropomorphic end effectors and selects and tests designs to understand what solutions are capable of using tools such as a drill on a construction site.

4. End Effector Development

4.1. ACTUATION & MATERIAL TESTING

Collaboration between robots and humans will be essential for work on a construction site and consequently, the designed end-effector must meet a range of requirements, in particular, the flexibility to manipulate or use the tool itself and reducing the risk of injury. With this in mind, the research focuses on the use of soft materials such as silicon and how this material can be actuated.

Figure 1. A range of silicons tested based on their Shore Hardness ranging from 00-10 to A90.

In its first iteration, the research looked at ten different silicons based on their shore hardness, then chose three to further experiment within the finger and actuation stage. An extensive range of silicons was tested with shore hardness ranging between 00-10 to shore A90 (See Fig. 1). The silicon needed to feature qualities such as low viscosity to enable pouring into a range of complex moulds, have different durability and a high range of movement so as to change form when actuated and to grasp a range of different shaped objects.

Based on these first tests the silicons that were chosen for continuous testing in the next iteration were: Platsil gel 00-10, Platsil Gel 00-30, Transil and Mold Star 16A

Different actuators seen throughout research within robotic hands and soft robotic hands were compared and evaluated them against the qualities needed for construction. Most commonly used designs were *Pneunets* and *Pneuflex* (continuum actuators) and cable-actuated hands using servo motors (Kontoudis, 2015; Mosadegh, 2014; Deimel & Brock, 2018) The chosen silicons were tested and evaluated in creating these particular actuators, to see how they behave and how successful they are in different scenarios.

4.1.1. PneuNet

Figure 2. Example of Platsil Gel 00-30, Mold Star 16A, Platsil Gel 00-10, (Left to right).

This actuator contains two layers: the first contains a series of air chambers that are connected by a channel and a second bottom layer that restricts the first layer to only move in a bending motion. These two layers are sealed together, using silicon or silicon glue to create a bending actuator that when inflated causes the soft air chambers to expand and causing a bending motion similar to the finger. Previous research shows that the change in volume through increasing or decreasing the size of the chamber or the number of chambers can reduce the strain on the material making it more durable over time which is needed for the construction industry (Mosadegh, 2014).

Platsil Gel 00-10 The first silicon tested was *Platsil Gel 00-10*, however it was difficult to get out the mould, due to its softness (too soft and stretchy) and the silicon was ripped apart upon removable. In summary and upon testing it was determined that it would not be durable enough for a construction site thereby reducing cost efficiency.

Platsil Gel 00-30 The second silicon tested was *Platsil Gel 00-30*, which was more suitable to the complex mould of the Pneunets and stayed intact when being removed from the mould.

Transil *Transil silicon* is harder than the *Platsil* Gels and consequently more durable. This silicon was used as a base layer of the PneuNet to create strain to influence the way that PneuNet bends. However, there is limited room to embed sensors as the actuator takes up a large amount of space, which is essential for collaborative work. Although the actuator has good grip force, the design of this actuator would have to be altered to increase the in-hand manipulation for the use of tools such as a power drill to have more precise movement.

4.1.2. PneuFlex

In this second iteration, a fibre reinforced *PneuFlex* actuator was tested using *Platsil Gel 00-30* silicon. This actuator has a large chamber with fibre running at two alternate angles or a single fibre running at a single angle on the outer side of the silicon. As air pressure inside the chamber is increased, the length of the actuator increases, depending on the fibre angle(s) of the actuator, it can cause the actuator to extend, bend or twist (Polygerinos, P, 2015).

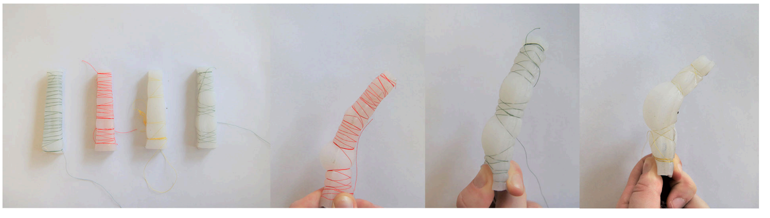

Figure 3. Experimentation with Fibre Reinforced Actuators.

This research experimented with the different types of patterned threads to see if the change in the pattern could create a larger bend. The patterning of the thread affected the direction of the actuator and despite challenges regulating the movement and direction, it was able to replicate the movement of the knuckle by being able to adjust the spacing (See Fig. 3). As the end-effector needs to be able to pick up and use tools found on a construction site, the actuator needs to be more predictable to control and needs stiffer components to be able to hold the weight of tools. In future, the fibre reinforcement could be used on a refined design to add control.

4.1.3. Cable Actuated

In the third iteration, a cable-actuated process was tested. Cable actuated processes are popular within the robotic hand design field as the silicon used is mostly hard and rigid allowing for a smooth movement. Here a simple finger design that replicated the structure of a human finger was used. The research tested different cables and their strength with different tubing to see how the silicon behaved and bent. *Transil* and *Mold Star 16A* were too rigged in comparison to *Platsil Gel 00-30*.

Consequently *Platsil Gel 00-30* was used for the remaining actuation tests. The most successful solution for cabling was 1.5mm rubber tubing with a nylon wire running through it, spectra speed cord also produced similar outcomes. Tests such as aluminium tubing and stainless steel wire caused the silicon to collapse instead of bend. One could potentially overcome the problem by using harder silicon or a combination of *Platsil Gel 00-30* fingertips to increase friction and a *Transil* backing to add structural strength to the finger design.

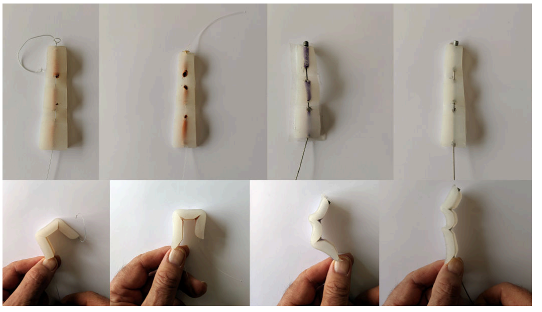

Figure 4. Different iteration using different tubing and cable examples and the results.

In our research, a full hand design was created using just *Platsil Gel 00-30* with rubber tubing and nylon wire. Here the prototype was able to hold the weight of a hammer. This actuation system was the most successful out of the three systems tested as it demonstrated the ability to hold heavy objects, had the most control range of movement, which would allow for in-hand manipulation in the future and could be compliant enough to create a strong grip and friction to an object.

Figure 5. Platsil Gel 00-30 hand holding the weight of a hammer (left) and the hand (right).

4.2. SENSORS FOR SAFETY AND COLLABORATION:

Intelligent systems will be crucial for the transition of robots onto a construction site, including intelligent end effectors. Initially, for this research project, a range of sensors were chosen to test on the premise of safety, through research on collaborative end effectors such as "Co-act" series by SCHUNK. Currently, there is only a limited range of stretchable and flexible electronics that are commercially available for soft robotic hands because most sensing systems are designed for rigid robotic hands. This research tests a range of current sensors for hard robots to test how they behave when embedded into the different types of silicon. This research focuses on flat, small or flexible sensors that could be seamlessly integrated into the soft robotic hand. The chosen sensors were force resistor/pressure sensor, piezo knock sensor, piezo vibration sensors and motion capture PIR sensor.

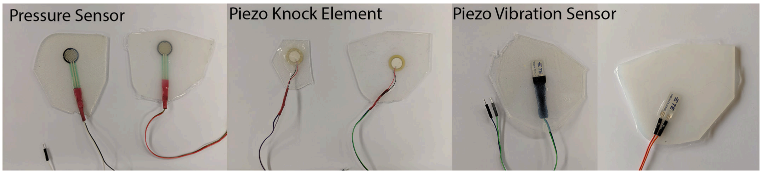

Figure 6. Sensors Embedded into silicon to test changes in their behaviour.

Force resistor/pressure sensor. The first sensor evaluated was a force resistor sensor, that is flexible and can provide an output based on the pressure applied. Initially, in its normal state, the sensor was highly sensitive to touch and would output low values between 0-100 with very low force applied. With large amounts of force applied using fingers the sensor would read outputs values up to 1200. The second test that was undertaken involved the sensors being embedded into a 3mm layer of transil gel. This test showed that the sensor lost some of its sensitivity in the silicon as more pressure needed to be applied to get similar values. The highest value that the sensors could detect was 900 showing how the sensitivity changed due to the silicon. The third test was in the *Platsil gel 00-30*, the results were similar to the results of *Transil*, although the sensor could output results up to 1000, suggesting that the softness of the silicon plays a role in the value that the sensor could output. To get the best readings from the force resistor, the research concludes that it should be located within the softest element of the finger design.

Piezo knock sensor. The next experiment used a piezo element that can be used for knock detection or vibration. A piezo element sensor was used in these experiments to detect knocks on a small scale. In the final design of the end effector, this could be used on a larger scale to detect collision between the end effector with objects or humans so the end effector that it knows to stop the task at hand to reduce any further damage or risk to safety. The sensor was tested without being embedded into silicon to test the sensitivity. The piezo element was knocked to turn on a light. It was highly sensitive to knocks, so if it was going to be used within the end effector it would have to be programmed to reduce the sensitivity and would need to be able to be controlled. Similar to the first experiment the sensor was embedded into 2mm of *Platsil gel 00-30* and *Transil* to see if this changed the way that the sensor behaved. The silicon made minimal changes to the sensitivity of the sensor as results were similar in both *Transil* and *Platsil Gel 00-30*. The threshold was increased, thereby reducing the sensitivity of the sensors and all results are similar for all three test case experiments. To use this sensor within the end effector for construction the threshold of this sensor would need to be high. This sensor runs the risk of false positives.

Piezo vibration sensors. Piezo sensor can also be used for vibration and come in the form of thin sheets. Considering the construction industry, the data provided from the sensor would allow the user to program the end effector to understand the pressure or force needed to complete certain tasks through the vibrations that created, for example drilling through timber. The piezo vibration sensor is highly sensitive and is constantly monitoring the environment giving readings between 0.00 and 4.00. The sensor in 2mm of *Transil* silicone is not as sensitive to vibrations as the sensor in its natural state, giving more 0.00 readings. It requires higher amounts of vibrations to get similar readings. This would need to be considered programming the sensor for the construction industry and the depth of the sensor in the silicon as it is shallow in this experiment. The sensor in 2mm of *Platsil 00-30 Gel* results had different results it got similar results as the sensor in its natural state and was giving readings between 0.00 to 3.50.

Motion capture PIR sensor. Motion capture or a PIR uses light sensors to detect either the presence of infrared light emitted from a warm object or absence of infrared light when an object interrupts a beam emitted. This device could be used within the end effector to sense the presence of human co-workers that are working close by. This aids safety as the motion capture sensor could allow the end effector to stop using a tool if a human co-worker comes within a working range. The sensor was tested by using a 2mm layer of *Platsil gel 00-30* sheet covering the sensor to test if it affected the light. This is important to understand the placement of the sensor and whether it needs to be internal or external. The motion capture sensor didn't behave the same in silicon as the sensor in its natural state. The silicon blocked too much light for the sensor to accurately detect motion on each trial. Some tests picked up motion but this could have been movement of the sensor against the silicon affecting the light emitted. It is clear that the sensor would have to be positioned externally for use on the end effector. The sensors would be able to detect human movement within 1 metre of the robot arm, as a Kuka IIWA collaborative robot (the one used in the testing) has a working range of 840mm, it would be successful in turning into safe mode before a person got too close helping mitigate risk.

5. Conclusion

The main objective of this research was to develop an understanding of the material, actuation and sensors needed for a soft anthropomorphic end effectors for on-site use. The research investigated soft robotic techniques and sensor technologies and evaluate their efficacy. The focus was finding solutions that met the following criteria; the ability to pick up a range of tools, of different shapes, sizes and weights, understand the surrounding environment including human co-workers through the use of sensor technology, flexibility for a range of tasks and low cost to purchase. The hypothesis of the research is to develop one collaborative end effector that is capable of using a range of tools, rather than a range of custom end effectors for each task require, increasing costs.

The results showed *Platsil gel 00-30* was the most suitable silicon as it had the highest range of flexibility, could be used within complex moulds, and the soft nature of the material added compliant qualities that increased the grasp function of the end effector. At this point, it lacks the strength to hold tools such as a power drill and hammer properly. *Transil*, on the other hand, was suitable to create a rigid element to aid the controlled bending of fingers and increase strength. These silicons could be combined to improve finger design. Cable actuated fingers were the most successful form of actuation suited for the use of construction. Both *PneuNets* and *PneuFlex* would have to be re-engineered to be suitable for construction, as the bending motion was not as controlled which is a requirement for in-hand manipulation to be able to use tools such a power drill.

This research explored a range of sensors that were small, flexible or flat and created an understanding of the capabilities of each sensor and the role they could play in creating a collaborative end effector that enabled human collaboration safety on site. Although they all showed potential, their sensitivity and functionality were reduced due to the way silicon absorbs impact, pressure and vibrations before it reached the sensor. In further research, it would be beneficial to explore sensors that are soft, stretchable and a part of the material architecture of the end effector.

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SEQUENTIAL MODULAR ASSEMBLY

Robotic Assembly of Cantilevering Structures through Differentiated Load Modules

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Abstract. The principles of computation, robotics, and modular building elements offer excellent opportunities for automation in architecture. A building system that incorporates these principles could cope with detachable building elements, sequential assembly processes, and algorithmic adaptability. In this paper, we investigate the strategic distribution of weight through a set of modules with different weights to build cantilevering structures. The modules are designed to have self-calibrating qualities, to allow a precisely defined positioning and thus be suitable for a robotic assembly. We implement an algorithm that automatically calculates the position and amount of weight modules. The exact placements are translated into robot instructions. By removing or adding a single module, we stimulate the collapse of the assembled structures, highlighting the precise measures of our approach. This approach may find application in scenarios where it is necessary to build without temporary support while still having a stable construction through each assembly step. Finally, we illustrate a framework to build structures that can easily be disassembled, thus allowing the reuse of the building elements.

Keywords. Discretization; Multi Modular Assembly; Automation; Robotics.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 375-384.

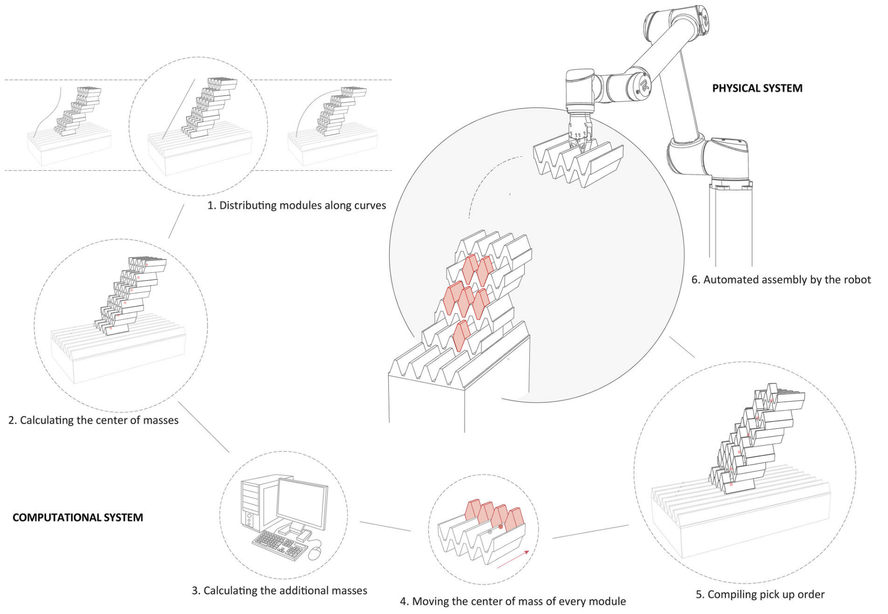

Figure 1. Process Diagram.

1. Introduction

Modular building systems are well equipped for automation, and when carried out in a detachable manner, offer the possibility of future reuse. Guidelines for designing such detachable components suggest giving up fixation through nails, screws, or adhesives (Geldermans 2016). Instead, the application of geometrical principles such as topological interlocking (Tessmann 2012) or the use of self-load (Ariza and Gazit 2015) can be sufficient to fix an assembly while still offering the possibility of disassembly. Buildings are constructed from a multitude of different components. Most modular systems use only a small number of different modules due to the exponential growth of possible combinations. The act of limiting these to a defined set of geometrical elements and operations is defined as discretization (Retsin 2016).

Simultaneously, the focus on a limited set of operations with unified geometries enables the automation of the tedious assembly process. In recent years, we have seen numerous projects dealing with topics of robotic assembly in architecture (Gramazio et al. 2014). A majority of them deal with the vertical stacking of elements that allow for the building of highly articulated structures. Although these investigations are impressive and novel, they largely focus on geometrical differentiation. Moreover, the assemblies are irreversible due to the use of adhesives or are limited to wall-like assemblies. Ron et al. (2018) suggest a robotic assembly process for a falsework free production of walls and arches.

We propose a modular system coupled with a set of algorithms that enables the construction of detachable modular assemblies. Through a limited number of different modules, a wide variety of geometrical differentiation can be achieved (Tessmann and Rossi 2019).A self-aligning modular system is used to allow differentiation in module size as well as for variation in connectivity. We show the manner in which static considerations can be incorporated through an additional module set to enable the assembly of cantilevered structures (Heisel et al. 2017).Moreover, we show a sequential robotic assembly process that is self-standing without support or additional falsework. The robot can cope with different sizes and types of modules within one assembly process.

2. Method

We developed algorithms that use simple Non-uniform rational B-Splines (NURBS) curves as an input to preposition modular units in space (Fig. 6). The curves, in this case, were created manually and represent simple cantilevering forms, but they could also be extracted from more complex geometric forms. The main modules for this research were not produced on cantilevering structures. They were designed for an exhibition to be constantly reassembled by a robot and later reused for this research. Being made of styrofoam, they are very lightweight while also having enough compressive strength to be carried with a robotic gripper. The modules have a zig-zag form that has several advantages. On one hand, they are self-calibrating in the x-axis as the spikes interlock with the notches. On the other hand, the y-axis of the modular elements is free and allows for continuous movement along the y-axis. In our research, the modules do not interlock with each other, as they were originally designed to do, but stand atop each other with their spikes. The fixation of the modules works with compression only and does not require any mortar or adhesive. The disadvantage of these modules, whether they interlock or not, is that they have limited positions in the x-axis, which are defined by the distance between two spikes. The specifications of the modules provide infinite combinatorial possibilities (Fig. 1). The modules do not have preassigned positions in the assembly. Their exact position is a consideration between their inherent and geometrical properties.

In this research, we focused on cantilevering structures. Cantilevering structures are often realized using falsework during cosntruction. Another way of creating such structures is by exact weight distribution. Upon keeping the center of mass of the cantilevering module above the physical edges of the underlying module, the cantilevering module will stay stable. The maximum overhang that can be created using this technique is half the length of a module. By adding extra weight to the cantilevering module, the center of mass can be moved off-center (Fig. 2). As a result, the module is able to cantilever much further. By stacking several cantilevering modules, the exact distribution of the center of mass for each module becomes more important. In terms of the lever principle, the force needed to create the same moment is proportionally less to the distance to the fulcrum. Therefore, if a weight is placed far away from the fulcrum, it requires much more weight to move the center of mass above the physical edges of the lowest module. We developed an algorithm that calculates the masses needed to keep the modular aggregation in equilibrium.

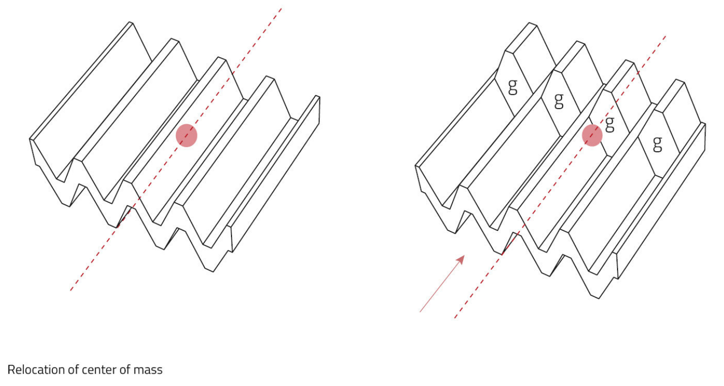

Figure 2. Relocation of the center of mass using heavy weight modules.

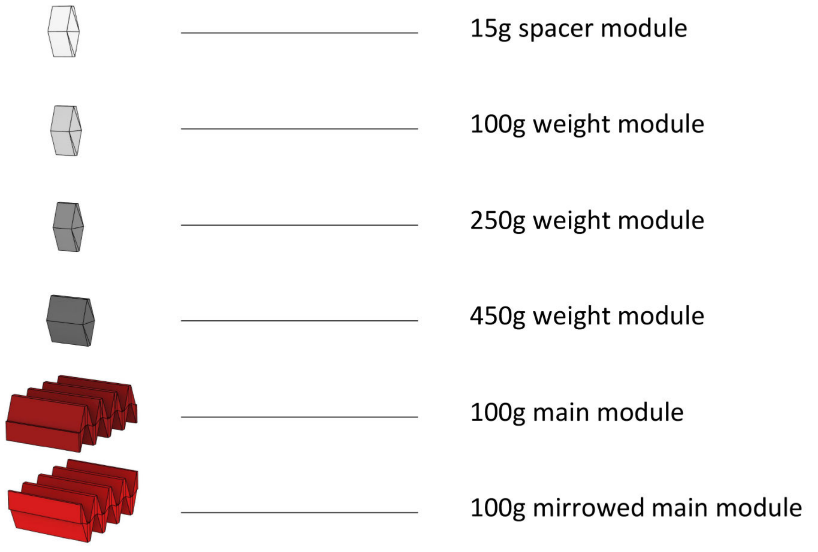

Figure 3. Set of modules and their weight.

To build this structure with a robot, we developed special heavy weight modules that fit into the existing modular system. Similar to the original modules, these also have a free y-axis, which allows us to place them at exact positions along the y-axis. To build this cantilevered structure, differentiated weight modules were produced (Fig. 3).

We obtained different weights with the same volume by filling hollow weight modules with sand. In the lower sections of the aggregation, we needed more weight; therefore, we developed heavy modules that have double the volume of the standard weight modules and weight 450g (Fig. 3).To fit the weight modules into the existing modular system, we flipped the original modules around so that they do not interlock with each other but stand atop each other. The weight modules then fit into the interspaces. The spacer module's purpose is to align the modules when they are stacked by the robot.

Additional weights are required to be installed to keep the aggregation in equilibrium at all steps. By installing weight to the module on top, the center of mass of the module below is moved in the direction of the additional weight. This needs to be considered when calculating the additional weights for the modules beneath.

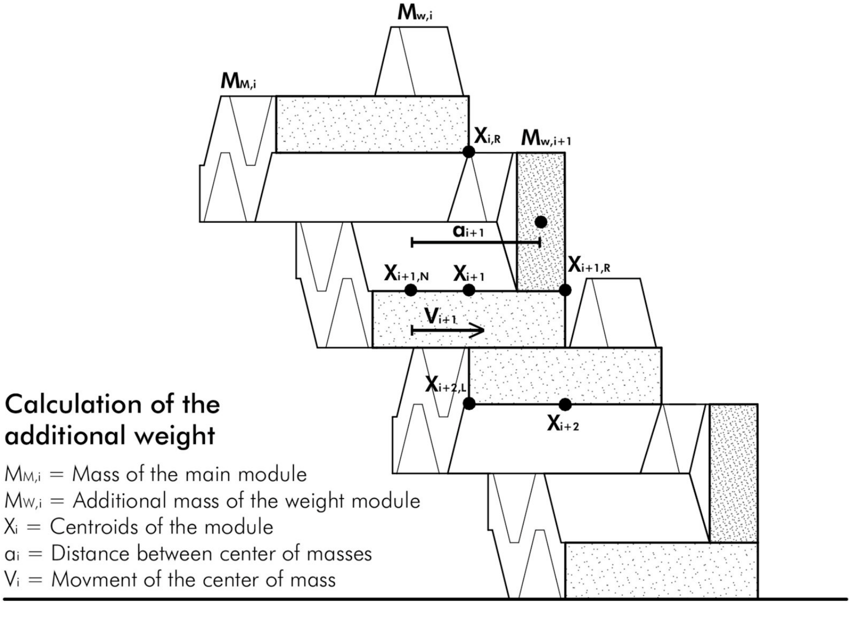

Figure 4. Diagram for the calculation of mass distribution.

To calculate the additional mass Mw,i+1, several other parameters need to be calculated. First, various constants need to be defined. The position of the modules is generated by dividing the input curve into segments with equal height and placing the modules along these segments. Next, the weight as well as length of the modules have to be defined.

With these constants, the shift (Vi+1) of the center of mass of module i+1 (Xi+1,N) can be calculated so that it is beyond the physical edges of module i+2 (Xi+2,L). In the calculation, we introduce a safety tolerance of 10mm. The constants also serve to calculate the distance between the two centroids (ai+1)

Xi+1,N and Mw,i+1. With these two values, the additional mass (Mw,i+1) can be calculated. Using these calculations, every step can be determined for every main module added in the assembly.

In the automated process of building cantilevering structures, the robot picks up the main modules and predefined weight modules at different pickup locations (Fig. 5: 1-6). The order in which the robot picks up the modules is defined by our algorithm. We use the output of the calculation to define the number of different weight modules and integrate the size of the weight modules into the building sequence so that the larger weight modules are beneath smaller weight modules. All the parameters ensure that the assembly is in equilibrium at all steps. The generated assembly sequence leads to the stable construction of the cantilevered construction (Fig. 5: 7). The use of the robot guarantees a high level of precision as even a slight deviation in the placement of a module can lead to the collapse of the system.

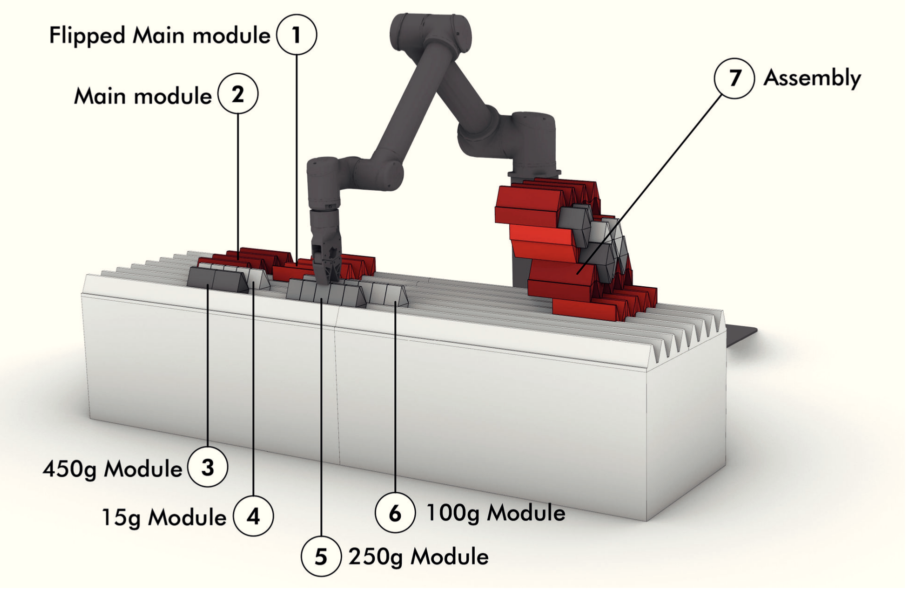

Figure 5. Digital simulation with pick-up locations, robot, and assembly.

3. Results and Discussion

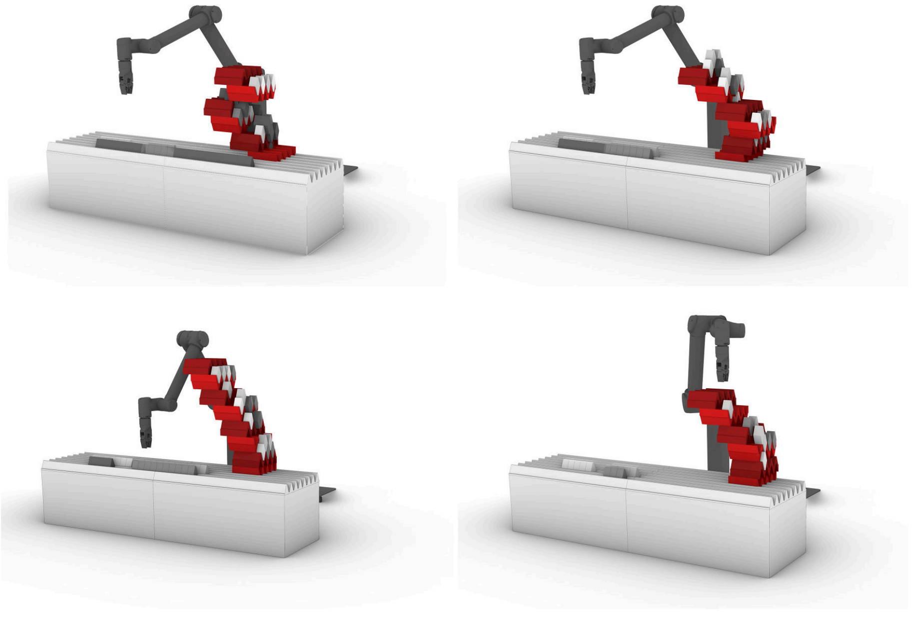

Figure 6. Different input curves were tested.

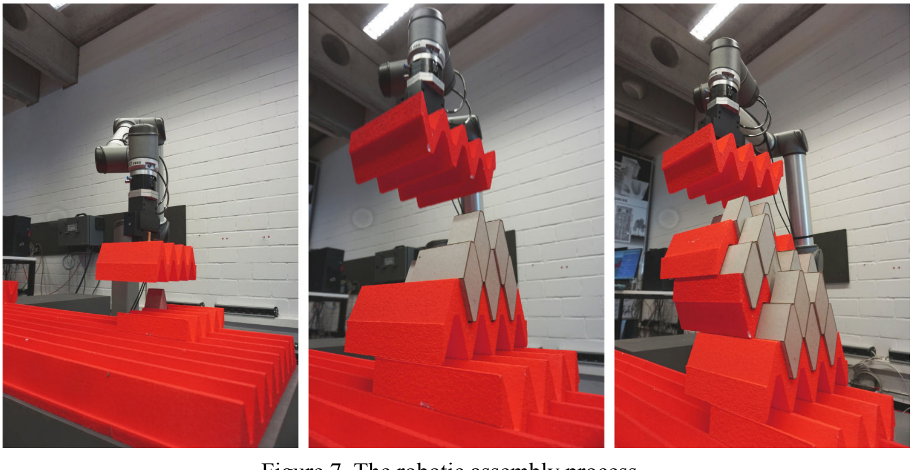

Figure 7. The robotic assembly process.

Our algorithm was able to map the modular elements into different geometries by negotiating the modular properties with the structural needs and availability of modules. We assembled different setups highlighting aspects of the re-assembly of modules (Fig.7). The delicate balance of our approach is exemplified by two demonstrationsions. In the first case, we show that by simply removing a single weight module, the whole structure collapses (Fig. 8). In the second case, we add one extra weight module to stimulate the collapse (Fig. 9).

Currently, our algorithmic implementation is limited to planar curves. Moreover, due to the limitation of robotic workspace and payload, we were able to build only small scale demonstrators.

While our research focuses on the idea of building with modules that can be re-assembled, there have been numerous projects constructed from bespoke elements (Rippmann and Block 2008). Our research focuses instead on the idea of building with modules that can be re-assembled. Approaches such as modular distribution through topology optimization might allow us to shift towards more complex assemblies (Rossi and Tessmann 2017).

Beyond illustrating the precision delivered by the robotic assembly, it also highlights the formalization of the assembly with a set of modules at different pick-up locations and a translation of a design model into robot instructions.

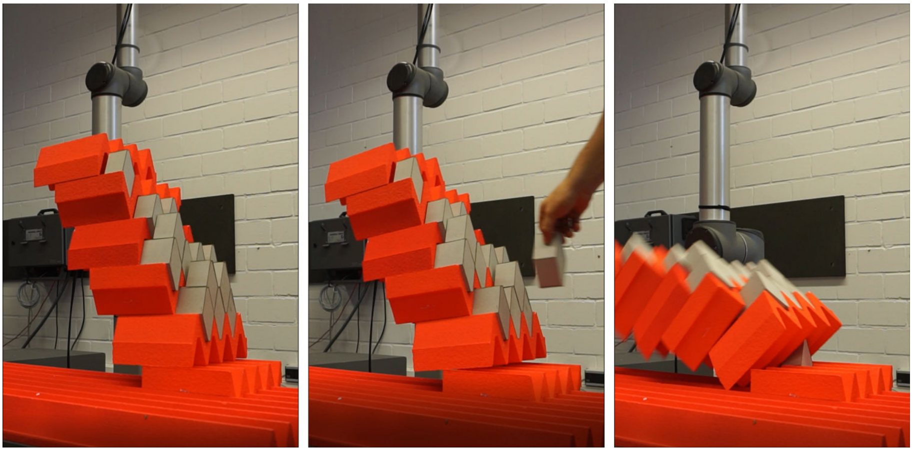

Figure 8. Removing weight from the cantilevering structure.

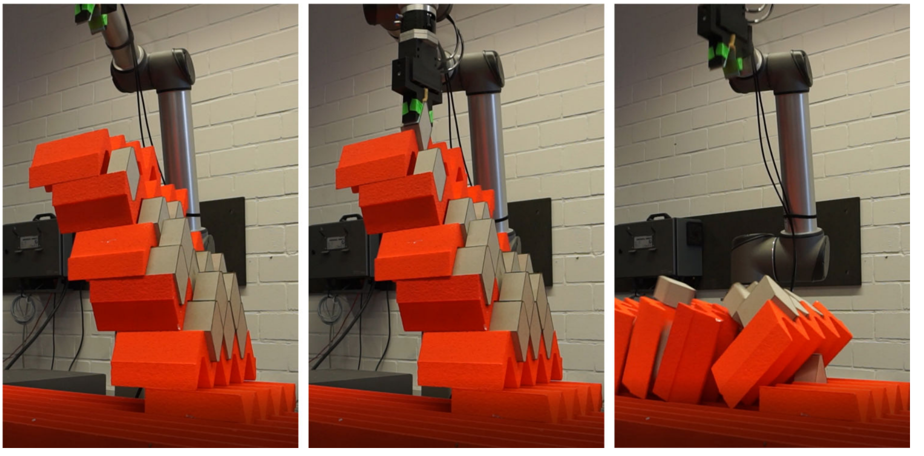

Figure 9. Adding weight to the cantilevering structure.

In future approaches, we would like to build larger structures that can be comprised of one or more cantilevered structures. These could be bridge-like structures that otherwise need falswork to be built. This system can then be scaled up to architectural structures. The combination of the modularity, detachability, and automation of the system will allow for the simple reuse of the elements.

The approach could be used to build temporary structures such as bridges or pavilion-like roofs. Moreover, it can be used as a temporary falsework in scenarios where it is impossible to reach the ground level. The hollow weight modules could be transported to the construction site and filled with local material to achieve the necessary weights. Overarching structures can be built by gradually building the structure from each side until they meet in the middle to form an arch (Fig. 10).

4. Conclusion

Our approach generated complex results with a standardized set of modules. We demonstrated a method to use digitally fabricated modules in building cantilevered structures. This could lead to a new way of using mass-produced modules with dry fit connections and would also open up possibilities for the reuse of modular building components. Instead of relying on falsework, we presented an approach that uses weight distribution to balance all the steps in the assembly process of cantilevering structures. Therefore, the automated translation of a design model into robot instructions for an assembly process was implemented. Our proposal provides the necessary foundation with which to develop future modular systems for the automated discretization of design and fabrication. Providing architects with such a tool to reuse building components and automate the assembly could help reduce costs and carbon emissions.

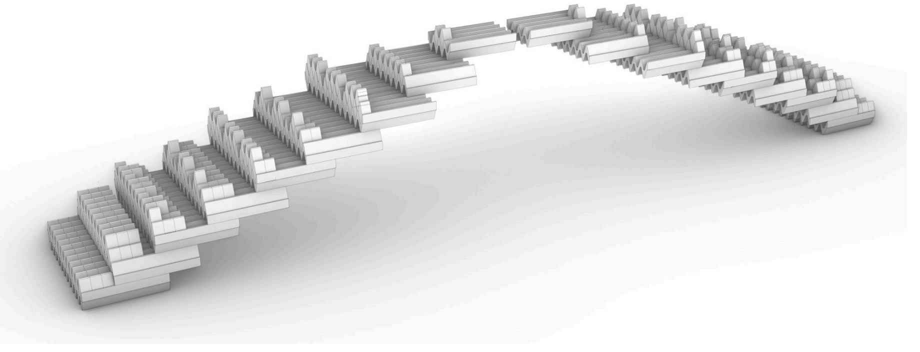

Figure 10. Future approach of a bridging structure.

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DE GRADUS

Programming heterogeneous performance of functionally graded bio-polymers for degradable agricultural shading structures.

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Abstract. This paper presents an holistic approach to the digital design and fabrication of fungi- and algae-based biopolymers, based on studies and simulations of material properties and post-fabrication behavior. The research is motivated by the problem of plastic waste, the need to create more sustainable manufacturing processes, and the opportunity for material composition and organization to be informed by performance, leading to homogenous, complex and integral architectural elements for temporary architecture of agricultural shading systems. The paper details design and specification methods for functionally graded biopolymer panels, as well as fabrication methods through the making of prototypical built elements. The research details parallel trajectories of: material exploration made out of renewable and biodegradable resources available and abundant in every habitat on the earth; advancement in tools and methods for in-situ robotic additive manufacturing of viscous bio-polymers; development of the strategy for functional grading of the material properties to optimize site specificity and material distribution, and to reduce building material waste. It presents comparative material characterizations, an integrated simulation-based approach to support the process of programming localized performance, and architectural application tested via full-scale prototypes.

Keywords. Functionally graded material; bio-polymer; programmable matter; robotic farbication; multiscale modeling.

1. Introduction

Architecture and building materials are often assumed to be everlasting, while temporary architecture is most often associated with ease of disassembly and transportation - the use of prefabricated and standardized modular components determines the principles of architectural design. Prefabricated elements are built off-site and assembled on-site. Materials and architectural components intend to be disassembled and reused, following the circular economy and sustainable concept of the closed life cycle. Nonetheless, waste management is a large concern

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 385-394.

in the construction industry. The United States generates 160 million tons of construction and demolition waste annually, where demolition was responsible for 90% of the total waste in the year 2000 (Cruz Rios, 2018). Furthermore, building construction and manufacturing industry consume 40% of the total amount of raw materials needed in the global economy (Akbiyikli et al, 2012). And those materials such as sand and minerals are finite. Moreover, the industry is accounted for 36% of global final energy use and represents the largest share of total global energy-related carbon dioxide emissions, which in 2017 achieved nearly 40% (IEA/UNEP, 2018). The implications of this contemporary practice challenge architects and engineers to rethink their approach to materials, design and fabrication processes.

Modern human-made structures are inefficient when compared to nature, which creates complex, dynamic structures, with functionally graded material properties, able to adapt to changes in environment and reuse the biomass. Mass production and industrial automation contributed to generalization of the architectural elements and compartmentalization of form-making as a process independent of its sources in material knowledge. The complexity of biological organisms is based on matter and it results in multi-functionality of the body, having structural hierarchies and customized dynamic functionalities (Keating, 2016). The gradient of material properties allows complex functionality and benefits, such as the improvement of the weight vs bending strength ratio generated by the radial density in bones (Michalatos and Payne, 2013). With current computational design tools and possibility of use new technologies in fabrication, architects and engineers are able to advance complex structures and material optimization.

Functionally graded materials (FGM) are a relatively new generation of materials characterized by gradient variation of micro-structure and mechanical properties - according to prefixed requirements. They consist of two or more constituent phases with a continuously variable composition creating properties that change spatially within the structure, for instance in order to design components optimized for specific applications (Maalawi, 2018). Human-made FGM was first introduced in 1984 in Japan during the Spaceplane project in order to develop a thermal barrier capable of withstanding surface of high temperature gradients.

An environmental crisis and a problem of white pollution encourage numerous investigations focusing on novel, sustainable materials such as bio-polymers - an alternative for non-bio-degradable plastics based on fossil raw materials. Polysaccharides, proteins and lipids are degradable polymers from renewable, cheap available, bio-compatible and environmentally friendly ingredients - these include recently extensively investigated: cellulose, starch, chitosan, seaweed such as alginate, carrageenan, agar (Abdul Khalil et al., 2016). **Bio-polymers (BP)** can be reproduced anywhere without special facilities.

2. Background

In 2011 researchers at Harvard's Wyss Institute have developed *Shrilk*- **chitosan-based bio-polymer (CBBP)** isolated from shrimp, which exhibits the strength of an aluminum alloy, being at the same time twice lighter (Fernandez and Ingber, 2011). Chitin is a BP which occurs naturally as a major component in the skeletal or exoskeletal structures of lower animals, arthropods and fungi. It has structure similar to cellulose, however, it provides more rigidity to the structures. (Fernandez et al., 2014) have advanced a method to fabricate 3D objects out of this BP, with complex shapes using traditional casting or injection molding manufacturing techniques.

The fabrication method of crustacean-derived BP was further explored by MIT Media lab, which has developed a water-based additive manufacturing process of crustacean-derived CBBP (Mogas-Soldevila et al., 2014). Robotic fabrication based on the extrusion system allowed to produce large-scale 3D objects omitting the need of molds. Composites were premixed and extruded or mixed statically at the nozzle on-the-fly, achieving a wide range of material composition and enabling the deposition of functional material gradients. Extruded artifacts were homogeneous in form, but various proportions of the material components gave different material properties, which shaped the leaves resembling objects.

3. Aims and goals

3.1. CONCEPT OF BIO-DEGRADABLE SHELTER

If the life cycle of the products begins with the biodegradable materials, one doesn't need to concern about potential recycling - moreover, the matter of the objects could be recycled - not by saving the materials, but by commanding the objects to decompose into programmable particles or components that then can be reused to form new objects and perform new functions.

One of the significant contributor of the plastic waste production is an agricultural sector. Although it has minor contribution to the total plastic waste production (5%), it is recognized as a sector significantly able to commit to the plastic waste reduction (De Lucia and Pazienza, 2019). The plastic membranes are used to cover the soil for purposes of weed suppression, temperature enhancement, fertilizer uptake and more. This phenomenon has been defined as a "plasticulture" (Xiong et al., 2019). The long-term residue of plastic mulch in the farmland destroys the structure of the soil, causing the decline of the farmland quality. Moreover, the plastic residues turning into micro-plastics through the natural environmental degradation (Xiong et al., 2019). New bio-polymeric materials offer an alternative perspective: that of structures and systems that are programmed to disappear. Within an agricultural context, this implies structural life-cycles that after the seasonal use return to nature and enrich the soil, to grow the raw resources and use them again as a building material, and necessitates new design and fabrication perspectives that integrate structure, daylighting and color, and which can create localized and sustainable in-situ manufacturing processes.

3.2. SUSTAINABLE DESIGN TO FABRICATION PROCESS

The primary goal of the research employed an integration of the design process from the ground-up by synthesizing material creation, digital modeling, robotic fabrication and assembly in a holistic approach - based on the structural and optical demand of the agricultural shelter. Within this framework, several sub-questions have been investigated. Material-based design approach attempts to create a material which would degrade and through that - be beneficial for the farmland soil and agriculture. Likewise, this gives an opportunity to begin the process from the raw resources and make the bespoke design and construction process easy and affordable to everyone. On the other hand, this investigation undertakes a probe of decrease the overuse of material resources by the building construction sector and tests an approach of informing the digital model by the material properties data to build with minimal material and maximum performance. In this way it obtains construction and assemble of the architectural parts in the most possible sustainable process, which includes use of the local raw materials and in-situ fabrication.

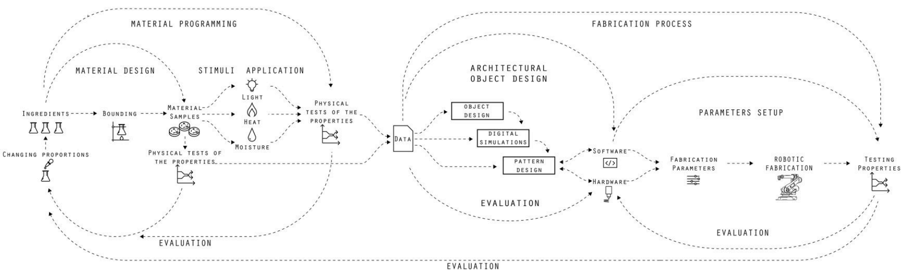

Figure 1. Workflow of the design to fabrication process integrates material design and its behavior, digital model, hardware and fabrication logic.

4. Methods

The key challenge of this investigation was to integrate the material composition and behavior, digital modeling, hardware tool with fabrication in the way that the form generation is driven by maximal performance with minimal resources through local material property variation. To obtain that, a multi-scale modeling approach was introduced. The design problem is decomposed into distinct but interdependent models according to scales and data is transferred between these models (Nicholas et al., 2015). It contains of three scales: micro, meso and macro, which are responsible for material design, pattern design and architectural design.

The investigation was based on parallel trajectories of : material exploration made out of renewable and biodegradable resources available and abundant in every habitat on earth; advancement in tools and methods for in-situ robotic additive manufacturing of BP; development of the strategy for functional grading of the material properties to optimize the material distribution and reduce the building material waste. Following this constraints, methodology of this research was based on the circular design workflow, where each phase informs another, which was a consequence of the ambition to connect an empirical material design with a formal architectural approach.

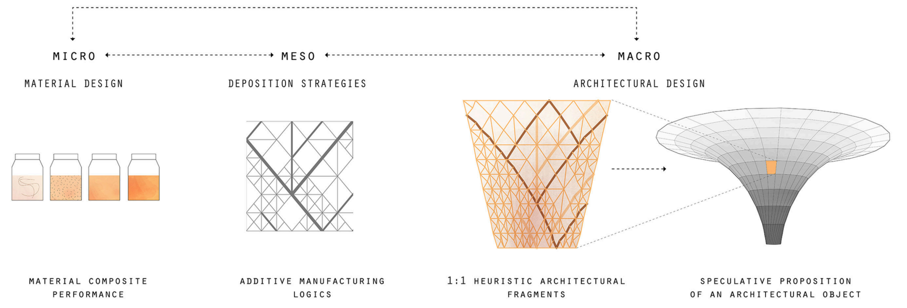

Figure 2. Scales of an architectural exploration incorporate material design (micro scale), deposition strategy within a pattern (meso scale) and architectural design (macro scale). .

4.1. MATERIAL COMPOSITION

The research was initiated by an empirical experimentation of the material search. Compounds of the base ingredients: fungal chitosan, seaweed derivatives agar-agar and sodium alginate were mixed with water, acetic acid and other additives like glycerin, olive oil, in various proportions.

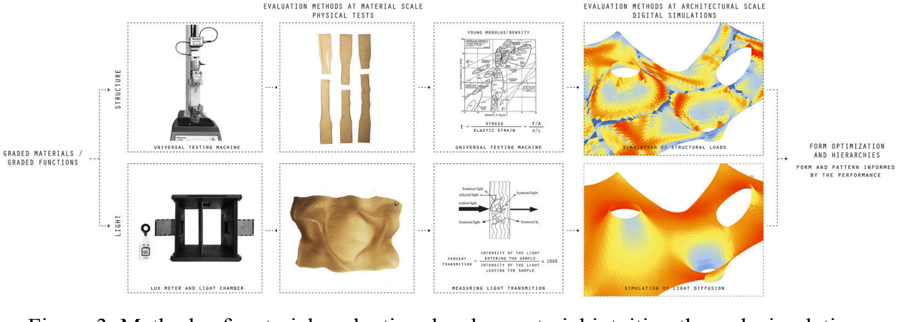

Figure 3. Methods of material evaluation develop material intuition through simulation.

Changing the proportions of these constituent ingredients results in a diverse property of the material samples, which varies on few levels: elasticity, stiffness, mechanical strength, flection, tension, transparency, density, color, transparency, strength and flexibility. Due to certain requirements of the architectural proposal, only color, transparency, tensile strength and elasticity were taken into consideration in this investigation. The material samples were tested using a universal testing machine to test the tensile strength and elongation. The best results show probe which consist of 12% chitosan with a thickness 0.02 mm, engineering stress σ= 19.2 GPa, maximum force Fn=21.3 N and Young Modulus

E=5.1 GPa, however elongation of the sample achieved only 2%. Adding 5% glycerin to the mixture improves ductility of the material to E=22%, at the same time reducing significantly tensile strength. The transparency was tested in the light chamber with a lux meter. The emission of the light through samples varies from 67 lux (9% chitin, 5% glycerin) to 1120 lux (15% chitin, 2% sodium alginate, 2% olive oil) with a light in chamber 1170 lux.

4.2. COMPUTATIONAL FRAMEWORK OF PROGRAMMABLE PERFORMANCE

FGM are those whose properties can be adjusted accurately and continuously and tailored to their particular use. The aim of this research was to create a system that gradually varies its functionality by varying the properties to achieve: an optimization of the structural performance of a tensile structure, decrease the solar radiation and gradation of the color of the material depending on the high of the structure. The gradient of transparent on the bottom, through yellow and red on the highest position on the structure, was determined by agricultural purpose of the membrane, where red is considered as a color which attracts insects. The structural and visual characterizations of the material grading were informed by the tests of the samples with various proportions of the components. Therefore, the project develops through an iterative cycle of physical and digital prototyping. The gradation of the material properties - rigid and pliable, transparent and solid or colorful, heavy and lightweight - is possible by combining the components with a particular property in various proportions. The variability of the material distribution aims to create a complex, multifunctional body.

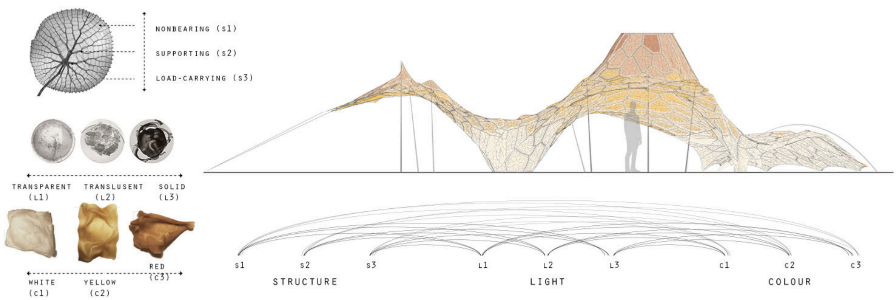

Figure 4. Left: The key parameters for a material distribution: Structure, Light and Colour. Right: Visualisation of a digital model with generated data about material distribution.

The global shape of the architectural membrane was form-found using a physics engine in mind to be reminiscent of typical membranes used on farmlands. The membrane was divided into the elements to simplify the assembling process, which were further generated by clustering the mesh points using the k-mean method, which relies on a simple machine learning algorithm. The learning input included position of the elements and direction of the mesh normals. The elements were further partitioned using aforementioned algorithm and their edges were subsequently relaxed and developed into specified pattern of customized panels for the sake of fabrication and assemblage. The functionality of the materials implemented in the system was investigated in two main directions: structure and light. Therefore, the structural performance of the global form, as well as solar radiation on a specific site, were computationally simulated.

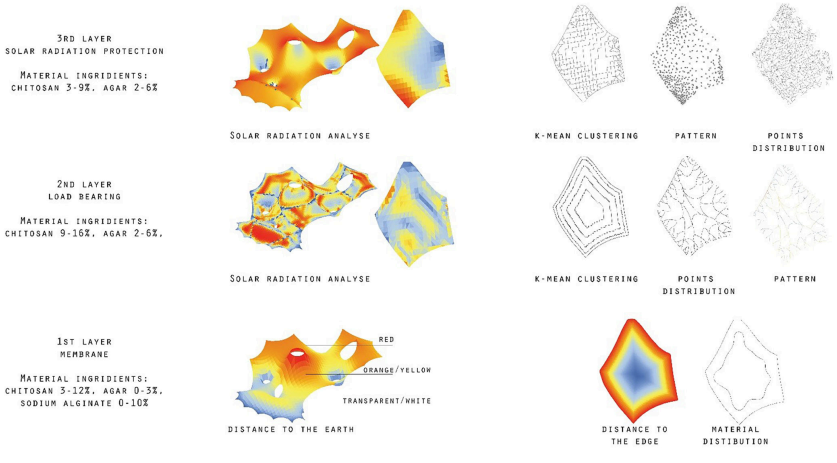

Figure 5. Digital model informed by the data of the material results and simulation of structural performance, solar radiation and distance to the ground as a base for pattern generation of material deposition.

Grading of the materials was obtained by generating distinct layers for specific functions. Thus, three layers of customized patterns were generated for each panel. The first layer acts as a membrane and it is specified by the distance to the ground. Therefore, the upper panels of the structure are red (in order to attract insects) and the closer to the ground, the more yellow, white and transparent the material becomes. The material grading on this level was achieved on the macro scale by creating one material composition per one panel. The composition was adjusted by changing the components: agar-agar, chitosan and sodium alginate in order to reach desired color and transparency. Additionally, the area of the edges contains more glycerin, which makes the material flexible in order to enable sewing to assemble the panels together. Next layer consists of load-bearing pattern, informed by the simulation of the structural behavior of the membrane. Points on the mesh of the panels were grouped by the k-mean clustering method by the distance to edges and structural behavior. On this base, a branching pattern with varying width was generated. Parallel to the visual pattern, the database which informs the robot about material composition was created. This varies based on the computational simulation results and the physical tests of material samples. The chitosan differs between ratio 9-16 % and agar-agar 2-6%. The higher the ratio of both ingredients is, the stronger and heavier is the pattern. The final pattern is responsible for the solar radiation protection. Therefore, the pattern of this layer was created by grouping areas of similar radiation results of the computational simulation. For each of the areas random points were generated with various density and connected it with the shortest path. In this way the created pattern was denser for the areas with the highest radiation results. As in the previous layers, parallel to the pattern generation, the data for fabrication process were created. This varies in ratio of chitosan, agar and sodium alginate based on the distance of the panel to the ground and density of the pattern. Material should vary from transparent on the ground and orange and red the higher the panel is position and the denser is the pattern.

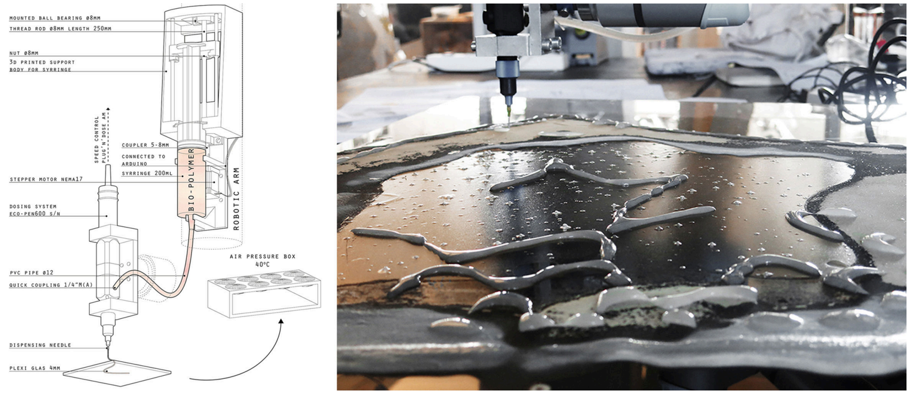

Figure 6. Fabrication tool for robotic deposition of bio-polymers.

4.3. FABRICATION

The project employs an additive manufacturing (3D printing) as a method of fabrication of liquid BP, by extruding the paste of the BP composition via robotically controlled system. This method was chosen because of its sustainability approach - it allows for an in-situ fabrication and no need of use of additional molds. The system of fabrication process consists of a 6-axis Robot arm UR5-e with a working radius of 850 mm and maximum payload up to 5 kg, dosing dispenser eco-PEN600 with a speed control plug'n'dose (ViscoTec), and a custom-made extrusion system (see figure 6). The set-up of the hardware was based on research of Dritsas et al. (2018), who explored a manufacturing process deploying natural composite materials, where the objection of the project was in the concurrent design and developments of the material along with the manufacturing process. To determine gradient in material deposition, following aspects were investigated: material composition and concentration, pressure variation, which results in continuously varying material accumulation and layering, which provides higher degree reinforcement rather than one-layered surface. Working with the multiple material properties of functionally graded structures, requires adjustable deposition setups. Because of multiple material compositions with various properties, refining the deposition set up - inter alia flow control, speed and pressure needed to be considered. This was solved by testing chosen material compositions and applying an adjustable flow configuration to each material, which was informed by the material analyses and real-time tests of the deposition. The intermolecular attractions of the particles in the wet water-base material allow to create a continuous graded system of heterogeneous performance, which would not be able to achieve using other fabrication methods. The viscosity of the materials allows also for total self-bonding and self-repair of layers in the print. The fabrication process of creating a material from the ground up and deposition in a viscous state required properly controlled environment and process setup in terms of production. Due to the viscosity of the material, after extruding each layer, the following panels needed to be cured in an air-pressure box under 40 Celsius degree to obtain quasi-solid state. The wet depositions of the BP are under internal directional evaporation stresses, while drying. This means it is very important to control the environment of the extruded artifacts while the evaporation process.

Figure 7. First generation of robotically fabricated panels and mock-up for assembly test. .

5. Conclusion

The contemporary architectural workflow includes a stark division between design, performance parameters, and fabrication techniques. Most of the designs are iterated using CAD technologies, without reference to scale, performance, or material, neither thinking about the ecology of the design nor fabrication process. This paper has presented a conceptual and methodological framework of material-based, large-scale design to fabrication process implementing customized BP design for the real-world application of the temporary membranes with circular life cycle in the form of seasonal agricultural shading system. It shows a strategy of rethinking materials and fabrication methods in the development of new fabrication and design tools in a sustainable approach. Driven by novel biodegradable bio-materials, this research showed a new structural design perspective, combining mushroom- and algae-derived BP, which create a sustainable manufacturing process from the material selection to the fabrication and post-fabrication use. The material design and organization were informed by the structural performance of the plastic film, creating homogeneous and complex architectural elements for temporary architecture of shading system, which degrades in soil and in water after the seasonal use and improves the quality of the soil. An early integration of performance parameters and fabrication methods into a threaded workflow, may produce an integrated design process resulting in designs which embody their performative constraints and fabrication procedures. In this way research investigates a multiscalar modeling, connecting empirical material design with a formal architectural approach.

Acknowledgements

This paper presents research development of the master thesis by Joanna Maria Lesna supervised by Prof. Paul Nicholas. The authors would like to thank Prof. Martin Tamke and Ayoub Lharchi for their assistance in setting up robotic arm. This work was supported in part by funding allotted to J. M. Lesna by the Boligonden Kuben.

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A NEW ALGORITHM TO GET OPTIMIZED TARGET PLANE ON 6-AXIS ROBOT FOR FABRICATION

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Abstract. In usual robotic fabrication by 6 axis industrial robot such as KUKA ,ABB and other brands ,the usual robot's 4th ,5th and 6th axis is exactly converge in one point .When this type robot (pieper) is doing movement commands ,setting the degree of 4th axis close to zero is an ideal condition for motion stability ,especially for putting device which connect to tool head on 4th axis arm part.In plastic melting or others print which not cares the rotation angle about the printing direction(the printing direction means the effector's output normal direction vector, KUKA is X axis,ABB is Z axis) ,the optimization of 4th axis technology not only makes printing stable but also makes better quality for printing.The paper introduces a new algorithm to get the analytics solution.The algorithm is clear explained by mathematics and geometry ways. At the end of paper, a grasshopper custom plugin is provided ,which contains this new algorithm ,with this plugin, people can get the optimized target path plane more easily.

Keywords. 3D printing; brick fabrication; robotic; optimization algorithm; grasshopper plugin.

1. Introduction

In robotic fabrication, it is not sensitive to rotation around the nozzle's normal, such as plastic layer printing, spatial structure printing, and even brickwork. As long as the vector v of the nozzle of the tool head is kept constant, change the rotational angle around v (under the premise of not causing a robot collision), there will be no difference in the printing result. If you further adjust it, you will find an optimal angle which makes the printing result and the robot motion both get better.In practice, it is found that the radial coordinate plane Fig. 1 is better.For example, the movement of robot with default target planes Fig. 2 is different with radial target planes Fig. 3(in this article We will use KUKA's KR6 R900 for introduction, the corresponding software is Rhino + Grasshopper + FUROBOT).In plane printing, the direction of the nozzle of the tool head is usually the normal direction of the curved surface. This radial printing plane is very simple. It only needs to use the robot's root coordinate XY value as the center point to connect each target point. You can generate the Z-axis vector, combining the known X-axis

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direction (that is, the direction of the nozzle of the tool head), and then multiplying the Z-axis by X, we can get the Y-axis direction. With X, Y, and Z 3 basis Vector, we can generate a coordinate plane Fig.1.Not only is the printing result better than the default coordinate system, but also the rotation of the joints will be improved for the robot.Compared with Fig.3, this 4th part rotates more distorted, and it will be clearer from the perspective of the angle value graph: When printing the default target coordinate system plane, the rotation angles of the 4th, 5th, and 6th axis of Fig.4 are significantly larger than the radial target Fig.5 of coordinate system plane, especially 4th axis and 6th axis.

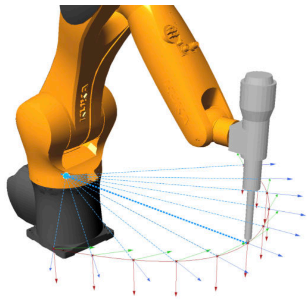

Figure 1. Radial target plane.

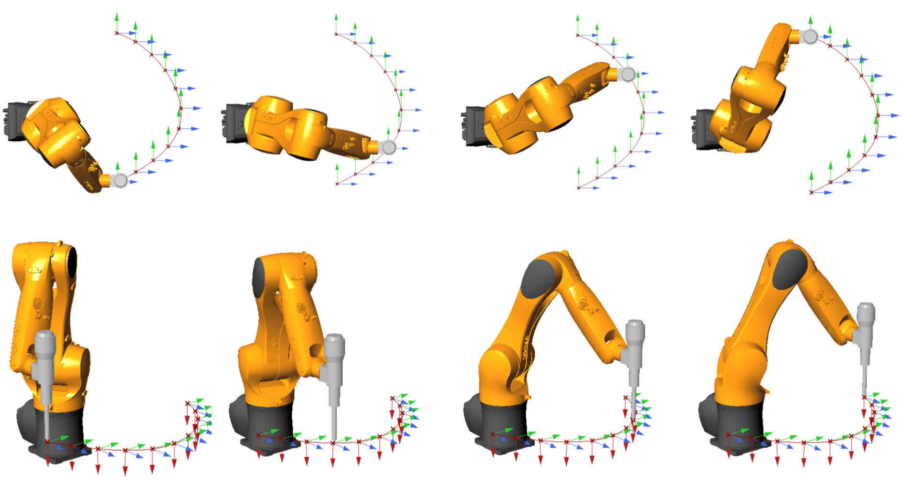

Figure 2. default target plane.

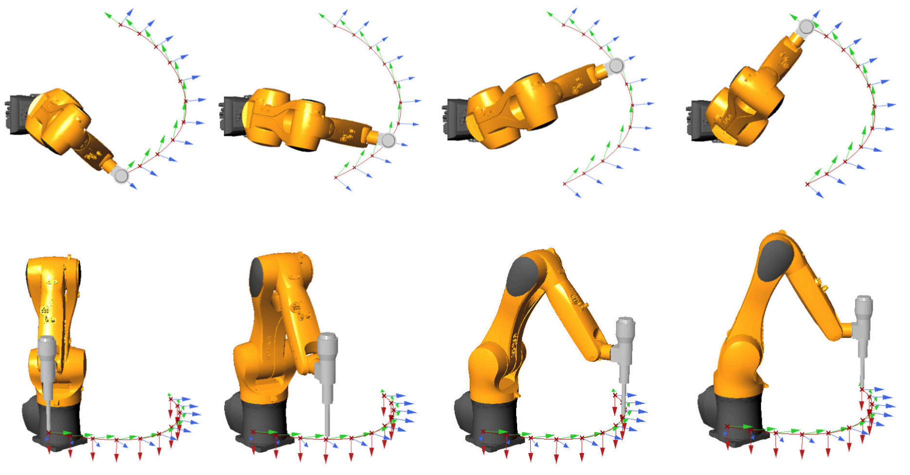

Figure 3. radial target plane.

The smaller the angle of the robot in printing, the smoother the printing, and the better the print quality. Sometimes, some tool head equipment is bound to the elbow joint of the robot. At this time, reducing the rotation amplitude of 4th-6th axis will reduce the shaking accordingly. In practice, it is found that in the radial situation, the 4th axis of Fig.5 becomes 0, and the changes of the 5th axis and 6th axis will also decrease. So we intend to minimize the value of the 4th axis as a method to optimize the print target plane.

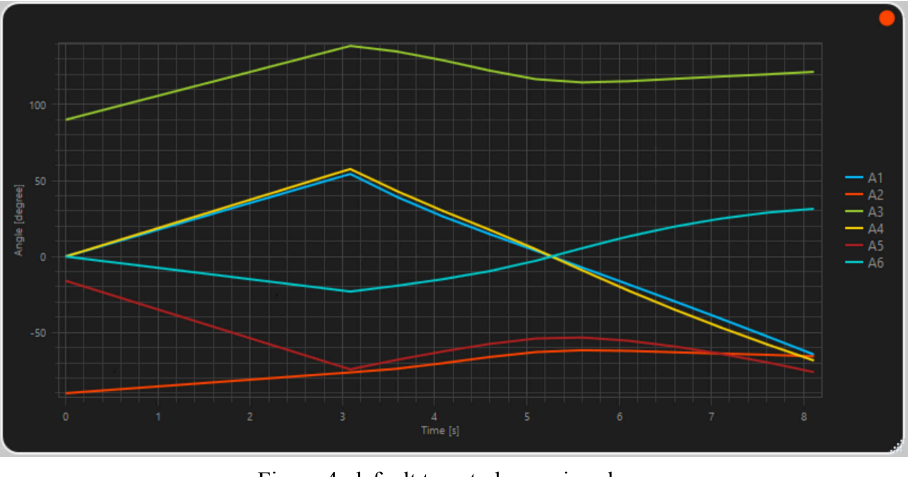

Figure 4. default target plane axis value.

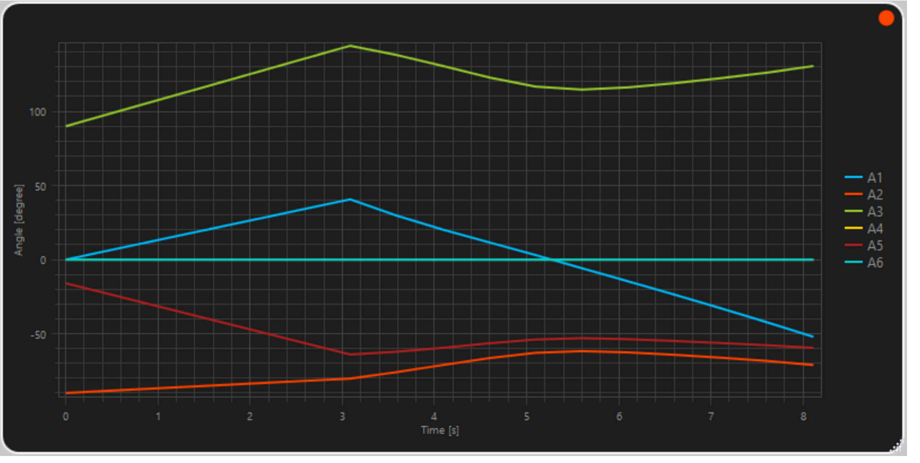

Figure 5. radial target plane axis value.

Figure 6. equipment on robot.

2. Surface case

Now let's take a look at the more general surface printing Fig.7. In the case of surfaces, we choose a better radial target based on intuition. Similar to the plane algorithm, we only ensure that the XY components of the Z-axis vectors of all target planes converge at one point of the root coordinate. The reason for this is because the X-axis direction of each target plane (that is, the normal direction of the surface) is not the same. Looking at all the target planes from the TOP view, all the Z-axis vectors seem to be converged to the root coordinates of the robot as in the case of planes. But these Z axes are not horizontal. The axis angle diagram obtained by this plane-like algorithm is Fig.8. Unfortunately, it can be seen from this figure that the 4th axis is not 0.Our goal is to make the 4th axis zero. At the same time, the constraint is to keep the direction and starting point of the X axis unchanged, so this coordinate system has only one degree of freedom left, that is, arbitrary rotation around the X axis. As long as we can find this angle, it is possible to make the 4th axis zero.

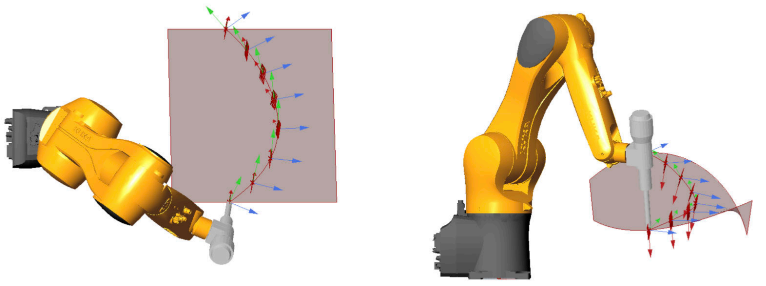

Figure 7. radial target plane in surface.

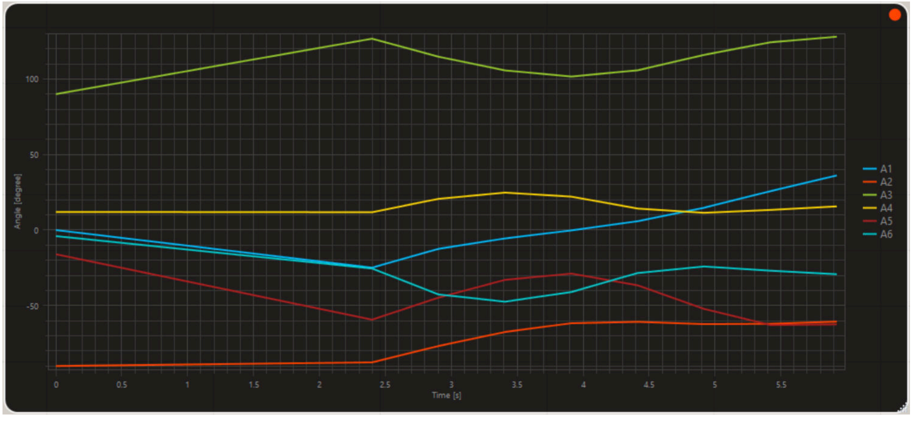

Figure 8. radial target plane in surface axis value.

2.1. GENETIC ALGORITHM

The most intuitive way is to iterate this angle variable to find the optimal solution, so that the absolute value of 4th-axis is the smallest or 0. The using of genetic algorithm component of grasshopper “galapagos” to solve this problem is a direct choice (Rutten 2011). Select the angle of rotation around the nozzle direction vector as the iterative variable. Let this variable be θ Fig.9. In this example, we find a certain value of θ, which makes 4th axis angle become 0 Fig.10.Iterative calculations need to be performed point by point. In this example, we have only 8 points and need to repeat the same iteration task 8 times. However, in actual printing, we may have tens of thousands of points. Using genetic algorithms may take a long time and cannot guarantee accuracy. Therefore, this method cannot be used effectively and can only be used as a means to verify the analytical solution algorithm.

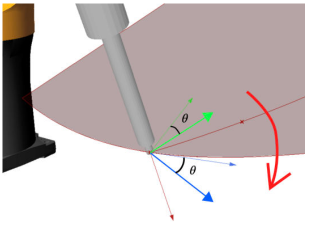

Figure 9. define angle value.

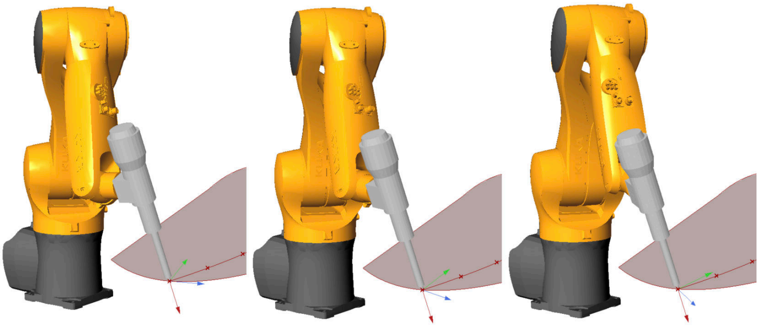

Figure 10. find a angle to make 4th axis angle=0°.

2.2. ANALYTICAL SOLUTION

Our ultimate goal is to find an analytical solution to improve the efficiency and accuracy of the solution(Strang 2009 ; Craig 2017 ; Spong et al. 2005).

According to the surface, we have obtained the normal vectors of each target point on the curve, and then unitize these normal vectors.Then we need to construct an initial target plane by ourselves. This target plane consists of three vectors XYZ and an origin. The X axis of this target plane is known as the surface normal vector $T_x = (x_1, y_1, z_1)^T$ and original point $p = (x, y, z)^T$.

We assume that the Z-axis direction of the target plane is $T_z = (1, 0, z_3)^T$.The benefit of this design is: from the Top view, let this vector be parallel to the X axis of the world coordinate system. This direction can be set arbitrarily, it can be parallel to the Y axis or any direction, it depends on your habits. Generally speaking, choosing the X axis is more in line with the habits.

What needs to be determined now is the value of z_3 component of T_z.Because this coordinate system is an orthogonal coordinate system, the x basis vector is perpendicular to the z basis vector, that is:

$$T_x \cdot T_z = 0 \tag{1}$$

Expand to get:

$$x_1 \cdot 1 + y_1 \cdot 0 + z_1 \cdot z_3 = 0 \tag{2}$$

Get:

$$z_3 = -\frac{x_1}{z_1} \tag{3}$$

Get T_z:

$$\left(1, 0, -\frac{x_1}{z_1}\right)^T \tag{4}$$

So the length of T_z can be calculated as L.

Normalize the T_z,make it become unit vector:

$$\left(\frac{1}{L}, 0, -\frac{x_1}{z_1 L}\right)^T \tag{5}$$

Since the Y-axis vector can be obtained by the Z-axis cross product the X-axis:

$$T_y = T_z \times T_x = \left(\frac{x_1 y_1}{z_1 L}, -\frac{z_1}{L} - \frac{x_1^2}{z_1 L}, \frac{y_1}{L}\right)^T \tag{6}$$

Now we get 3 basis and original point, the initial target plane can be get T^0_{initial}:

$$T^0_{\text{initial}} = \begin{bmatrix} T_x & T_y & T_z & p \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Because the only degree of freedom of the robot is the rotation around the X axis of the target plane, that is, the rotation transformation R_x:

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

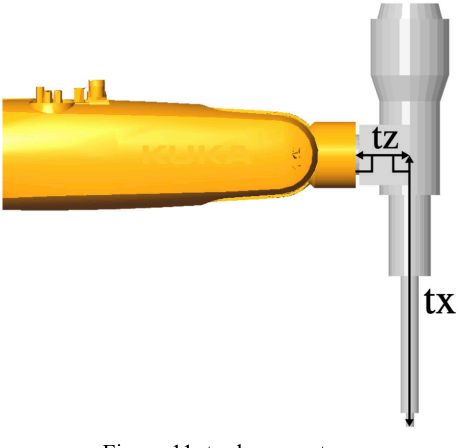

Figure 11. tool parameter.

Before starting to solve, we also need to assume the tool head parameters as shown in Fig.11. This is the most common 3D printing tool head. All the corners are orthogonal. This choice was made because our 3D printing tool heads are all in this form:

Both t_x and t_z are known quantities, we can get the transformation of the tool head relative to the flange $T_{\text{tool}}^{\text{flange}}$:

$$T_{\text{tool}}^{\text{flange}} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

According to the structure of the robotic arm, we can get:

$$T_{\text{initial}}^{0} R_x \left(T_{\text{tool}}^{\text{flange}}\right)^{-1} = T_{\text{flange}}^{0} \tag{10}$$

The left side of (10) are known terms, which can be calculated:

$$T_{\text{initial}}^{0} R_x \left(T_{\text{tool}}^{\text{flange}}\right)^{-1} = \begin{bmatrix} x_1 & a_{12} & a_{13} & a_{14} \\ y_1 & a_{22} & a_{23} & a_{24} \\ z_1 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

where:

$$a_{13} = \frac{\cos\theta}{L} - \frac{x_1 y_1 \sin\theta}{L z_1} \tag{12}$$

$$a_{23} = \sin\theta\left(\frac{x_1^2}{L z_1} + \frac{z_1}{L}\right) \tag{13}$$

$$a_{14} = x - t_x x_1 - t_z\left(\frac{\cos\theta}{L} - \frac{x_1 y_1 \sin\theta}{L z_1}\right) \tag{14}$$

$$a_{24} = y - t_x y_1 - t_z \sin\theta\left(\frac{x_1^2}{L z_1} + \frac{z_1}{L}\right) \tag{15}$$

When 4th-axis angle = 0, let's look at the top view of the robotic arm. Fig.12:

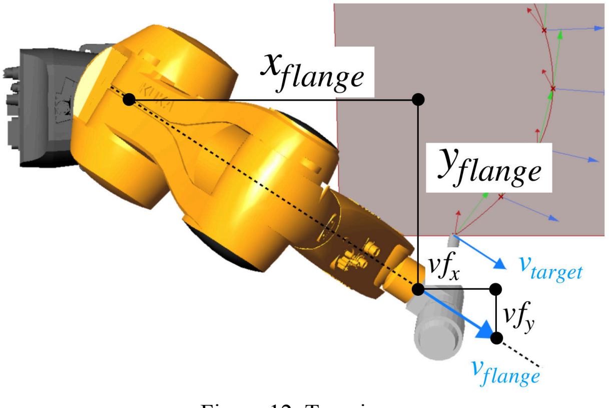

Figure 12. Top view.

$$vf_x = a_{13}, vf_y = a_{23} \tag{16}$$

At the same time x_{flange} and y_{flange} are the coordinates of the origin of the flange coordinates in world coordinates. It is parallel to the dotted line,then:

$$x_{\text{flange}} = a_{14}, y_{\text{flange}} = a_{24} \tag{17}$$

Because v_{flange} is parallel to the dashed line, we get:

$$\frac{vf_x}{vf_y} = \frac{x_{\text{flange}}}{y_{\text{flange}}}, then : \frac{a_{13}}{a_{23}} = \frac{a_{14}}{a_{24}} \tag{18}$$

Substituting the previously calculated $a_{13}, a_{23}, a_{14}, a_{24}$ into (18), (18) is a univariate equation of unknown quantity θ ,calculate to get θ :

$$\theta = \arctan\left(\frac{z_1(y - t_x y_1)}{x_1 y_1 (y - t_x y_1) + (x_1^2 + z_1^2)(x - t_x x_1)}\right) \tag{19}$$

Bring the actual value into (19) and calculate the result, which is same with the result of genetic algorithm.

3. Conclusion

3.1. SUPPLEMENTARY NOTE

The algorithm described in this article is applicable to the result that 4th-axis angle is strictly to zero under the specific tool head. If the tool head is not strictly orthogonal or there is a distance offset, in this case, the 4 axis cannot be strictly zero. After experiments, this method can make the 4th axis value fluctuate around zero(In the case of using an irregular tool head, only the t_x and t_z values of the tool head are retained, and the others are 0. The result is also better than the default generated target point coordinates), and at the same time, it can produce better stability than the default path, so that the robot can avoid unnecessary axis rotation, so this algorithm can be used for almost all tool heads.

If you are using ABB or other brands of 6-axis (3-axis intersecting pieper) robots, you only need to match the nozzle vector with the axis of the corresponding brand robot, and then orthogonally rotate the TCP according to the matching result. Or just change the coordinate direction.

3.2. GRASSHOPPER PLUGIN

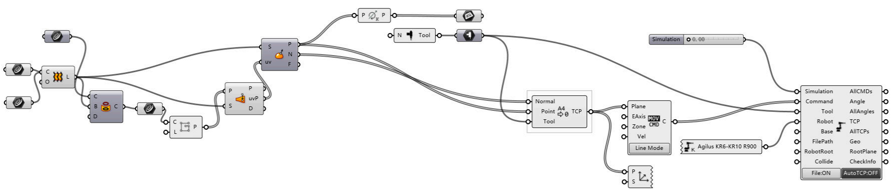

Figure 13. optimization by FUROBOT.

This algorithm consists of two steps.First step, calculate the angle θ. Next step, rotate the initial T^0_{initial} about its X axis (because each robot has a different definition, so it is precisely the axis that is consistent with tool's normal vector)by θ . We have written these two steps into a component called "OptimizeA4axis", which is integrated into the Print Package of FUROBOT . FUROBOT can be download from Food4Rhino.com and it is free for generating offline program and robot simulation. So that users can perform 4th-axis optimization Fig.13 even if they aren't familiar with the algorithm.

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ROBOTIC CONNECTIONS FOR CLT PANELS

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Abstract. In a climate where standard methods of construction are being challenged, developments in engineered timbers are allowing mass timber construction to be explored as a sustainable alternative to current building methods that can change the future of the built environment. Cross-laminated timber (CLT) is at the forefront of this evolution and, with the advancement in computational design and digital fabrication tools, there lies an opportunity to redefine standard construction. This project creates connections inspired by traditional Japanese joinery that have been adapted to be used for the panel construction of CLT structures. Using a combination of digital modelling and advanced digital fabrication, the project utilizes CLT offcuts as a primary connection material. The system not only reduces waste but also mitigates thermal bridging and lowers the number of connection points whilst increasing the ease of building and fabrication. Connection systems are designed and prototyped using a robotic arm and are then evaluated within the context of a building scale and considers large□scale fabrication and on□site assembly whilst continuing to focus on the reduction of waste.

Keywords. Robotics; CLT; Connections; Waste; Timber.

1. INTRODUCTION

With the climate in a state of emergency, the construction industry needs to take responsibility and move towards a more sustainable built environment. Construction is one of the biggest contributors to New Zealand's landfill waste and the most commonly used construction materials, concrete and steel, makeup 9-12% of global greenhouse gas emissions (Branz, n.d.; Green & Taggart, 2017). One way to reduce the effect of the construction industry on the planet is to increase the use of timber. The following research focuses on cross-laminated timber and creates a connection system for CLT panels. Thanks to developments in digital and robotic fabrication, there are now more opportunities than ever to explore connection possibilities. This research uses computer-aided design (CAD) programs to design and simulate connection systems and a 6-axis robotic arm to prototype and test these designs. The connection design uses a combination of influences from existing systems and traditional Japanese joinery to create a timber connection that removes the need for metal fasteners. As the connections are being designed for use in large scale construction, this research also investigates

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existing CLT factory processes and machinery in order to design a system that can be fabricated within existing environments.

2. BACKGROUND

2.1. TIMBER CONSTRUCTION

Timber has been used as a primary construction material all over the world for many years and is said to predate stone construction (Mayo, 2015). Concerns about the overuse of wood and the potential to deplete our forests coupled with minimal understanding of its structural capacities and properties have restricted the use of timber to small-scale buildings (Organschi, 2014).

The benefits of timber speak for themselves; it is locally available, has a low weight and low thermal conductivity, is a sustainable form of solar energy, is an energy source and is a universal construction material (Jeska & Pascha, 2015; Wegener, 2011). Wood is the only commonly-used resource that does not use primary energy throughout its formative stages, meaning less CO2 emissions, whilst also requiring no interference as it is completely self-sufficient (Steurer, 2006). Waugh, (2014 pg 27) wrote, “The more timber we use, the better it is for the environment.”

2.2. CROSS LAMINATED TIMBER

Cross-laminated timber is at the forefront of developments in mass timber construction and has become the material of choice for many projects. CLT is made up of layers of glued timber lamellas laid at 90 degrees to each other and compressed to form a structural panel. The crossing of the boards provides relatively high strength in both directions which produces a high axial load capacity and high shear strength along with good thermal, acoustic and fire performance thanks to the solid nature of the panels (Taylor, 2013).

CLT makes use of small, low-grade pieces of timber that would otherwise be waste and is faster, easier and safer to erect on site (Wood Solutions, 2012). It also uses far less CO2 throughout production and construction than the more commonly used concrete and steel. Though the benefits are many, a key concern within the CLT construction industry is the panel connections. Ringhofer, Brandner, & Blaß (2018, pg 850) wrote, “CLT is in the process of catching up two very important steps: standardization and development of optimised connection type; the latter area still offers a lot of room for further developments and improvements.”

2.3. CONSTRUCTION WASTE

Waste related to the construction industry is commonly thought to be one of the largest contributors to landfills internationally. It is often stated that construction and demolition waste makes up 17% of total landfill in New Zealand (Storey, Gjerde, Charleson, & Pedersen Zari, 2005). In reality, construction and demolition waste could account for up to 50 % of all waste in New Zealand, with 20% of this is landfill and 80% in clean fill (Branz, n.d.). Tam, Tam, Zeng, & Ng (2007, pg 3642) wrote, “Construction waste is defined as the by-product generated and removed from construction, renovation and demolition workplaces or site of building and civil engineering structure". These waste items come from many material sources such as wood, concrete, steel, brick, plasterboard, glass, plastics and more, however, it is estimated that concrete, plasterboard, and timber make up 81% of all construction and demolition waste (Inglis, 2007). A study conducted by John & Itodo (2013) identified that material wastage contributes an average of 21-30% to the cost overrun on a project and therefore any effort to minimise waste would be beneficial.

2.4. DIGITAL FABRICATION

The 20th century saw construction adopt industrial manufacturing processes which allowed for the prefabrication of building elements and standardised housing. The beginning of the 21st century is seeing another change in the way we build - one that is led by digital fabrication and robotics (Bock & Langenberg, 2014). Architects have always drawn what could be built or built what could be drawn but with the advent of CAD and digital fabrication, architects can design for the machines and push the capabilities of construction (Kolarevic, 2003). This new 'digital workflow' means that designing and building are no longer separate, they can be seen as one process that allows architects to break old boundaries of form and geometry (Agkathidis, 2010; Kloft, 2010).

For the last 20 years, the timber sector has been at the forefront of digital fabrication in the building industry, commonly using 3 to 5 axis CNC machines so it provides an ideal market for further development (Stehling, Scheurer, & Roulier, 2014). Robotic fabrication provides an opportunity to combine computer-controlled systems with traditional woodworking machines such as rotary blades and milling cutters to reimagine the way in which we use wood (Menges, 2011). Thanks to the efficiency and precision providing by digital manufacturing systems, there is the opportunity to reuse traditional timber connections such as dovetails, pegs and lap joints which have since been replaced by fixing plates and other metal and engineered solutions (Stehling et al., 2014).

3. PROCESS

Using a research through design approach with a focus on iterative prototyping and evaluation allowed for continuous exploration of the question through the design process. The research began with a literature review that identified key issues within the CLT construction process before conducting an evaluation of existing CLT buildings and connection systems in order to create a base for designing an initial connection solution.

Following this, an exploration of initial design ideas and digital fabrication techniques was undertaken. During this time, first stage prototypes were made in order to assess the capabilities of the robot and CNC machine. Throughout this, designs were critically reflected on against case studies, previous designs and defined assessment criteria. This information was used to inform future designs and to select systems to be prototyped and evaluated in detail.

The use of prototyping at this stage allowed for an understanding of machine movement and limitations which influenced the subsequent designs. These designs are further refined following an exploration into factory fabrication which investigates how the designs might be altered to work on a large scale within a real-world environment. By researching fabrication techniques within existing CLT factories the system can be designed to align with processes that are already in place.

4. DESIGN

4.1. DEFINING THE ASSESSMENT CRITERIA

Through the literature review and existing system studies, six areas of concern arose, these became the assessment criteria in which to evaluate any future designs, these are as follows. Aesthetics: the impact the system has on the interior aesthetics of the space. Number of pieces: how many parts are required to use the connection system and how often they are needed. Wastage: how much material is wasted in the process of construction and how much extra material is needed to complete the connection, i.e. extra plasterboard needed to cover connections. Ease of building: in line with the number of pieces, the number of people required to complete the connection, the time it takes to complete and the ease (or simplicity) of the connection to complete. Ease of fabrication: the ease in which the joint and pieces can be fabricated, considers time and simplicity. Thermal Bridge: the potential for thermal bridging through the connections and the size of the bridge.

4.2. DESIGNING A CONNECTION

Given that two of the criteria are the thermal bridge potential and the aesthetic qualities, the first step in the process was to completely remove any metal fasteners as this would have an immediate effect on addressing these criteria. This decision could also reduce the number of pieces required to join the panels as well as having the potential to reduce wastage.

This is where the influence of Japanese joinery comes in. The traditional wood on wood joints provide an ideal base for design exploration as they incorporate principles that can be mimicked and adapted to create a connection for CLT panels. Many of the traditional joints are splicing joints, used to connect pieces of timber to create a longer beam in a single line. There are also traditional connecting joints that were used to connect beams and columns at 90-degree angles. These were designed to connect a single beam and column as opposed to connecting two large panels. Therefore, the first design challenge consisted of finding a way in which these traditional, and very successful, joints and techniques could be applied to panel construction. Particular consideration was given to maintaining the proportions and shapes seen in the traditional joints as these are part of what makes them so successful.

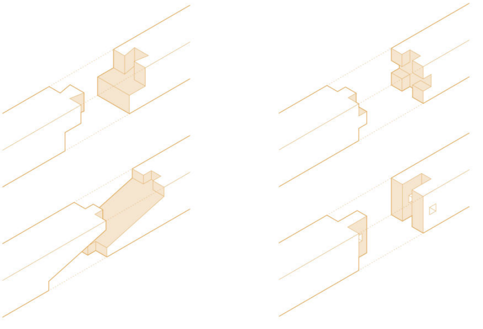

Figure 1. Traditonal Japaanese Joints: (top to bottom) Dovetail lap joint, scarf with stub tenon joint, stub tenon with pin joint, cross stub tenon joint.

When looking again at the existing CLT connection systems, they are all achieved by adding external pieces to the construction, a key of sorts. Though using metal pieces such as these is not the goal of this research, the idea of a key stood out as being particularly interesting. The traditional Japanese joinery ideas and proportions could be adapted to form a key. An initial key design was tested against the assessment criteria and was much more successful in terms of wastage, ease of building and ease of fabrication compared to traditional systems. Most interesting, however, was the reduction in wastage potential. A massive 28% of the wastage is avoided by using a key instead of a repeating system. Though this is dependent on the number of keys required and their size, it is nevertheless, a huge reduction.

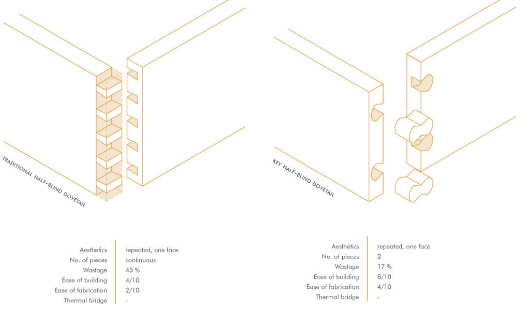

Figure 2. Comparison of traditional design to key design within the assessment criteria.

Having established that a key would be the most successful way to create a connection system, the next stage was to find that key. Using traditional principles, a series of design tests were conducted and evaluated against the assessment criteria to define which would be prototyped and tested further.

5. FABRICATION

5.1. ROBOTIC SETUP

This research uses an ABB IRB 6700 robotic arm with a spindle attachment, used for milling. Milling is achieved by attaching a bit to a spindle that is attached to the end of the robotic arm. Given the nature of this research and the large scale material, the 20mm diameter bit is used as it is large enough to cut all the way through CLT and thanks to its larger diameter, the toolpaths can be simpler.

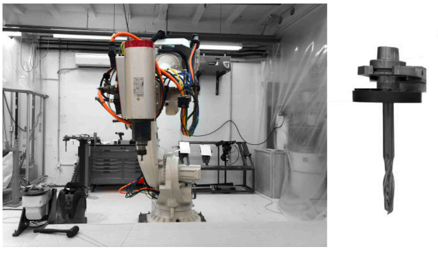

Figure 3. (left) ABB Robotics Workshop at Victoria University of Wellington. (right) 20mm milling bit.

The code used to control the robot was made using Grasshopper for Rhino and a plugin, HAL Robotics. The nature of this coding means that the user has absolute control over every part of the robotic movement, from the design, the way the robot moves, the speed in which it does so and much more. The robotic arm executes tasks by following a defined toolpath. This toolpath is the visual product of the code created in Grasshopper and gets converted into RAPID code along with the tool and speed instructions to inform the robot of the actions it needs to take.

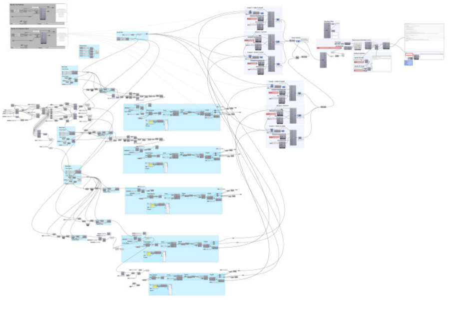

Figure 4. Grasshopper code to control the ABB Robot.

In order for the robot to understand the instructions, the curves created in the design phase are translated into targets that contain a directional plane. These targets define where the robot moves to create the desired action. As the robotic arm can move around 6 axes, the directional plane is key to ensuring that it is moving in the correct way.

This toolpath creation process is also where tolerances are crucial, both for correcting forms to account for the bit radius and for the spacing of targets. If the targets are too far from one other, the robot will find the simplest way from one to another. In the case of a straight line, this is not an issue as the robot will move from one end of the line to the other in a straight line. However, for more curved forms, this is an issue as the robot could create a straight line where there was meant to be a curve as there were not enough targets to define the curve.

5.2. PROTOTYPE FABRICATION

Throughout the prototype fabrication process, there was a reoccurring result, the key needs to be a perfect fit. Too tight and it needs a lot of labour to complete, too loose and the joint is weak. Along with this, there was a lot to be learned from both a design and fabrication point of view. The prototypes also showed that simplicity is key and wedges are stronger.

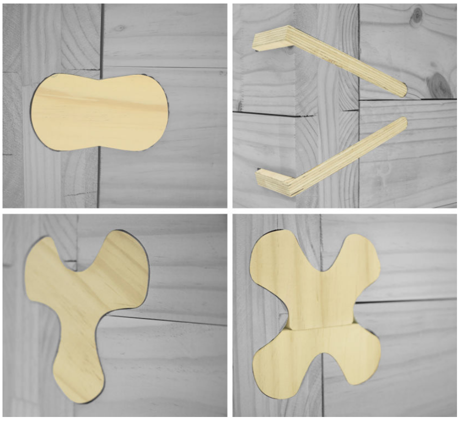

Figure 5. Robotically fabricated prototypes of timber key connections.

Simplicity comes in the design and fabrication processes, though not always together. The simpler the design, the faster the cutting time and the cleaner the cut meaning creating the right fit is more achievable. It also makes assembly of the joint far easier and less labour intensive, further reducing the time required to complete the connection. The use of a wedge to complete the connection means fabrication is not as simple but it is by no means complex as it only requires one extra cut. It does, however, create a much stronger joint that is less reliant of a perfect fit as the wedge creates friction that pulls all the pieces together.

Creating the prototypes provided valuable insights into machine processes. It was evident from the beginning that tolerances play a large role in the manufacturing process and will make or break any design. It was also clear that tool selection has a large impact on cutting time as well as the level of detail of each design. The smaller the milling bit, the more detailed to connection can be but the longer the cutting time. Whether using a robot or not, these are factors which are applicable to many types of digital fabrication and therefore become a large part of the subsequent design process.

6. BUILDING SCALE APPLICATION

6.1. CLT FACTORIES

The design of a connection system means very little if it can't be applied to industry. Though there are differences in each factory, the base procedure to create the panels is the same, timber lamellas are finger jointed, cut and sorted into long and cross laminations before being stacked and bonded together. Once bonded, the panels are cut in a gantry style 5-axis CNC machine.

This process has been designed to produce as little waste as possible, after all, the creation of CLT was partly driven by the desire to use 'waste' timber. However, there is still waste produced in production such as this. As the panels are treated in the factory, panel offcuts are often sent to landfill as they cannot be reused. Finding another use for these treated panels is where this research is key. As these connections are for CLT panels, the fact that the timber is treated is irrelevant therefore can be used to create the connection keys. This also allows for a much smoother manufacturing process as all the tools and materials required are already in the factory and there is no need to outsource the fabrication of the joints creating a one-stop-shop for both panel and joint manufacturing.

One of the most commonly used CNC machines in CLT factories is the Hundegger PBA router. This machine can process panels of between 8cm and 48 cm thick and is accurate to the millimeter. There are 8 tools available for this machine, of particular interest to this research is the circular saw, vertical milling and 5 axis milling unit. The milling bits, similar to those used with the ABB robot, just on a much larger scale, come in a variety of sizes and shapes, including cylindrical, end mill and dovetail cutters with diameters of up to 310mm and have the ability to undertake similar tasks to those undertaken with the robot.

6.2. ADAPTING FOR BUILDING SCALE

Being that CNC machines in CLT factories are gantry style and able to process 16m x 3.6m panels, it will be inefficient to cut one key at a time. As the waste produced by the factories is in panel form, it makes sense to use these to create the keys, reducing the waste and making use of material that would normally go to landfill. These 'waste' panels can be any shape and size so the keys need to be able to fit on as many of these as possible.

This is where the idea of tessellation comes in. If the key can be designed to not only create a strong joint but also follow a repetitive pattern, multiple keys can be manufactured at once. With a tessellated pattern, time to cut and excess material waste is minimised as each cut will create multiple keys.

The chosen design uses the most successful qualities from the previous prototypes, simplicity and a wedge shape, combined with the proportions of a traditional Japanese dovetail. The simplicity means that cutting time within the factory is much quicker and once on site, the pieces are far quicker to put together. This is aided by the wedge of the pieces as they mitigate the need for a perfect fit meaning less time is spent creating exact matches and is instead spent pulling the panels together.

7. FURTHER RESEARCH

The research undertaken offers many possibilities for future research into improving this connection system and applying it on a large scale. Structural testing could be undertaken to determine the strength of the joint under more rigorous circumstances, including earthquake simulation. This research could be furthered with the advent of full scale in factory prototyping. If the speculated factory fabrication technique, using waste and the CNC router could be tested, it may become clearer as to whether or not this is a viable solution for waste minimisation and reuse.

Full-scale prototyping would also allow for large scale structural testing of the key system as test structures could be made and further examined against structural requirements. This research could also lead to cost explorations. It was assumed that with the use of a timber on timber connection, the interior surfaces of the walls would not need to be covered, meaning less cost and less time. It would be interesting to compare whether the cost of fabrication and installation is lower or if it is comparable to the cost saved through the removal of interior finishes.

8. CONCLUSION

The aim of this research was to explore how digital fabrication and traditional timber joinery could be combined to create a connection system for cross laminated timber. Through the use of digital design and prototyping, this research has shown that an alternative timber connection system for CLT panels can be designed to reduce and re-use waste using existing fabrication methods.

It became clear through the research that there is no one solution to this question and that there a number of factors to consider when designing an effective system. The identification of criteria determined that aesthetics, number of pieces, wastage, ease of building and fabrication, and thermal bridge potential were the focus areas for design. Computer aided design became a large part of this research, both in the use of the robot for prototyping and in the design development of the connection system. Whilst designing within this digital workflow and the identified criteria, a defining conclusion was made; the connection required a timber key. Over the design process, robotic prototyping and simulation determined that maintaining simple forms and including wedged shapes would create the most successful system.

The design of a connection for a material such as CLT means very little without considering full scale and built application. The investigation into factory fabrication also gave way to an additional design parameter, tessellation. The development of tessellation in the design process answered many questions surrounding efficiency of fabrication and the application to full-scale projects. Mitigating the need for one-by-one fabrication, it became both a limitation and an opportunity for design and ultimately led to the most successful design outcome.

Though conclusive statements cannot be made in regards to the success of this system on a full building scale, the link between digital fabrication and connector technology has been made and has highlighted the potential for further exploration. This research has shown that timber connections for CLT can reduce construction wastage through the use of digital design and fabrication.

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ROBOTOWN

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Abstract. The potential robotization of architecture, its fabrication and assembly impacts design education today. In the near future it will contribute to the emergence of the new forms of urbanization. Our design research is focusing on the small scale urban conditions and build fragments that make up intelligent city. It is undertaken by the multidisciplinary team of architects and mechatronics engineers in academic context. The ROBOtown is understood as an urban structure containing intelligent town fragments. It has to consider the participatory design process involving architecture, mechatronic, robotics and lessons derived from Industry 4.0.

Keywords. Design; Internet of Things; Architectronics; Mechatronics; Robotics.

1. Introduction

Future cities should become more efficient, inclusive, and sustainable. This can be achieved through more efficient resource management, improvement of governance at the local level, effective connectivity and public participation. Robotics play an increasingly important role in responding to the anticipated exponential growth of the XXI c. urban populations (Sassen 2018).The intelligent robo-town calls for design research of small urban modules that make up the neighborhood as an alternative to the prevailing, large scale urban projects. It combines the concepts of information flow in the city (Stock 2011) as well as proposals for the design and reorganization of buildings and infrastructure using robots and mechatronic systems at the scale of dwelling, building, neighborhood, or town. Robotics are deployed not only in fabrication but also in activating new, interactive and responsive urban environments.

1.1. BACKGROUND

Robotics can be seen today as creative tools in the processes of designing, modeling and urbanizing global society of knowledge. The use of automation and robotics affects the city of the future and its architecture is of central importance. In the architecture supported by mechatronics, like in the industry 4.0. all phases are managed with IT and online (Berroneet al. 2018). From the creation

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 415-424.

of the concept, through design development, virtual modeling, and simulation, automated and robotic construction, quality control, marketing logistics, service and repairs, to utilization of generated waste - all phases are managed with information technology. In the future towns mechatronisation of the design process, building and using architecture in the context of intelligent, responsive urbanizations will play a significant role (Schmitt 2015). Fabrication, assembly of structures and elements of architecture built with the use of robots become a reality. Kinetic architecture can be also one of the forms of interface, responsive to changing environmental conditions and changing user's requirements. These dynamic conditions and requirements for the modern city are direct analogies of changing requirements and their implementation in relation to Industry 4.0 products and processes. Social participation can be applied on a large scale thanks to modern technology and information solutions belonging to the new industrial revolution. The postulate of open data and ability to easily obtain data from the Internet of Things (IoT) based on the current needs of users and the safe cooperation between human and robot systems can increase the role of participation and automatization in architectural and urban design.

2. ROBOstudio

ROBOstudio is an experimental project, implemented at the Faculty of Architecture of the Warsaw University of Technology in cooperation with the Faculty of Mechatronics since 2011, based on the concept of Architectronic (Meyboom, Wojtowicz 2010) - synergy cooperation of architecture and mechatronic, is a new approach applicable in the area of prototyping and fabrication as well as designing responsive structures (Wrona, Wojtowicz 2017).

ROBOstudio aim to solve technological problems by going further than simply reusing existing solutions, already adopted in architecture. Students are encouraged to be creative and draw inspiration from various technologies and fields. While still in the conceptual phase, the main goal of the studio is a creative search for future generation of solutions that may now seem utopian, but can serve to improve the quality of life architectronic users, including seniors and the disabled.

2.1. ROBOSENIOR IN URBAN PLANNING CONTEXT

The ROBOsenior - topic of the editions carried out in 2017/2018 and 2018/2019, the project involved solving problems of the elderly and starting research on individual problems they face. The basis of the design is an attempt to solve the real problems of residents - it initiates the possibility of creating and thinking about the new intelligent town.

The projects went from the scale of details - equipment increasing the comfort and safety of seniors, through the design of the entire residential unit, to the vision of creating neighbourhood spaces by a group of capsules, or their integration with the existing urban tissue.

A series of lectures accompanying the project introduced students to the basics of mechatronics, the concept of architectronic and the integration of digital systems in the field of fabrication and responsive architecture. In addition, course participants attended introductory workshops on robotics, provided by the Faculty of Mechatronics of the Warsaw University of Technology.

In the first phase of the project, students got to know and did research on available and planned technologies both in the field of care for the elderly and technological equipment that would increase the quality of seniors life. At the same time, they got to know the technical aspects responsible for the possibility of implementing the kinetic architecture and residential capsules.

In the second part of the course, students were focusing on the needs of residents, they developed a detailed design of functional solutions of the capsule, a plan of a residential unit and the concept of its functioning in urban, suburban or free space, depending on the individual approach to the topic of the group.

The final task of the course was to focus on one particular kinetic aspect of the proposed solution and build a physical, performing model of it. By that time, students already completed Arduino workshops and were ready to program basic actuators on their own. Work on the physical model was aimed at encouraging students to do in-depth geometric analysis of solutions and checking their feasibility. It also helped them develop algorithmic thinking, required to program their abstract designs into a real, working proof of concept.

In the first edition, they were to concentrate on the best technical solutions which can be implemented in an architecture environment to solve seniors' problems - physical, psychological and social. During the second edition taken in 2018/2019, students were encouraged to consider the future of the robotic capsule (Dąbrowska-Żółtak, et. al., 2018), and ask what are effects of a wider range of solutions, located mostly to the city center (figure 1.).

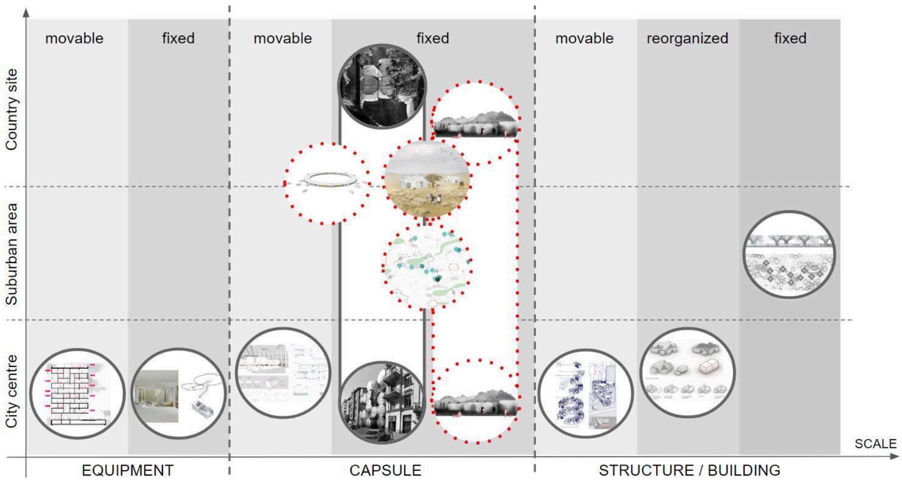

Figure 1. Comparison of areas of implementation and degree of mobility of ROBOstudio projects released in 2017/2018 (circles outlined dotted line) and 2018/2019 (circles outlined solid line).

2.2. ROBOSTUDIO 2017-2018

The first edition of this topic, implemented in the 2017/2018 academic year, tutored by prof. Jerzy Wojtowicz and Karolina Dąbrowska-Żółtak, assumed that the result of the project must be a self-sufficient, mobile capsule adapted to provide comfort and safety for the elderly and disabled. As a result of such assumptions, the solutions developed in most cases took the form of extensive modular suburban buildings. Examples of such projects are the projects: Connectivity Net, Housing Ring and Flexible Membranes (Graduation Towers).

2.2.1. Suburban Capsule Net

Figure 2. ROBOsenior Connectivity Net project. .

In the scale of neighborhood units, the residents of **Connectivity Net** assumed the possibility of implementing neighboring elements such as creating cities based on a network of connections - neighborhood units - walking to the nearest services, including health care. The city as a safe network enables navigation, eg. using augmented reality, control points in the city and provides security and access for people with dementia.

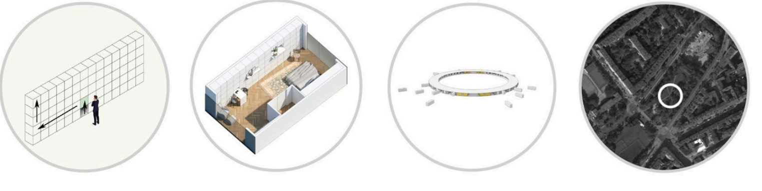

Figure 3. ROBOsenior Ring project. .

In the **Ring** project, a physical network was set up to enable services on an urban scale - quick transfer of physical items between capsules in the ring, like laundry, meals, shopping. The extension of this project is the elements responsible for transmitting physical data within a neighborhood unit or city - automated mail with delivery to a building or house being able to replace people in the services sector.

Figure 4. ROBOsenior Flexible Membranes project. .

In the project **Flexible Membranes** external material of the capsules create a favorable microclimate inspired by graduation towers and common caves. The tent structure of the living capsule and telescoping retractable windows would allow the living space to be expanded if, for example, children and grandchildren are hosted.

2.2.2. City Centre Capsule

Figure 5. ROBOsenior Multigeneration Hauses project.

The exception was the **Future Capsules - Multigeneration Hauses** project, in which students assumed that an alternative to living outside the city could be the use of roof surfaces in the city centers, where capsules could be set up with a flexible structure to adapt their shape and dimensions to the current needs of users.

2.3. ROBOSTUDIO 2018-2019

The second edition of the ROBOsenior theme implemented in the 2018/2019 tutored by prof. Stefan Wrona, Karolina Dąbrowska-Żółtak and Marcin Strzała, instead of focusing on designing easy-to-transport housing units, allowed students reinterpret the capsule as an apartment, mechatronic equipment of existing housing, supporting seniors and their safety, or megastructures equipped with mobile housing units dedicated to elders. Prepared projects present an overview of solutions from minor interventions in the existing urban tissue through the introduction to existing apartments of modular mechatronic solutions enabling equipment (POKEhouse, Robotic Arm), through independent capsules they fit into free urban spaces in a smaller room, as well as mobile units (Truncated CUBE, ROBOtaco) and the larger buildings (Doors) where individual capsules are a mobile part of appropriately dedicated building cores, up to mega-structural assumptions containing residential and service parts, both those located in the city centers (Moving Capsules) as well as in green areas (Integrator).

2.3.1. Equipment

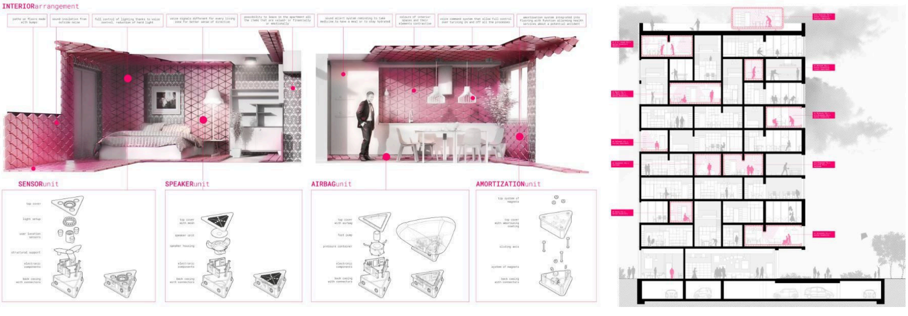

Figure 6. POKEhouse. (on the left) The active modules that make up the surfaces of the POKEhouse system. (on the right) Diagram showing the possibility of installing the POKEhouse system (marked in pink) in existing apartments, as well as inserting the new capsules with built-in active modules (example on the roof of the building). .

The **POKEhouse** project assumed the creation of a modular system consisting of a range of basic modules performing various functions, including; sensors collecting data and detecting potential threats, speaker that can send warning signals and messages in order to interact with the user, system resembling an airbag, opening at the time of detecting the risk of falling, to minimize a user's injury.

The modular system adaptable to existing flats, assuming that it can become a residential capsule of the future after equipping them with modern technological systems aimed at improving the safety and comfort of users. Consisting of active repetitive units it gives the opportunity for the future development of the project and supplementing it with new types of modules along resulting from the discovery of further user's needs and technological development.

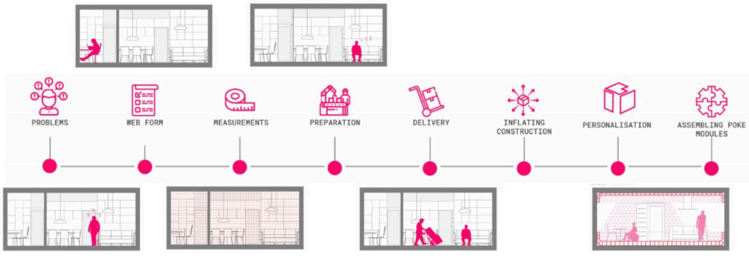

Figure 7. POKE house. Sequence from ordering through design, scanning of the apartment, preparation of production, to delivery of the POKEhouse system to the user location and assembly. .

The project assumptions are the new industrial revolution, including the possibility of mass customization of orders based mostly on modules produced as part of serial production, and the automation of the process of collecting data on apartments that would be adapted to the needs of older people by equipping them with the POKEhouse system.

The basic premise of the **Robotic arm** project is to equip the future living space with a multifunctional robot arm suspended from the ceiling. It would act as an assistant helping seniors to perform basic tasks and protecting them from physical fall. The project assumed the use of safe collaborative robots suspended on a ceiling system that would limit the number of robotic arms while ensuring their access to all required space in the capsule or apartment. The project assumed the possibility of installing the Robotic arm system in existing flats as well as in the mobile, modular housing capsules.

2.3.2. Independent capsules

The **ROBOtaco** project involves the use of space above the parking lots located in city centers. Capsules raised above cars would be a mobile, flexible and inexpensive alternative to apartments in well-connected and served locations of the city. The size of a single capsule would fit within a 2.5 x 5m parking space.

As part of the project, two basic types of modules are envisaged - (1) capsules with a flexible structure of the outer covering enabling free joining and reorganization of several capsules, and (2) transport capsules, designed to run a set of several capsules that make up a given residential unit during road transport.

Figure 8. Truncated CUBE. System of capsules located respectively in the natural environment as well as infilling undeveloped fragments of street frontage. .

The **Truncated CUBE** project assumed the creation of modular capsules that could partially adjust their dimensions. The external dimensions would affect both the size of the interior of the capsule as well as a close fit to existing gaps in the building, in case the capsules were to be filled in the city gaps.

The interior of residential capsules would be equipped with a system of pneumatic walls and furniture that would flexibly adapt to the current needs of the user, thanks to which a quick and relatively inexpensive interior rearrangement would be possible. It could be done by the use of a compressed air system and materials with shape memory.

2.3.3. Buildings & Structures

Doors project focused on meeting the social needs of seniors and creatively exploiting their potential. As a solution, a proposal was presented to combine flats for the elderly with flats for students, where kinetic structural elements and furniture allow privacy control for each part while sharing the kitchen, dining and garden parts. In addition to the mobile equipment, the project proposed the use of a movable partition system enabling the connection or separation of staggered capsules of seniors and students.

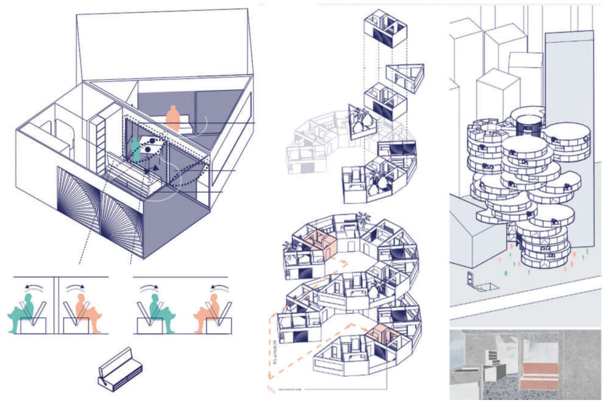

Figure 9. Doors. (on the left) Kinetic partitions and movable furniture enabling easy rearranging the interior. (on the right) The alternating order of mobile capsules and wedges with the function of a kitchen or winter garden, located around the communication core.

Capsules for students and seniors are mobile units mounted on vertical communication cores equipped with elevators enabling transport of the entire residential unit. This function would serve the possibility of transporting the senior along from his basic living space to both recreational and medical purposes. It was proposed to use a system of movable partitions enabling connection or separation of staggered capsules of seniors and students.

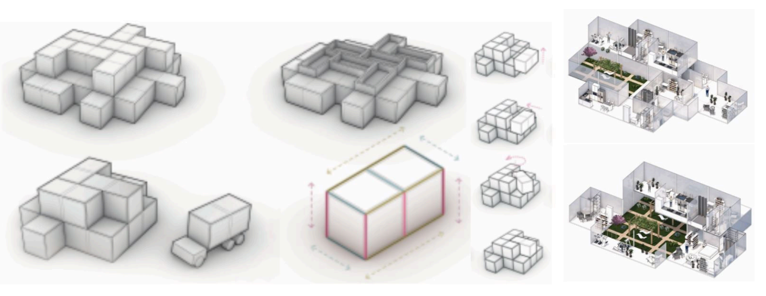

Figure 10. Mobile capsules (on the left) A set of movable capsules, and presentation of the degrees of freedom provided for the mobile capsule. (on the right) Sample combination of modular capsules.

Mobile capsules project is kinetic megastructure, consisting of the unit, which thanks to the built-in rails and drives would be able to move within the megastructure. This dynamic reorganization of residential modules gives the opportunity to shape social bonds through easier access to common spaces and services within the complex and the ability to move the housing capsule in the vicinity of more friendly people without having to move.

The presented vision of mobile, modular architectural fabric may refer to a broader issue - cities of the future, which may be able to be easily reorganized and adapted to the dynamically changing users needs.

The **inteGRAtor** project focuses on meeting the psychological and social needs of seniors and harmonious integration between participants of social life and the natural world. The project involves the construction of a set of residential towers, in which the set of living spaces. raised above the ground floor level, would be located. The residential complex should be located in a green space, to ensure privacy and contact with the surrounding nature, well connected to the city center. Capsules will be equipped with a system of sensors and screens with the personal assistant displayed on them to keep company with seniors and support the user in accessing information and managing the house.

3. Conclusions

A study based on the *research by design* method carried out as part of the second edition of the ROBOsenior theme enabled the extension of search areas and specification of the basic areas of robotic and kinetic solutions implementation. The investigation aimed at improving the quality and safety of residents life, including seniors and the disabled, specifying the possibility of using new technologies in architectural scale in the areas of:

- improving the quality of existing buildings,
- design of modular customized capsules that can become a filling of undeveloped urban spaces, including narrows places between existing buildings and parking spaces,
- design of modular customized capsules that can become a filling of undeveloped urban spaces, including narrow spaces between existing buildings and parking spaces creating building cores, which can be equipped with modular rooms and reconfigured depending on the needs.

4. Future research

Future research directions are to be focused on the integration of mechatronics, architecture and urban design. Our research aim is to develop cooperation between Architecture and Urban Design with Mechatronics.

In the research experiment in 2019/2020, building on the past ROBOstudios, is expected to explore the potential of robotics and mechanized common space of ROBOneighborhood, thereby directing the study from the scale of the detail and the apartment to neighborhoods, cities, and agglomerations where common space is a natural bridge to the urban scale.

Acknowledgments

ROBOstudio students - Connectivity Net: M. Korotko , S. Szczotka, A. Grzybek, M. Rudnicki, M. Walczak; Habitat Ring: L. Czaja , K. Kowalik, T. Ploch, M. Rusak, B. Kalyan Teja; Flexible Membranes: M. Koczewska, H. Li, M. Mikosz, S. Molenda, B. Swinder; Future Capsules- Multigeneration Hauses: M. Gosk, A. Krudowska, J. Ogińska, B. Pająk, P. Rodzeń. POKEhouse: G. Bratkowska, I. Jansen, M. Koszalski, M. Pajda, M. Żak; Robotic arm: F. Karlicki, C. Kępka, M. Kulesza, J. Marasek, W. Marek, M. Witkowski; ROBOtaco: A. Baryła, K. Bondar, D. Ma, M. Pyka, E. Szeląg, W. Y. Tan; Truncated CUBE: I. Cząstkiewicz, K. Gajek-Hołówko, H. Osman, W. Poszwińska, M. Wewiór; Doors: J. Otrębska, S. Pędziejewska, K. Rebelo, M. Szymanik, M. Wójcik; Moving Capsules; J. Czumaj, T. Dzieduszyński, J. Gizelska, K. Janaszek, D. Kicior; InteGRAtor: K. Altangerel, A. Banaś, M. Dławichowska, A. Kaim, E. Stawowy

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TRANSIENT MATERIALIZATION – ROBOTIC METAL CURVING

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Abstract. This paper introduces the notion of transient materialization to investigate a novel approach of robotic fabrication. Transient materialization explores a new logic of materialization that takes the advantage of differentiated material states to generate form at a particular moment through computation and fabrication technologies. Specifically, this design research explains a unique design and fabrication process, opening up a new method of materializing architectural form that emerges from the interweaving of data, the material capacity (plastic deformation), timing, and machine capacity. Hence, to examine this research direction, this paper conducts an experimental project, Robotic Metal Curving, through hands-on material experiments, as well as the development of algorithms, robot motion, and prototyping machines. This experiment utilizes an induction heating technique in cooperation with a six-axis industrial robotic arm and fabrication equipment used to shape each metal rod into a three-dimensional curve at a transient moment. In addition, the project focuses not only on developing a robotic metal curving system but also apply this technique in large scale by fabricating a wire-frame structure.

Keywords. Robotic Fabrication; Digital Fabrication; Metal Bending.

1. Introduction

This research explores the notion of transient materialization, which seeks to bring material experimentation to the forefront of design by associating it with computation and fabrication technologies that challenge the current state of digital fabrication in architecture. Transient materialization also investigates reciprocal processes between computation, materials, and machine systems. In contrast to typical digital fabrication used materials as a passive way of generating form, transient materialization explores material performance and embraces the features of material dynamics that emphasize a more highly integrated approach for design exploration in which material behavior, data, and machine capacity are fully connected.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 425-434.

The intent of this paper is to explore transient materialization as a fundamentally unique idea in digital fabrication. To further this research, this paper presents an experimental project-Robotic Metal Curving-which utilizes a heating technique with an industrial robotic arm and related fabrication machines that bend straight metal rods into three-dimensional curved shapes. In contrast to typical cold bending techniques, which have less of a plasticity effect, this experiment focuses on exploring the hot bending method, which locally heats the metal to a temperature that is conducive to bending with little effort. This idea is further inspired by the principle of induction heating, which can soften ferrous metal or electrically conductive material quickly via the law of electromagnetism to produce heat directly within the workpiece. Therefore, this paper demonstrates a novel workflow of digital craftsmanship for curving metal rods through the interweaving of computational design, the precision of robotic motions, the capacity of heating machines, and a custom feeding system.This paper first describes the existing works that inspired this research. Second, it explains the material experiment and focal system, including induction heating, material feeding, and the robotics system. Third, it described the demonstration of the current test results. The following are the contributions of this paper: 1) A description of transient materialization, which may trigger the pursuit of new possibilities in digital fabrication. 2) The development of algorithms and machines in cooperation with an industrial robotic arm and an induction heating machine for curving three-dimensional metal rods. 3) A summary of current progress for further development.

2. Context and Previous Experiment

Several previous works have focused on robotic metal bending (Figure 1). For instance, the wave Pavilion built by Park MacDowell and Diana Tomova in 2010; the Australian Pavilion at the 2012 Venice Architecture Biennale by Supermanoeuvre, in collaboration with Matter Design Studio; Brass Swarm by Roland Snooks, Cam Newnham and Ben Verzijl in 2015; WireVoxels 2016 by B-Pro Design Computation Lab - Research Cluster 4, The Bartlett School of Architecture, UCL in 2016; BENDILICIOUS by Maria Smigielska in 2018, all aimed to design and build architectural installations with an industrial robotic arm with either a bending machine or custom bend tool head to design and build architectural installations. The wave Pavilion was perhaps the first case, showing the potential of exploiting the robotic bending and computation system to develop a complex pavilion with a gradient of patterns across it. Supermanoeuvre, in collaboration with Matter Design Studio and The Bartlett School of Architecture, UCL, also tend to use a similar setup of robotic bending systems for building wire-frame sculptures. The Brass Swarm project developed through multi-agent and self-organization algorithms to generate an intricate ornamental installation. This structure was fabricated by the collaboration of two robots, which bend the brass rods into specific shapes. In another example, BENDILICIOUS developed a unique rotary tool, which is attached to the sixth axis of the robotic arm, to bend each steel rod. In contrast to the wave Pavilion, the Australian Pavilion, WireVoxels, Brass Swarm, and BENDILICIOUS developed robotic bending systems with no additional numerically controlled machines. Many of the projects described above developed robotic cold bending techniques for exploring complex and large space-frame structures. Compared to cold forming a bend in a rod from the above projects, this paper presents a robotic hot bending system that locally heats the rod and bends it into a curved shape (within a transient moment). Moreover, the research project not only takes advantage of an induction heating technique to develop a non-standard robotic bending system, one able to produce and customize various continuous curves with less machine power needed, but also aims to demonstrate and examine this novel technique by fabricating a large wire-mesh structure to be assembled with each specific metal rod as case studies.

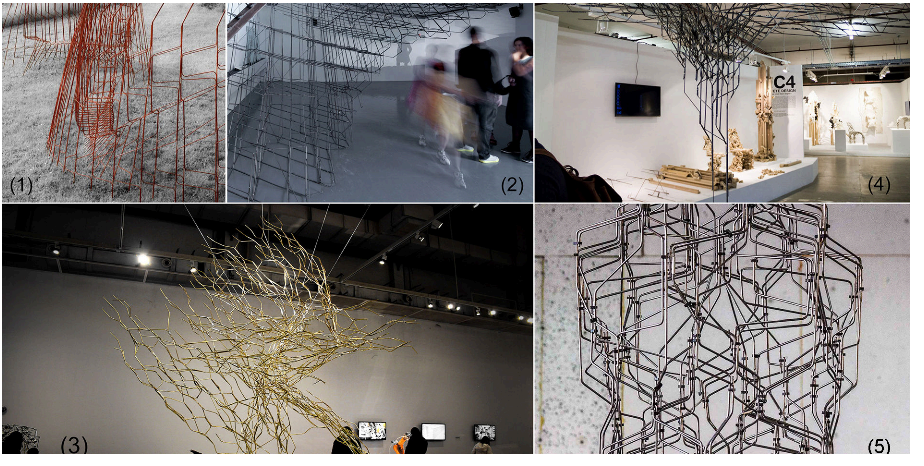


Figure 1. Related work on robotic metal bending. (1) the wave Pavilion (Park MacDowell and Diana Tomova, 2010). (2) the Australian Pavilion (Supermanoeuvre and Matter Design, 2012). (3) Brass Swarm (Roland Snooks, Cam Newnham and Ben Verzijl, 2015). (4) WireVoxels (B-Pro Design Computation Lab - Research Cluster 4, The Bartlett School of Architecture, UCL, 2016). (5) BENDILICIOUS (Maria Smigielska, 2018).

3. Robotic Metallic Rod Curving System

The system consists of two main components: a six-axis KUKA industrial robotic arm (model KR1100, 110-cm reach a 10-kg payload) with a pneumatic clamping gripper as an end effector, and an integrated fabrication platform for feeding, heating, and cooling (Figure 2). The fabrication process utilizes an industrial robotic arm (a generic machine with high movement precision in space), which can be programed to accomplish various tasks through the placement of different tools on its sixth axis. In addition, for the purpose of fastening and bending metal rods, a two-finger parallel gripper (SCHUNK PNG 80-1) is used and mounted to the flange of the robot. The state of the gripper (open and closed) is controlled by solenoid valves and an air compressor and custom aluminum fingers corresponding to the diameter of the rod. The integrated fabrication platform includes: 1) an induction heating machine, locally generating the heat in a certain range of the rod's area depending on the length of the coil, 2) a metal rod feeding machine containing a 200 mm-long linear motion actuator with stepper motor a pneumatic chuck that is placed atop the linear track and controlled by solenoid valves, an air compressor to grasp the slippery metal rod, and an anchor plate for bending. The linear track together with the pneumatic chuck delivers the metal rod to a specific distance in each cycle time. 3) two cooling fans to avoid the further deformation of the metal rod. Through the integration of these two components, the following are the sequences of robotic bending process via this system: 1) the linear motion actuator is set to the initial stage, and the metal rod is manually fit into the pneumatic chuck. 2) the given curve geometry is divided into segments by means of Rhino 3D and Grasshopper. 3) and then within this platform, we develop an algorithm to generate the bending data (translation and rotation), and a bending simulation for collision detection between the rods and robot. In addition, based on this bending data, the motion of robot is generated, and then merged with I/O messages for communication between the robot and the material feeding machine via TACO that generates the KUKA code. 4) the code is uploaded to the KUKA controller, and the robot is running to the starting position via a teach pendant as the heating machine is turned on. 5) the robot begins to work simultaneously with the material feeding system-the material feeding system pushes the metal rod forward, and the robot bends the metal rod after it has been heated by the coil. Finally, the process is repeated from step 5 for all remaining segments that need to be bent.

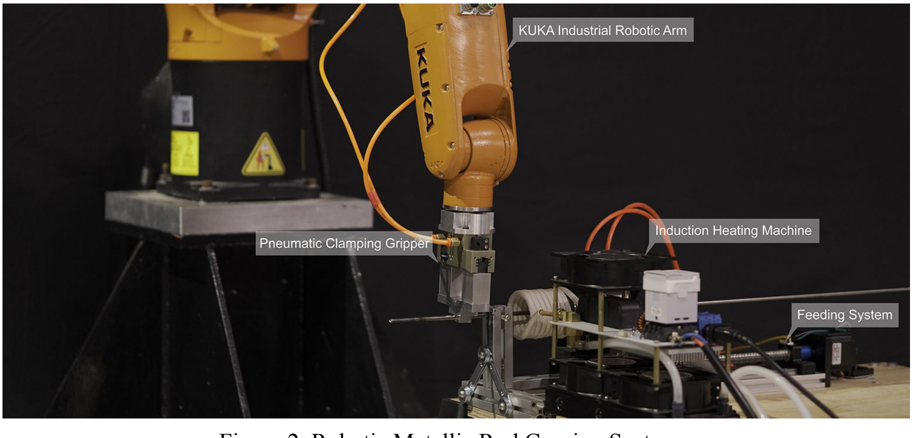


Figure 2. Robotic Metallic Rod Curving System.

3.1. INDUCTION HEATING

The principle of the induction heating system is the alternating of the magnetic field via the current (AC) that heats the conductive material (metal). This system comprises an induction heating board, a helical coil, a water pipe, a mini water pump, and an adapter. The adapter converts the AC current to stable DC current. The induction heating board uses a parallel resonant inverter control method that converts the input's DC voltage into 100 kHz high-frequency voltage AC, which generates a very rapidly changing magnetic field through the coil. In addition, when the metal is placed within this alternating magnetic field that heats up the material. In the meanwhile, the water pump and pipe circulate the water through the copper coil for cooling.

3.2. MATERIAL STUDY

In this experiment, ferrous metal was tested to validate its induction heating performance. A heater was employed to test metal rods with different diameters, and thus suitable dimensions were chosen based on the machine's performance and the copper coil's dimensions. After suitable heating materials and dimensions were chosen, the cooling fan and support plate were employed to improve the bending system's stability in order to prevent the heated metal rods from deforming. The test was divided into two parts as follows:

- Selecting the proper dimension for heating: in this test, metal rods with diameters of 4 mm, 6 mm, and 8 mm were heated and manually bent to validate whether materials with different diameters could be heated and bent (manually), whether the heating time was sufficient, whether the machine could heat up and bend metal rods over a long period of time, and whether the heated and softened metal rods could be bent into a curve (Figure 3). In the experiment, metal rods with a diameter of 4 mm were placed in the copper coil. After less than six seconds of heating, the metal turned red. We found the metal could be easily bent into a curve by hand with a clamp. The metal rod with a diameter of 6 mm could be easily bent after it was heated for approximately 10 seconds. The metal rod with a diameter of 8 mm could be bent, too, but, it took a great deal of power to sufficiently heat the metal with this thickness. The excess power destroyed the MOSFET of the heat guard. As a result, the machine could not run normally. In consideration of machine performance and the material's constitutive property, 6 mm was chosen for further use in this experiment.
- Heating and deforming: in the material test, the metal rod hovered after it was heated and bent by a heater (material was still heated but not hardened). The metal rod then deformed and fell due to either external force or gravity. To solve this problem, after the metal was heated and bent, a radiator fan was installed in the base frame to cool down the bent metal, and at the same time a waffle plate (with the same height as the bending point) was installed in the base frame to support the heated metal rod to ensure the accuracy of the bent metal.

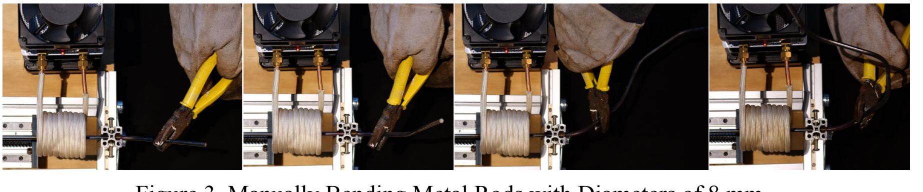


Figure 3. Manually Bending Metal Rods with Diameters of 8 mm.

3.3. END EFFECTOR AND MATERIAL FEEDING SYSTEM

As required by the hot bending system, a heater was installed along with 1) a metal rod conveyance platform installed on the outside of the robot and 2) A pneumatic gripper installed in the robotic arm flange. A linear motion rail (including pneumatic chuck, stepping motor, screw, and bearing) served as a material conveyance system, which conveyed metal rods to the heating and bending area. A six-axis industrial robot and its arm flange were employed to bend the heated metal rods.For the accurate control of metal rod bending, conveyance distance was determined each and every time before the machine started to bend the metal rod (the distance was calculated using Rhino and Grasshopper). An accurate mechanism was needed to overcome resistance each time the metal rod was conveyed. For this reason, a conveyance platform was constructed in which the stepping motor, screw, and linear rail served as a power device, and a pneumatic chuck was installed to clamp and convey the iron rod. The digital signals triggered by robots controlled the pneumatic gripper and conveyance platform and triggered the Arduino micro control panel to control both mechanisms' motions. This is how the process worked: the conveyance platform sent the pneumatic chuck to the initial position near the heating coil, and the robot provided with a gripper moved to the initial position in front of the bending point and then placed the materials in the conveyance machine. As soon as the iron rod was preheated, the robot transmitted a digital signal to the pneumatic gripper's Arduino micro control panel (A1) and to the conveyance platform's Arduino micro control panel (A2). Upon receiving these signals, A1 activated the pneumatic gripper. Upon receiving the signal, A2 activated the conveyance mechanism to move the materials the designated distance. At this time, A1 activated the pneumatic gripper to bend the metal rod. When the motions were completed, A1 moved back to its initial position. This process was repeated to complete the hot bending.

3.4. COMPUTATION METHOD

For accurate control of the bending angle at each and every bending point, we selected 3-D models for bending into 3-D curves. Next, we disassembled all such 3-D models using Rhino and Grasshopper software. Then, each curve was equally divided in order to calculate the precise position for the robot to bend the metal. Please check the description of the arithmetic process as follows:Firstly, an anchor point in the material conveyance mechanism was designated and a bending point in the center of robotic pneumatic gripper was selected. The distance between both points was measured. The conveyor had to move the metal rod forward to the same distance each and every time. Secondly, each and every curve acquired by disassembling the 3-D models was equally divided. The length acquired from the division was treated as the distance between anchor point and bending point. Next, the perpendicular frame was placed on the equal point, and the tangent vector acquired from the curve and equal point was treated as a reference vector. The Z axis of the frame was aligned with this vector. The robot's bending position was found using the changes of movement of the frame pairs on the curve (Figure 4). Lastly, the robot's bending positions and the corresponding digital output signs were integrated into a sequence.

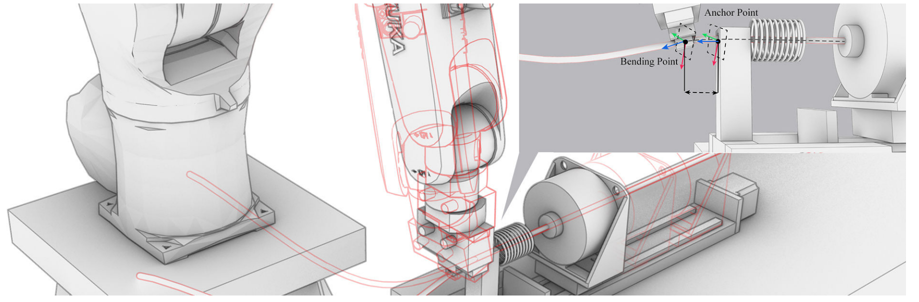


Figure 4. Bending Method.

4. Design Experiment

This research aimed to represent a complex surface with non-planar contour curves to examine the accuracy of our three-dimensional metallic rod bending method. This approach may assist in overcoming the difficulties of building a substrate system when constructing curved walls.Our overall geometry was a single patch of a Gyroid (135cm W by 100cm D by 200cm H), which is a triply periodic minimal surface that was discovered by Schoen in 1970. In this case, the Gyroid unit is formed by eight patched surfaces with three-fold rotation symmetry, and each Gyroid unit is able to infinitely connect to others. The selected single patch of Gyroid (Figure 5-1) is firstly sliced into regular and grid curved networks (18 curved segments in each X and Y direction of the surface) via the contoured component of the Grasshopper (Figure 5-2). Based on these 18 curves, two variables (X and Y directions) of the contour component are manipulated to generate a weaving pattern, after which six naked edges of the surface are extracted. For assembly, the curves of the surface are classified into two groups: edges and contours. The edges are labeled from E-1 to E-6, and the contours are labeled by the direction of division, either from X-1 to X-18 or from Y-1 to Y-18 (Figure 5-3).

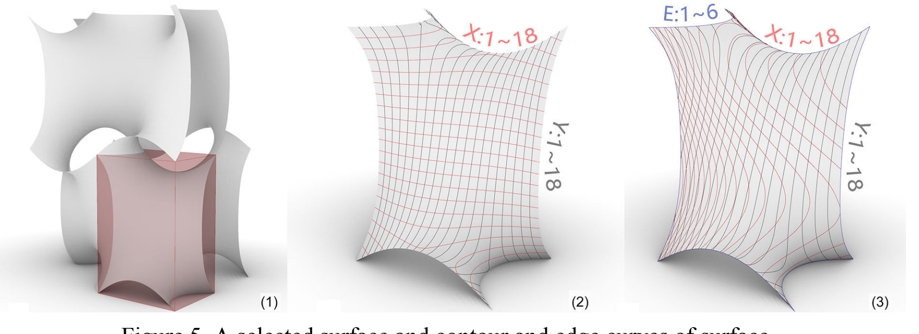


Figure 5. A selected surface and contour and edge curves of surface.

For fabrication, a low-carbon metallic rod is utilized because its malleability and ductility are well suited for this bending application. The length of each rod is ˜3 meters; the diameter is 6 mm; and the bending segment is 5 cm (the distance between the anchor point and the bending position). Each segment of rod is heated for six seconds and then conveyed to the bending position via the feeding system. The robot then grasps the rod and bends it into a specific position based on the calculation of the transformation of the frames between the anchor and the bending position.After the production of each bent rod, the following steps comprise the assembly process: 1) A frame structure (bounding box) is built to temporarily support the rods.2) Based on this supporting frame, six rods (curves on the edge of the surface) are placed and fixed to the corners of the frame structure via zip ties (Figure 6-1). 3) For the sake of verifying the end vertices of each contour, the curves are placed in the proper position along the edges of the surface (intersections between the edges and the contours of the surface), and labels are marked with tape on these edges as a reference position (Figure 6-2).4) With this layout, two selected rods (contour curves), with the largest span being across the surface in the X and Y divisions, are placed to ensure that these two contour curves are intersected and set on their edges (Figure 6-3).5) After positioning these two longest pieces, the rest of the rods (the X and Y contour curves) are sequentially placed in the right position and temporarily fixed to the nodes (the intersection between the two contour curves) by using zip ties (Figure 6-4).6) The last step is to weld all the intersected nodes (Figure 6-5) and remove the frame structure (Figure 6-6). Figure 7 shows the final results of utilizing this hot bending procedure.

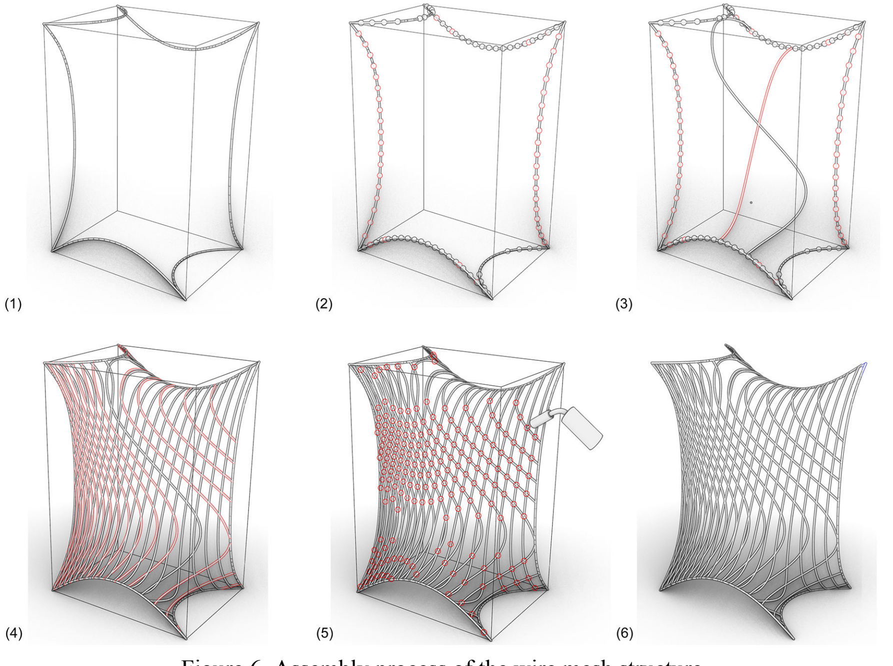
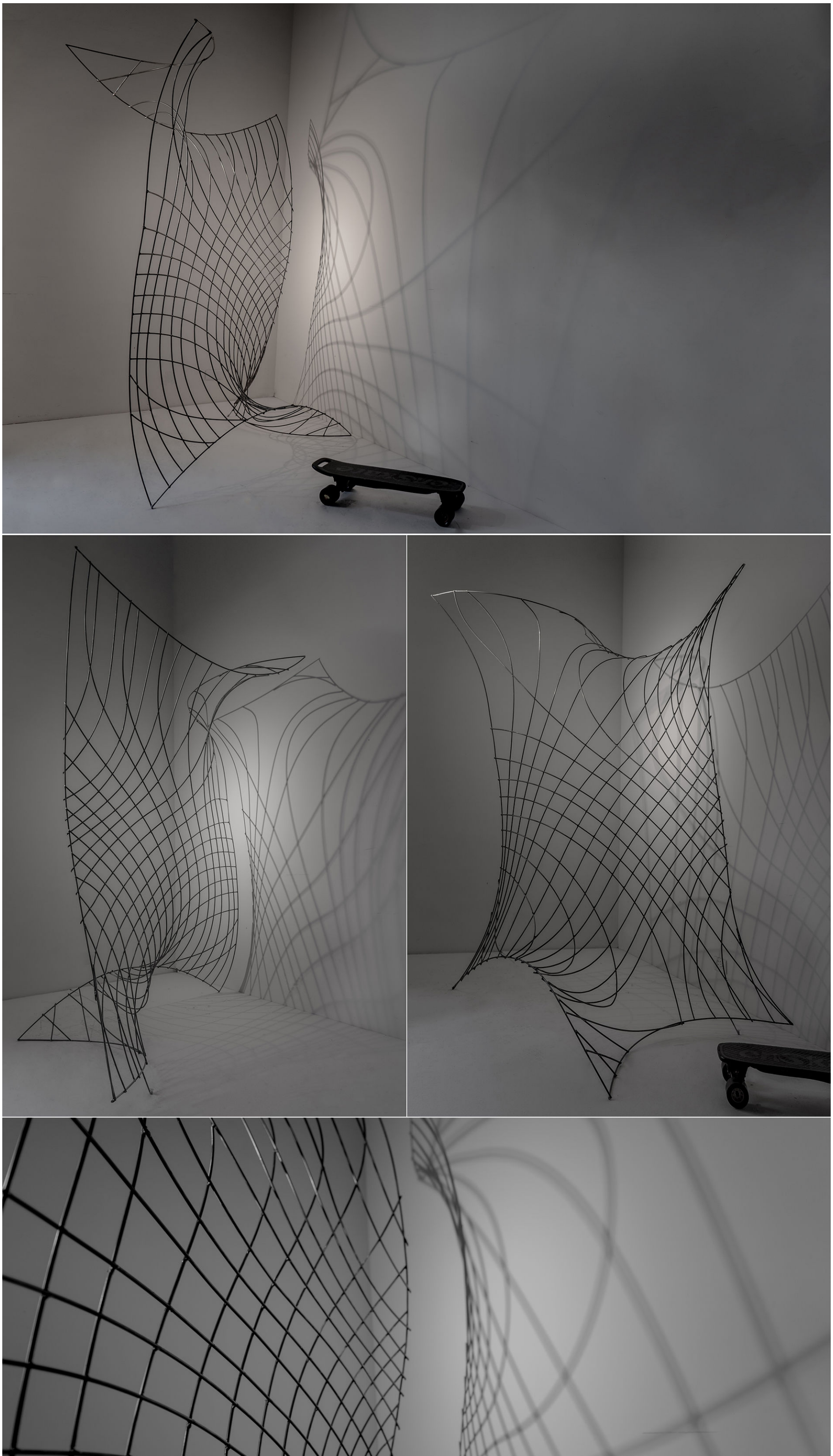


Figure 6. Assembly process of the wire mesh structure.



5. Conclusion and Further Step

Overall, this research exploits the differential material states of metal, computational tools, and advanced fabrication technologies to discover a unique digital workflow of a metal bending technique. Based on a series of experiments, the project successfully achieved a robotic rod curving system for the development of an intricate metal wire sculpture on a 1:1 scale. Unlike the cold bending method, this paper demonstrates a robotic hot bending procedure that shapes straight metal rods into three-dimensional curves. However, the current system is limited to bending each segment to a maximum of ˜70 degrees. In addition, the fabrication process is a semi-automatic: robotically bent, manually assembled and manually welding. The output of a bent metallic rod is manually supported to prevent any angle deviation that might be caused by the weight. Further research in this area will require: 1) adjustments to the current bending system and the development of an algorithm to improve the maximum bending and accuracy of the angle. 2) the development of robotic assembly and welding system to improve the fabrication efficiency.

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RO-PUZZLE

A robotic proposal for moving architecture

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Abstract. This paper presents a project-based research study called Ro-puzzle-a robotic architectural "puzzle," using robotic solutions to illustrate the possibility of an animated/dynamic architectural composition and configurations in the physical world. Through studying super-comportment (Wiscombe, 2014) in both dynamic and static scenarios, this research proposes a new reading to the traditional robotic task of "pick-and-place", through an intuitive motion design process using a custom-made bridge software, Oriole. By revisiting the notion of robotics in the field of design/architecture, Ro-Puzzle investigates the design possibilities of robotics, not merely as fabrication tools, but possibly as physical extensions of the design software into the physical world of architecture, and as a way to expand the digital design imaginations/possibilities beyond the digital screens. In this manuscript and initially tested at the desktop scale, Ro-Puzzle research investigation demonstrated the possibilities of robots as architectural "components" within the architecture/building. This research shows that through the development of custom software/hardware platforms, it is possible to domesticize robotic technology as an active agent in the design process through physical simulation.

Keywords. Robotics; Design; Animation; Robotic Architecture; Dynamic Architecture.

1. Introduction

1.1. ANIMATED ARCHITECTURE

For almost the past three decades, the introduction of digital design tools as a new medium for architectural/design thinking, has reshaped the design process in merely through digitalizing the analog design processes, but via augmenting the design process through computation or computerization (Leach, 2018). As part of this introduction and using animation software platforms as mediums for architecture, many designers started to speculate-again, about the potential of movement in architecture through the lens of animation and digital motion.

One of the immediate responses to the reintroduction of motion into architecture was capturing movement as "frozen frames" of motion (Gehry, 2004).

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 435-444.

These responses are clearly visible in the growing interest for “deformation” in the formal/architectural language of designers in the early 2000s (Pongratz, Perbellini,1999). Peter Eisenman’s The Max Reinhardt Haus (Eisenman, 1992), Greg Lynn’s idea of phenomenal motion (Lynn, 1999) and many projects including the Korean Presbyterian Church of Brooklyn (Lynn, Garofalo and McInturf, 1999) and embryological houses (Lynn, 2002), and Marcos Novak projects, Liquid Architecture (Novak, 1993), or Variable Data Forms, (Novak, 1999), are very few examples of using “digital” motion in architecture as a driver for form/space/experience making. Similarly, places and platforms such as TED, the MIT Media Lab, the Netherlands Media Art Institute, and Banff Center became a place for architects, media artists, and technologists who were searching for new environments and experiences related to the transformation of the building (Lynn, 2016).

Now as part of the contemporary design culture, animation became an accepted important experimental architectural design, simulation, and representation tool through which, animation concepts-such as deformation, blend-shapes, constraining, keyframing, graph-editing and gradual transformations, and physic simulations-to name a few, grown into architectural, formal and spatial strategies and language. As a result of this growth and in today’s conversation about design and architecture, animation and its frame of mind play a serious role when it comes to design thinking.

Following a similar interest, Ro-Puzzle design-research project focuses on “literal” motion-as Lynn describes. However, different from Lynn’s notion of projection of motion/animation through a sequence of parts transformation/deformation or carving space based on the motion-phenomenal motion, Ro-Puzzle looks into the effect of the literal motion through the lenses of flat architectural ontology and as a way to create dynamic parts and objects that are frequently and spatially changing.

1.2. ARCHITECTURAL ROBOTICS

Originally coming from industrial set-ups and other disciplines-e.g., engineering, domestication of robots/robotics as part of the design/architectural set-ups has been an ongoing question. Many researchers and projects looked at the novel ways of using a robotic arm and robotics as advance tools for fabricating parts beyond human fabrication capabilities. Although projects such as ICD/ITKE Research Pavilion 2014-15 (Doerstelmann et al. 2015), Wood Chip Barn (Devadass et al., 2016), and Mobile Robotic Brickwork (Dörfler et al. 2016) among many other projects, are advancing the robotic fabrication in creative ways, they all-more or less, use robots in a familiar industrial approach. In another word, while in these projects, robotic fabrication is used in novel ways, robots are not beyond makers and optimizers of the fabrication process.

As a result of such approaches, it is arguable that even though the process of making is digitally controlled, the outcome of the process-the architecture, is still-more or less, operating as an analog composition (Leach, 2018).

Seeking an answer for using robots as more active agents in architectural design and experience, there are multiple research projects investigating the representational capabilities of robots as a medium for experience. Box by Bot and Dolly (Bot and Dolly, 2013), The "Impossible Objects" design series by Kruysman-Proto (Kruysman-Proto, 2011), Mixed Robotic Interface (Poustinchi, 2018), and the "Aether Project" by Guvenc Ozel studio at University of California Los Angeles (Ozel, 2013) are some examples of these attempts to use robotic technology beyond its capability as a fabrication tool. However, it is arguable that these projects are mostly representational, and the robot has hybridized/animated the experience, not the architecture itself.

2. Methods

Ro-Puzzle aims to examine the possibilities of robotics and robotic motion in architecture, beyond their capabilities as a representation medium or fabrication tools. Tested and proposed at the desktop scale-with scalability considerations, Ro-Puzzle, looks closely at the possibility of architectural motion design, through the lens of robotics. In another world, different from representation and fabrication approach, this research investigation proposes robotic motion as part of the architecture itself and not as a method to represent it or to make parts of it.

Ro-Puzzle has been developed around three central themes: 1- How can literal motion become a design input to inform the design process from early stages of the design and though the formal, spatial, and organizational developments? 2- How can robotic technologies in architecture, move beyond the fabrication and representational capabilities, and augment the design process and the architectural outcome of it? 3- How can robotically animated architecture, move outside of the digital screens, and become a tangible reality?

3. Ro-Puzzle

Developed as part of the Hetero[Animo]genous design-research studio at the Robotically Augmented Design (RAD) Lab at Kent State University, Ro-Puzzle studies the potential of robotically animated architectural components and their effect on the design. Employing inside-outside relationships, miss/loose fit design language and the notions of part to part and part to whole relationships–as architectural and compositional design vehicles, this project examines the possibilities of physically animated architectural composition and its effect on the design process, form development, massing, and interior strategies. Conceptually, borrowing the ideas from Wiscombe's reading of a flat architectural ontology, Ro-Puzzle revisits the potentials of "super-component" and "interior object," as space-makers and through the lens of time-based custom-robotic motion design.

To be able to examine motion in relation to architecture, it was crucial to develop a theoretical and organizational formwork for the design language of the project. As an original form-making idea, two main ideas have been considered: 1- bounding the architectural parts and components and their motion as a three-dimensional whole-continuous approach, or 2- Breaking the mixture into parts that are distinguishable.

Through the lens contemporary readings of "Discrete," and in favor of scalability possibilities (Retsin, 2019), Ro-Puzzle looks at architectural composition as a mixture of separate parts and components.Keeping the project independent from scale-by considering scalability throughout the process, is specifically critical for this project since it is a robotic- design investigation at the desktop scale (Figure 1).

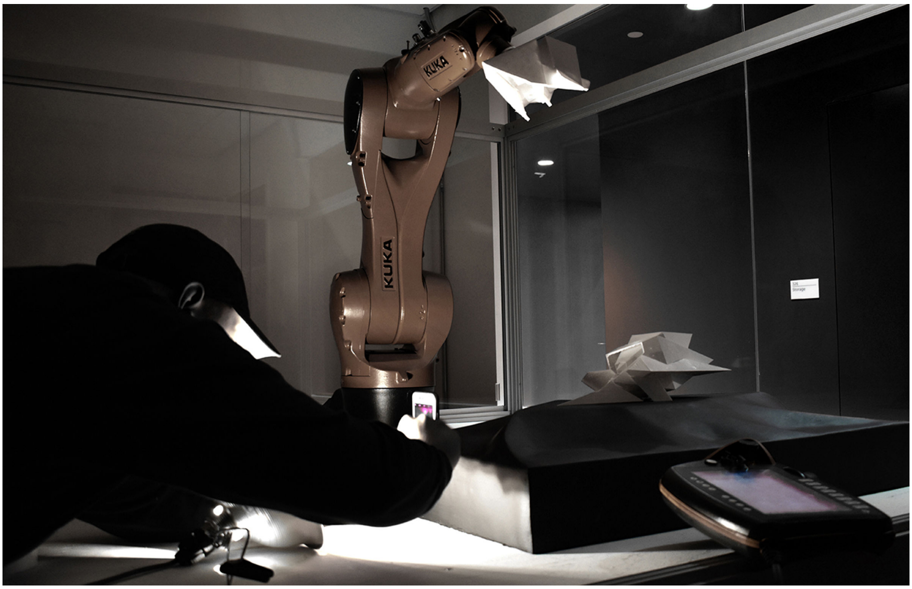

Figure 1. Ro-Puzzle set-up, as an experimental desktop scale configuration to look at puzzle-like qualities of architectural composition through the use of robotics.

However, different from digital “discrete” discourse and to produce spatial independency, the project borrows the idea of super-component from the Object-Oriented Ontology (Wiscombe, 2014). Super-component in summery is a component-part, that is small enough to be part of something else and big enough to operate as an independent object-whole. As a result, Ro-Puzzle is based on a hybrid concept of parts as “discrete super-components” (Figure 2).

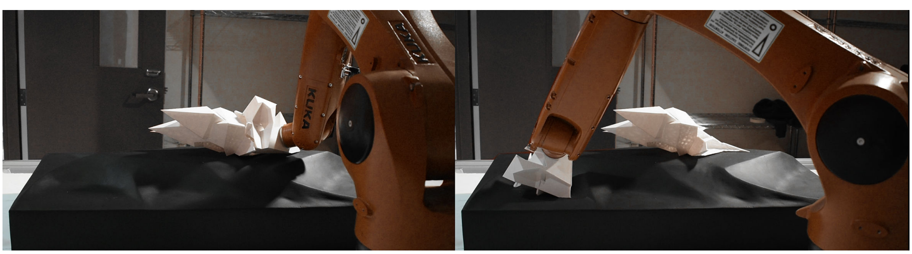

Figure 2. Discrete super-component operating as part of the Ro-Puzzle set-up.

By investigating multiple iterations in both animated and static scenarios, we reimagined the idea of super-component as an object like component that coexists as part of the "building object", to complete it, and as an extension to the "building object" to expand it. Precisely curating these different puzzle-like alignments, the orientational reconfigurations result in the new composition of parts and new spatial scenarios, where interior surfaces become exterior, the ceiling becomes the floor, and a component/part becomes object/whole itself. In another word, through motion, part to part and part to whole relationships are constantly changing from one to another; parts (components) become new wholes and whole divides into fragments and parts to address spatial and compositional interests. During these transitions, interiors-as an object or active void, continually changes its shape as well as its relationship to the exterior. Interior surfaces become the new façade for the moved- the re-oriented chunk of the interior object, and the absence of the animated part becomes a new interior surface to "complete" the "new" interior object (Figure 3 and 4).

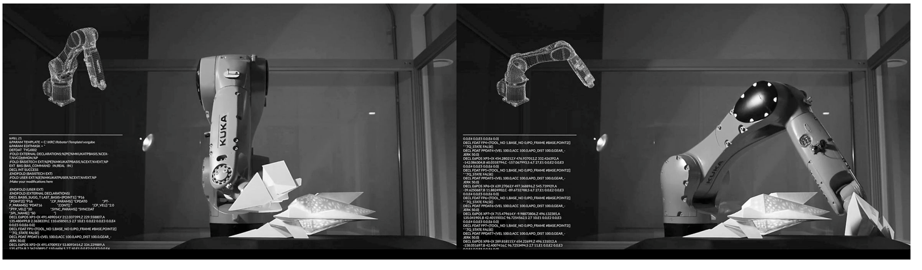

Figure 3. A physical test of the dialogue between inside and outside through an animated super-components .

Figure 4. Through video post-production, the idea of "animated void" has been tested as a form-making solution. .

To develop the project as a conceptual proposal for moving architecture-using robotic arms as possible scalable motion solutions, the design team studied the robotic motion and its relationship to the motion of parts from the early stages of design. Employing Oriole-as a custom-made robotic motion design plug-in for Grasshopper 3D (Poustinchi, 2019), we studied the robotic motion design as part of the design process. Put differently, it was aimed-from early stages of design, to design the "motion" and the architectural composition in a cohesive back and forth process, where the designer is not only designing the form, special organizations, and compositions but the robotic motion and physical animation scenarios (Figure 4). Oriole as a workflow platform enables designers to design the robotic motion of the "building" proposal, within the same digital environment of the schematic design, and as a "native" component of the process instead of a luxury add-on.

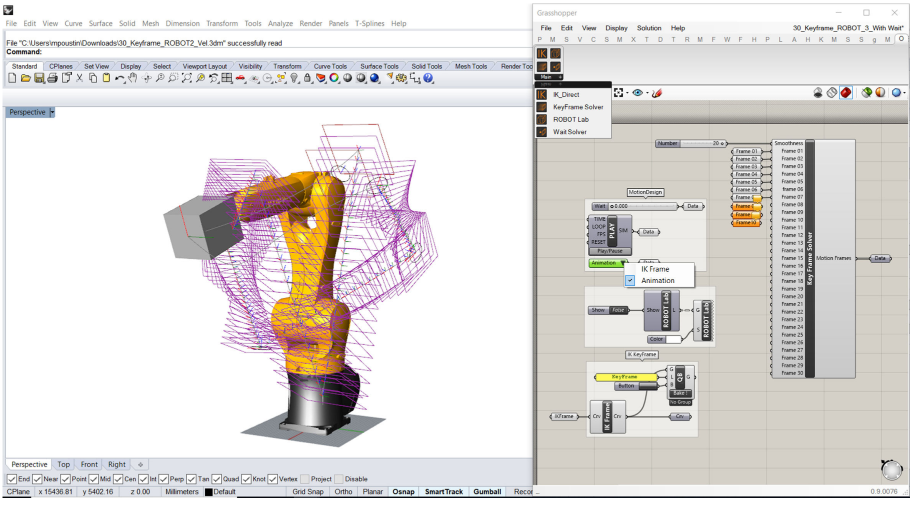

Figure 5. Overall preview of Oriole environment and its components and settings as part of Rhino and Grasshopper 3D environment.

Our research also verified that different from many digital animation investigations, physical tests with robots, are able to scale up to the scale of architecture since the kinematic and the mechanical logics of the robotic arms-KUKA industrial robot arms specifically, are similar in a variety of scales and payloads. We used a KR6 R900 Sixx robot arm to examine Ro-Puzzle design ideas at the desktop scale. A KUKA robot arm has been precisely chosen given KUKA's diversity in robot arm payloads, with an exact same kinematic mechanism-discussed further below. Designing a custom magnetic end-effector for the robot arm, as well as the moving part of the architectural puzzle, the robot arm was able to move the part is different orientations and re-configure them in different organizations. It is important to mention, different from the traditional robotic pick-and-place task, in this iteration of Ro-Puzzle, the robot and the moving super-component remain connected, and the robot moves the component around, without "picking" or "placing" (Figure 6).

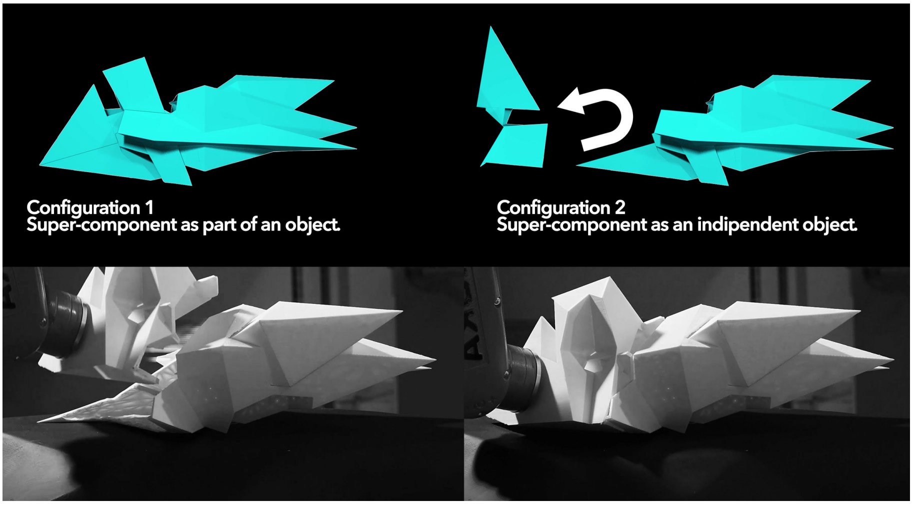

Figure 6. As an ongoing robotic pick-and-place task, the super-component–moving part, remain connected to the robot as an end-effector.

Through designing the motion and parts at the same time, designers were able to curate different special and organizational scenarios where the inside/outside relationships of the architectural composition-at the model scale, blur into a hybrid time-based mixture. Specifically designing the motion of the robot in relation to parts and their operations, the design team was able to employ the robotic motion to test the movability of parts in a puzzle-like desktop architecture model (Figure 7).

Figure 7. Using the physical animation of the parts and super-components, Ro-Puzzle also operates as a hybrid design medium to study design in relation to motion.

Although the Ro-Puzzle project has been defined as a compositional study-without any specific program, to be able to examine the inside/outside transitions of parts, the interior surfaces of components have been designed differently from their outside (Figure 8). This difference has been used as a vehicle to inform the motion design.

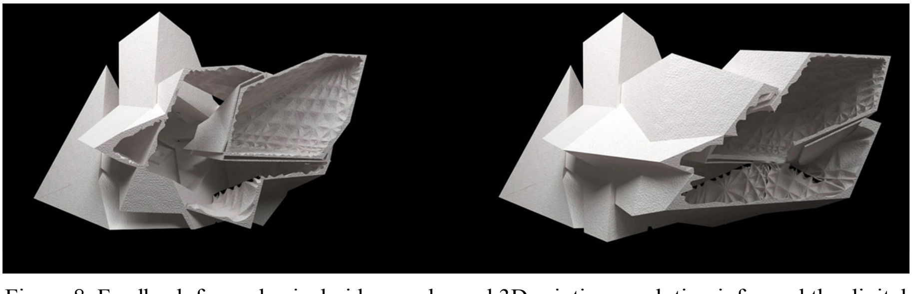

Figure 8. Feedback from physical videography and 3D printing resolution informed the digital design as feedback. The surface detailing is a result of this back and forth.

4. Discussion

As discussed above, Ro-Puzzle-at its current stage, is an investigation on moving architecture at the desktop scale, which is far different from the building scale. However-as mentioned above, it has been one of the core interests of the project-both from theoretical and performative views to consider architectural scale in its proposed workflow. Using a hybrid combination of notions of digital discrete, and super-component, theoretically enables Ro-Puzzle-as an experimentation and a conceptual workflow, to remain independent from the scale. Conceptually, the idea of architecture as a puzzle-like mixture of parts (components and super-components) is relative and valid at multiple scales, from product scale to the urban scale.

On the other hand, it is arguable that the second main component of the Ro-Puzzle project, the robot arm is also scalable. Using a KUKA KR6-R900 Sixx robot as part of this project and given the specific inverse-kinematics of KUKA robot-arms, the motion of these robots are scaleable by scaling up the robot arm and its payload. In another word, although this experimentation is done at the desktop scale, its solutions-including the motion-provider, are not limited to this scale; In fact, there are already robotic arms-KUKA KR 1000 Titan for instance, that are capable of moving 1000KG with six-axis of freedom. Other industries such as entertainment are using these robots to move chunks and part of the stage, cars, and clusters of amusement parks.

It is crucial, however, to mention that the design of the motion is not scalable. Ro-Puzzle is not proposing a motion-type, instead, it is proposing a workflow that involves designing the composition of the architectural parts, as well as their motion-through robotic motion design, at the same time and as a seamless workflow. Testing the motion in a physical workflow, considering connections, materiality, gravity, the imperfection of fabrication among other physical characteristics-even at the desktop scale, enables designers to think beyond the existing workflow of architectural robotics. Animated facades, moving rooms, and shells and tumbling buildings have already made their ways into the contemporary world of architecture. It seems essential to study these possibilities in both conceptual and practical manners. Ro-Puzzle proposes a workflow, to physically test a possible way to animate architectural components through using a scalable mover: robot arm.

5. Limitations and Future Plans

Although proposed as a design process/proposal instead of a final outcome, Ro-Puzzle-at its current stage, faces some limitations. One of the major limitations of the current research is the difference between the robotic motion, designed at the desktop scale and the one which ultimately will be used at the building scale. While-and as discussed above, the direct translation of the motion between scales is not one of the goals of the current project, it can be a valuable component to Ro-Puzzle research to investigate its possibility. To address this issue, currently at the Robotically Augmented Design (RAD) Lab at the College of Architecture and Environmental Design, at Kent State University, we are working on scaled chunk models of a building. Another limitation of the current research is the interface for these robotic motions. Although Oriole is an intuitive and visual platform for designing the motion of the robot-for designers, it is still housed within Grasshopper 3D as a node-based programming platform. We are currently working on developing a fully intuitive platform for designers with no programming or grasshopper skills to design the motion more fluidly as part of a routine design process of a building.

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ROBOTIC SAND CARVING

Machining Techniques Derived from a Traditional Balinese Craft

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Abstract. This paper presents research aimed at translating Ukiran Pasir Melela, traditional Balinese sand carving, into a new robotic-enabled framework for rapidly carving stiff but uncured cement sand blocks to create free-form and architecturally scalable unique volumetric elements. The research aims to reconsider vernacular materials and craft through their integration robotic manufacturing processes and how this activity can provide localized, low energy manufacturing solutions for building in the Anthropocene.Balinese sand carving shows potential advantages over current, and rather environmentally damaging, machining process primarily using soft materials state to make deep, smooth cuts into material with little torque. Transferring this manual and low-impact craft to robotic-enabled fabrication leverages heuristic knowledge developed over decades and opens possibilities for expanding and transforming these capabilities to increase the variability of potential future applications.

Keywords. Robotic Fabrication; Computational Design; Traditional Craft.

1. Introduction

Traditionally used to carve thousands small Balinese Hindu temples, the Balinese craft known variously as Ukiran Pasir Melela or Ukiran Pasir Hitam (literally translated as black sand carving)-is by necessity an expedient process (Karang, Ketut and Sudarmawan 2015). Ukiran Pasir Melela pairs the artisanry developed by a culture steeped in a tradition of carving for millennia with inventive materiality. Using blocks of stiff, but not cured, concrete with no large aggregates, craftsmen are able to insert knives deep into the material and create smooth surfaces in only a single pass (Figure 1). Soft stock material and sharp carving knives allow workmen to create deep relief, undercuts, and smooth surfaces over a large area many times faster than possible with typical stone or wood carving. The authors' efforts to understand and instrumentalise Balinese sand carving began

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 445-454.

with a site visit to Northern Bali to stage and document a series of test carvings. These observations offered both insights on how the process could be transferred to digital manufacturing, and confirmation on the craft's operative advantages over other conventional methods of subtractive machining.

The paper is structured in three parts. First, it describes a historical and operational overview of the traditional sand carving techniques. The cultural context of the techniques are framed through recent accounts. This context is enriched through field work in Bali staging a series of test carvings to comprehensively document the work of an experienced artisan as the basis for robotic processes. Second, the paper identifies key factors supporting the use of robotic sand carving over typical subtractive machining. As such, the paper argues that the traditional craft's robotic implementation expands its application and further amplifies its role within a wider network of sustainable construction. Third, the paper describes the methods and metrics that were developed after analyzing block-cutting operations using motion capture on site with the craftsmen. These studies resulted in computational strategies for simplifying the cutting movements into extractable fundamental operations that can be transferred to the robot.

This research aims to leverage heuristic knowledge to enable innovation in the field of robotic carving. In so doing, this research demonstrates robotic sand carving as a viable cutting approach that is well-positioned to negotiate the complex, multi-dimensional trade-offs between material stiffness, processing time, surface resolution, surface quality and environmental performance; considerations that concern all subtractive manufacturing research. Future potential application of this research includes the exploration of load-bearing stereotomic constructions using robotically carved blocks, and on-site robotic facade carving. In doing so, the authors hope to pair heuristic craft knowledge developed over the decades (Davies 2007) with the flexibility of a generic industrial robot arm.

Figure 1. An artisan carving temple elements.

2. Background: a historical and operational account on sand carving

Balinese sand carving developed into its current state of technology through a confluence of cultural and geologic forces. The demand for this ornamental work is satisfied partially by the abundance of volcanic soft carving materials. Originally carved from Batu Paras (a soft, and volcanic tuff), the carving in Bali has largely transitioned to Ukiran Pasir Melela upon the introduction of cement in the 1930's (Davies 2007). The current technique uses magnetite volcanic sand, cement and water to make temporarily soft blocks that are cut with sharp knives (Figure 1).

The process is simple: once cured, the carved concrete is considered finished and requires no further post-processing. Operational efficiency is also significant: instead of removing material in small chips, such as in the case of traditional stone carving or Computer Numerical Control-based (CNC) routing, cut material is separated from the stock in large pieces. Finally, material saving may be achieved, as cut material can be reused to carve subsequent parts, thereby making the process nearly waste-free. The carving technique could potentially achieve a wider range of applications by allowing for an increase in application scale while retaining the ability to make small intricate detail.

3. Sand carving visit and observations

To better understand the overall process of Ukiran Pasir Melela, the research group travelled to Bali to observe and document the traditional craft in its context.

3.1. BLOCK PREPARATION AND CUTTING TOOLS

Preparing the pre-cured blocks requires first the mixing of fine magnetite sand, cement and water. Starting with a 1:4 ratio of cement to sand, the craftsmen stirs and sieves the initial mix using a flexible sheet of open-weave fabric. The mix is then poured into a dry porous mold shaped with rough blocks, and de-molded approximately in half-hour time. Similar to construction-grade concrete, the sand carving-based concrete mix will remain workable for about 3-5 hours.

Tool movements, and the relationship between the cutting element profiles and the final carved geometries are arguably the most critical aspects of the craft in understanding how it may transfer into an automated framework. Tooling for the carvers includes large trowels and various metal knives similar to palette knives. Trowels are used to roughly outline blocks, while finer sharp knives allow for precise control and surface continuity.

3.2. CARVING MOVEMENTS: OBSERVATIONS

Several staged rounds of carving were executed on similar sized blocks. The process was documented with multiple cameras. The overall strategy was to observe carvings of typical Balinese patterns done by the craftsmen of more generic surface qualities. Some of the carved pieces included atypical small temple quoin ornaments, a wall block, and a molding.

After observing the carving of typical Balinese ornaments, a second series of simplified carving tests were conducted with the aim of simulating an automated process by creating more generalized patterns of material removal and surface types. This series includes: a pattern of curving ruled surfaces; a pattern of parallel concave troughs; and a single convex element (Figure 2). By using the shape of the blade drawn along the path of movements, the series of ruled surfaces efficiently translated motion into form.In contrast, the curving ruled pattern took longer to cut , and required the craftsmen to reposition the block several times for clearance so the tool could be drawn tangent to the surface.

Figure 2. Image showing carved test pieces with ruled surfaces, and a single convex surface.

Observing Balinese sand carving in context provided a valuable knowledge base of to begin transferring this manual craft into a robotic setup. Of primary concern to this translation is understanding the impact of tool movement on the base material. The complex sequence of moves performed in the manual practice can be distilled into manageable simplified shapes. Surface size, type and inflection greatly impact workability. Amongst the observed patterns, the V-groove ruled surface test proved the most predictable and expedient. In other tests involving small, or convex features, the impact of tangent tool positioning and its tendency to result in clearance and positioning problems was observed. These insights guided the setup of the preliminary manual implementation.

3.3. CARVING MOVEMENTS: MANUAL RE-IMPLEMENTATION

Building on the insight gained from the site documentation, an initial set of manual tests were completed in preparation for initial tests with the robot arm. Implications from the considerations of workpiece orientation, cut material behavior and tool orientation were gleaned from these observations.

Toolpath patterns started with variations of the V-groove patterns of ruled surfaces made with the flat and straight palette knife. In addition to this more direct toolpath, shoveling paths were also tested. This path purposefully left ‘tear’ marks on areas of the surface that were not directly smoothed with the knife (Figure 5). The initial tests also experimented with various knives, with tests being conducted using both the straight palette knife and the ceramic loop knife. The ceramic loop knife creates patterns similar to those created with ball-nosed CNC bits (Figure 5). Observing that the straight palette knife offered both greater freedom and predictability, respectively with regards to achievable cut depth and the relationship between the tool’s profile and the guide geometry, it was decided that the first end-effector to be tested would utilize this tool.

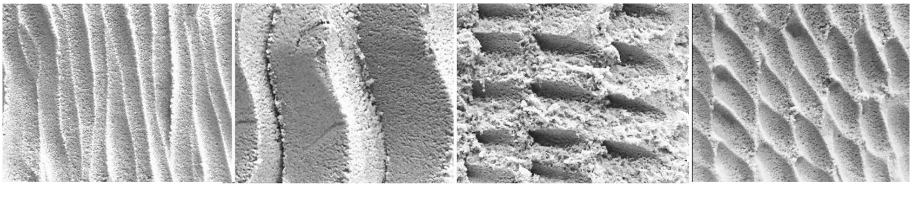

Figure 3. Manual toolpath tests using a straight and loop knives to carve surface textures .

4. Subtractive manufacturing in robotics fabrication

Establishing that there is architectural potential for the robotic implementation of Balinese sand carving, this section provides a brief overview on robotics-enabled subtractive machining methods in the field of architectural fabrication. Subtractive manufacturing allows for the creation of forms with material properties and surface quality that are difficult to achieve through additive manufacturing (Townsend and Urbanic 2012). Operationally, current robotics-enabled subtractive manufacturing can be broadly categorised as either kerf-based or non-kerf methods. Kerf is typically defined as the width of material removed by cutting, and kerf-based methods refers to freeform surface machining methods where the volume of material that can be removed in a single pass. By contrast, non-kerf based operations refer to cutting operations that achieves material removal by cutting a workpiece at tangents to the faces of the finished surface, so that cut material is sliced from the workpiece in volumetric chunks.

Notable experimental and investigations had alternatively explored the linear path-based motion of the kerfing operation to generate varied elasticity, (Menges et al. 2010) or distinctive surface patterns in the workpiece (Reinhardt et al. 2016).These techniques however are also time-intensive, since the approach requires the cutting tool to pass within the entire volume of the material to be removed.

Addressing the operational and geometrical shortcoming in kerf-based approaches are non-kerf based robotic cutting approaches, which may either use a knife or wire-based cutting element. With wire-based elements, common applications include the use of hot wire to achieve robotic production of doubly-curved molds using expanded polystyrene, (Søndergaard 2016) or the use of wire cutter to create finished structural elements, such as complexly shaped joints or slab elements (Weir et al. 2016; McGee, et al. 2012). Similarly, knife-based non-kerf cutting operations have also included techniques that could be applied to various materials to achieve a number of functional products including carving of extruded polystyrene foam to achieve complex volumetric molds (Clifford et al. 2014)..

Knife-based approaches can begin to address these issues by generating highly complex and intricate surface features and allowing a fuller range of robotic motion. Potential scalability and time constraints on these processes limit their potential applications in full-scale architecture.

5. Research methodology

5.1. SUITABILITY OF RESEARCH, OBJECTIVE STATEMENT, AND PAPER OUTLINE

The literature review of existing non-kerf subtractive machining processes reveals a complex multi-dimensional set of trade-offs between material stiffness, processing time, surface resolution and surface quality. There is little design and computational research that systematically classifies and deconstructs the techniques of carving, so that they may be computationally reformulated to generate new patterns at any scales.

This paper proposes that robotic sand carving may offer a compelling alternative to existing cutting approaches that can best negotiate between these performance criteria. Transferring sand carving to an automated workflow that utilizes an industrial robot arm could increase the scale of the finished pieces through increased reach, without reduction in geometric complexity. The research includes initial testing results, both manual and robotic re-implementation of specific carving moves, and provides suggestions for the translation of the ease and speed advantage of the traditional craft into an automated process at a larger scale.

5.2. CHALLENGES WITH GRANULAR MATERIAL AND COMPOSITES

Though Balinese sand carving has advantages over many current subtractive manufacturing processes, the softness of the stock material, its granular material composition, and the time limit inherent in carving pre-cured concrete are significant constraints to consider when devising the technique's robotic adaptation. Additionally, material removal poses challenges to this automation of the process. Traditional Balinese carvers rely on constant feedback with the workpiece, as they remove material intermittently with acute dexterity. This process would be complex for a robot to replicate. Thus, programming would instead have to incorporate automated simple procedures for material removal, while preventing large pieces of offcut to hit the finished piece with force.

5.3. GEOMETRIC SCOPE AND MATERIAL SELECTION

The implementation demonstrated in this paper focuses on the sand carving for stand-alone wall-like block elements. Particularly, the framework is implemented on blocks with approximate dimensions of 8”×8”× 3”. Due to difficulties in the procurement of the magnetite, preliminary testing and fabrications relied on a variety of alternative sand types as substitute aggregate material for the cement-sand concrete mix. Sand types explored include gabbro sand, which is a coarse-grained and similarly dark-colored igneous rock, and Kinetic Sand, which is a three-dimensional silica sand-based building toy bonded with polydimethylsiloxane to mimic the physical properties of wet sands. Adjustments have been made in the robotic programming in order to account for the different physical properties of the substitute sands, which typically exhibit greater surface tension, and therefore lending to more viscous-like behavior that may render cut operations more difficult.

6. Robotics tool, workflow, implementation

6.1. ROBOTICS FABRICATION AND SOFTWARE SETUP

This project uses a KUKA KR 6 R900 sixx small robot for initial robotic implementations of the characteristic carving moves, and a KUKA KR125/3 large payload robot for the production of the final patterned artefacts. The use of two different models explore the production of artefacts at different scales, and facilitate the development of a uniform tool-pathing strategy that can accommodate a variety of robot arms. A basic end-effector was custom-designed and 3D printed in ABS plastic. The thin steel palette knife is mounted into a 3D printed holder that cantilevers from the larger support plate, which in turn is screwed into the flange of the robot arm (Figure 7). A threaded opening within the cantilever holder allows for the insertion of a bolt, so that the tightness in the fastening of the mounted palette knife may be adjusted manually. The mechanism can accommodate a variety of palette knives, which allows multiple cutting techniques to be experimented easily.

6.2. ROBOTICS PLANNING

Since the cutting element is defined one straight edge, all resulting three-dimensionally carved volumes can be conceived as volumes bounded by developable surfaces. The carving operations exploits this geometric attribute and programs all robotic paths as ruled-surfaces characterized by two reference curves: a base curve that defines the depth of the cut, and a guide curve on the workpiece surface that effectively dictates the width and sloping angle of the cutting operations.

When a contour-like patterned field is initially generated and input, the curves are ordered and alternatively assigned as either base or guide curves. Each base curve is paired twice-once with each of its two neighboring guide curves. To convert the curve into robotic reach positions, each pair of base and guide curves are divided into an equal number of points according to a predefined division length resolution; a vector is constructed between each pair of points on both curves. The tool center point (TCP) runs along the base curve on each of its divided points while orienting the tool shaft using the corresponding vector. Finally, a tool plunge and retract movement is inserted respectively to the start and end of each pair of curve-based paths in alignment with the start and end guiding vectors (Figure 7). Following the completion of one curve, the tool retreats using Point-to-Point (PTP) movement to a predefined clearance positions above the workpiece, thereby resetting the robot's joint axes and minimizing the likelihood of joint singularities or axis limits for the subsequent pair of base-guide curves. Additionally, Status and Turn value settings for the PTP movement, which are binary values representing Axis 1 through Axis 6, serve to eliminate any ambiguities in the positive and negative turning of the robotic joint axis.

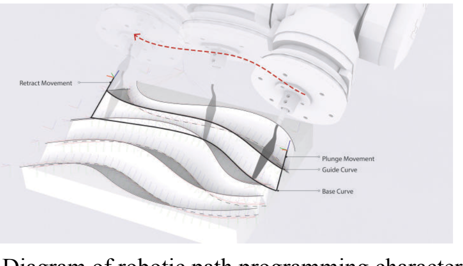

Figure 4. Diagram of robotic path programming characterization.

6.2.1. Robotic implementations, test results and observations

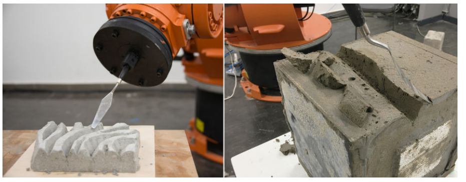

Figure 5. Robotic setup for initial tests.

Following the workflow and path programming methods described above, an initial series of tests were performed-both to provide validation to the proposed framework and to test the novel cement-sand mix using the crushed and finely screened gabbro stone. Building on the initial manual toolpath implementations, these tests used both the V-groove tool pathing type (Figure 10) and shoveling paths to achieve a variety of unpredictable geometries. Sequences of discrete whole geometry were attempted in a gradient pattern that were minute enough to expose the initial block surface, and variations of the v-groove carving pattern tested both continuous, cut-through moves and discrete moves that create branched geometry and terminating grooves (Figure 9).

Figure 6. Results from initial robotic tests with varied patterns.

The preliminary robotic tests yielded insights on both the tool pathing and material constraints. For instance, it was observed that despite the similarities in both grain size and textures, the gabbro sand simply did not cure to the same level of strength as the magnetite sand. Though compromised by the concrete mix, the initial results are nevertheless promising insofar as they demonstrated the feasibility of implementing the proposed framework to carve a range of geometric pattern types.

Emergent material properties were also observed in patterns that dragged along the surface, which contrasted with materials that cut along the toolpath such as the V-groove-based approach. Operationally, the tests showed a need to calibrate the orientation of the knife relative to the desired finished surface. For instance, it was noticed that orientation along the tangents of the toolpath curve geometry would tend to result in coarse geometry, especially in the case when small radius curvatures are desired. Finally, subsequent studies will also have to fine-tune the plunging and retraction moves, which tended to compromise the surface quality more severely than was observed in the manual carving implementation.

Several pattern 'cubes' were also fabrication using one or more of the techniques described above (Figure 10). Akin to craftsmen rotating workpieces to easily access other sides for carving, these blocks were carved one face at a time and rotated 90 degrees once a face has been completed. Future iterations could utilize an external positioner to automatically rotate the workpieces. To reduce weight, the blocks were hollow in the center and cast as an extruded square profile. One of the challenges faced while carving these pieces was making sure there was enough clearance for the lower half. This was resolved by raising the blocks 20cm of the work surface to allow ample room for the robot swarf motion. The surfaces were lightly brushed with a wet brush after they've been carved to smooth the textures. Some of the finer features crumbled after the mix cured due to the thinness and sharp edges.These tests show how flexible the process is and while we haven't tested carving two faces at once with 45 degree rotation, based one the toolpathing and robot motion range we think it's possible and might be worth further investigation to save time on workpiece resets.

Figure 7. Four examples multi-sided carvings using the techniques described.

7. Conclusion

This research has laid the foundation of a unique cutting method that carves stiff, but uncured cement-sand blocks to create unique volumetric elements-a process that lends to free-form, and architecturally scalable geometries. Replacing Balinese workmen with robots may seem an inevitable consequence of this research. When craftspersons in Bali were asked to participate there was anxiety related to just such a perception. However the aim of the work is not to enter the temple ornament market but to learn from innovative techniques that are established and robust. When craftsmen were told that the work was aimed toward this end their response was curiosity and an openness to work together to document the techniques. This type of cooperation and knowledge sharing elevates the work of peers who work in very different places.

Although the presented method neither contributes geometrical novelty nor improved cutting precision, this research has nonetheless provided modest innovation to the fields of robotics-enabled sand carving by focusing on a granular material that has high architectural scalability. In doing so, this research has demonstrated robotic sand carving as a viable cutting approach that is well-positioned to negotiate the complex multi-dimensional set of trade-offs between material stiffness, processing time, surface resolution and surface quality-performance considerations that concerns all subtractive manufacturing research.

Finally, it should be noted that while this research presents panels from a wall-based rectilinear block system, the method is not dedicated to this typology. Future potential application of this research includes the exploration of load-bearing stereotomic constructions using robotically carved blocks, and on-site robotic facade carving. In executing the carving operations using different robot arm models, and with various sand types, this research seeks to demonstrate that the proposed robotic-enabled cutting approach is neither limited to the forms of specific typologies, nor constrained to specific scale, material, or style. In this regard, this paper opens possibilities for expanding and transforming the capabilities of sand carving, so that future applications of the method may increase considerably in scale and variability.

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SUSTAINABLE SONIC ENVIRONMENTS

The Robotic Fabrication of Mass Timber Acoustic Surfaces

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Abstract. This research proposes that mass timber panels can not only enable a new type of architecture that is sustainable, but that also sounds better. As mass timber construction often exposes the wood structure, and these panels are carefully constructed in factory settings, these panels have the potential to be built so that the acoustically absorptive, reflective, or sound scattering acoustic properties of surfaces can be integrated into the constructive logic and architectural aesthetic of the building. This paper specifically investigates the potentials of the sound scattering performance of cross laminated timber (CLT) panels. Through design, simulation, and prototyping various surface designs are investigated.

Keywords. Architectural Acoustics; Robotic Prototyping; Sound Scattering; Acoustic Simulation; Mass Timber.

1. Background - Mass Timber

Timber has been used in architecture for millennia; however, in recent years, technological advances in gluing, fixing, and manufacturing have allowed new timber products to be used in bigger and more complex building projects. This new timber technology - mass timber - is a family of products made by connecting a series of smaller timber elements together to form larger panel or beam products. Mass timber construction describes buildings where the primary load-bearing structure is made of either solid or engineered wood. Engineered lumber is a composite material using mostly softwoods combined with adhesives to make structuralized elements into idealized shapes. Typical applications include beams, columns, arches, roofs, floors, and walls. These represent sustainable alternatives to the current dominance of steel and concrete in contemporary building practice in North America and Europe.

In recent decades the many large and hidden costs of our dominant building materials - in particular that of concrete and of steel - have driven the pursuit of more sustainable alternatives. If the built environment is to be carbon free by 2050 and meet Paris Climate Agreements targets architects must use lower embodied carbon strategies, or use carbon sequestering materials such as mass

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 455-464.

timber. Forests store vast amounts of carbon, and buildings constructed of wood continue to store it. The building sector is a significant part of the climate change problem and the embodied impacts of buildings are directly related to materials (King, 2017).

A number of proprietary systems with different levels of prefabrication have been developed by the building industry and are marketed for the construction of multi-storey residential and commercial buildings. The prefabrication of mass timber panels is an open building system that is customizable, and the increased use of computer-controlled materials handling and fabrication equipment ensures the quality and precision of the final product and facilitates smooth assembly on site (Dangel, 2017). One of the key aspects of the innovative use of mass timber is this ability to be prefabricated enabling a high degree of coordination between architect and fabricator. Given the high degree of precision of this process, and relative ease of cutting in multi-axis, a new approach to ornamentation and performance can be introduced.

2. Background - Acoustic Design

There are two main aspects to architectural acoustics: building acoustics - the study of the transmission of sound through structure, and room acoustics - the study of the characteristics of the sound field within a room. Previous studies of the acoustic properties of mass timber have largely focused on building acoustics - on the sound insulation qualities of mass timber construction (Mahn et al., 2020). This paper theorizes on how a move to mass timber construction could impact room acoustic properties. The central question is: how can building designers integrate room acoustic performance into the constructive logic and architectural aesthetic of new mass timber environments?

Sound scattering surfaces have been proven to benefit both performance spaces such as concert halls (Haan and Fricke, 1997), but also more common types of spaces such as classrooms and meeting rooms (Choi 2013, Peters et al., 2019). The importance of sound scattering has been recognized and this has led to the development of an international standard defining the sound scattering and diffusion coefficients and methods for measurement (ISO, 2004). The scattering coefficient is defined as the ratio of scattered sound to the total reflected sound. The scattering coefficient does not include any information about the directivity of the scattered energy. The scattering coefficient is needed for acoustic computer simulation to achieve accurate results. It has been found that the depth of the surface geometry relates to the frequency of sound at which maximum sound scattering will take place (Cox and D'Antonio, 2009). Along with the frequency effects of the depth of surface geometry, the amount of surface detail can impact the amount of scattering (Peters and Olesen, 2010).

3. Background - Fabrication

While the geometric complexity of sound scattering surfaces gives challenges for traditional fabrication, these geometries offer an interesting opportunity for digital fabrication which does not have the same limitations. In the last decade, numerous researchers and designers have explored sound scattering surfaces decade combining computational design with various digital fabrication methods and simulation prediction techniques. The length of this paper does not permit an in-depth review of all previous work in this area; however, some examples of the materials and digital fabrication methods that have been studied include: robotically-controlled nozzle-extruded polyurethane foam (Bonwetsch et al., 2008), plaster powder 3D printing (Peters, 2009; Peters and Olesen, 2009), thermo-formed panels combined with 5-axis CNC milling of MDF structural cells (Peters et al., 2013), robot-controlled folding and welding of a plastic (Vomhof et al., 2014), 3D-printing and laser-cutting (Turco et al., 2017), and robotically-controlled hot-wire foam cutting (Reinhardt et al., 2017; Walker and Foged, 2018). A notable built project that has merged acoustic performance and digital fabrication is the Elbephilharmonie Hamburg by architects Herzog and DeMeuron, which included 6000 m2 of sound scattering CNC-milled gypsum panels (Koren, 2018). The research described in this paper explores the use of robotic CNC-milling of mass timber panels. This research proposes that the acoustic surface can be integrated directly into the constructive logic of the building - in this case mass timber structure walls and ceiling - and does not need to be a surface or panel solution applied after the architecture is already built.

4. Background - Simulation

Today the computer simulation of room acoustic performance can be grouped into two approaches: wave-based, and ray-based (Siltanen et al., 2010). Ray-based techniques, also called geometric methods, assume that sound travels in a straight line and its reflection from surfaces is computed using geometrical methods. To predict the room acoustic performance of an interior space, geometrical acoustic simulation is the currently accepted method (Vorlander, 2008); however, a source of uncertainty for geometric acoustic simulation methods is how to model the effects of surface diffusion and diffraction (Christensen and Rindel, 2005). To predict acoustic performance at the level of the surface, wave-based simulation methods must be used, or physical measurement techniques (ISO, 2004). Wave-based computer simulation solves the wave equation numerically using different methods: the finite element method (FEM), the boundary element method (BEM), and the finite-difference time-domain method (FDTD) (Cox and D'Antonio, 2009). Numerical methods divide the space of the digital model into small elements or nodes. These elements then interact with each other according to laws of the wave movement phenomena. Element interaction must be calculated for each element in a time step sequence, and this leads to large calculation times for large numbers of elements and long durations.

While computational design can generate a wide range of complex geometries, understanding the acoustic impact of these geometries is far from obvious. Previous research by architects on sound scattering surfaces have taken a variety of approaches to measuring and simulating: sound reflection characteristics can be recorded and compared between design options - for instance comparing flat surfaces with complex geometric ones (Bonwetsch et al., 2008; Walker and Foged, 2018); scale models can be built and measured using the ISO 17497 method (Peters and Olesen, 2010; Turco et al., 2017; Reinhardt et al., 2017); and FDTD can be used to visualize sound waves (Peters et al., 2013; Belanger et al., 2018). In this research work, we were interested in the scattering coefficient, as this is the coefficient necessary for room acoustic simulation, and so we could either measure the coefficient using the ISO method, or use wave-based simulation to calculate it. There are challenges to the measurement of scale models (Choi and Jeong, 2008; Peters and Olesen, 2010), and so in this experiment computer simulation was used. In this experiment the BEM method was used to predict the scattering coefficient. The simulation software used measured the spatial characteristics of the reflections at different frequencies. We combined the BEM scattering analysis with sound wave visualization using a custom tool that utilized the FDTD method.

5. Experiments

In this experiment, four surface geometries were developed. These surfaces were developed using parametric modelling, simulated using BEM and FDTD methods, and prototyped at 1:1 using robotic CNC-milling. Two geometric types of surfaces were investigated: a sinuous but random wave-like surface, and a hexagonal pattern with regular widths, but random heights. Two different depths of each surface were studied to investigate the impact of the depth on the sound scattering performance. The two shallow depth options were milled from 5-ply CLT, and the deep depth options from 9-ply CLT. Using the relationship between surface detail depth and acoustic wavelength as suggested by Cox and D'Antonio (2009) suggest that the two deep options will have design frequency of around 1000 Hz, and the two shallow options will have a design frequency of over 2000 Hz, see Table 1.

Table 1. Calculated wavelength design frequency.

name	depth	width	frequency	wavelength
deep hex	0.130 m	0.085 m	1.3 kHz	0.260 m
deep wave	0.170 m	0.110 m	1.0 kHz	0.340 m
shallow hex	0.062 m	0.072 m	2.8 kHz	0.124 m
shallow wave	0.080 m	0.070 m	2.1 kHz	0.160 m

6. Computer Modelling

Several different geometries of sound scattering surfaces were developed using parametric design software. An algorithm was developed to generate sound scattering surfaces that would impact different frequencies. The algorithmic tool outputs surfaces with wave-like surfaces, random height rectangles, and random height hexagons, see Figure 1. The algorithm was implemented in Rhino Grasshopper. Four different surface geometries were selected to be simulated, see Figure 2.

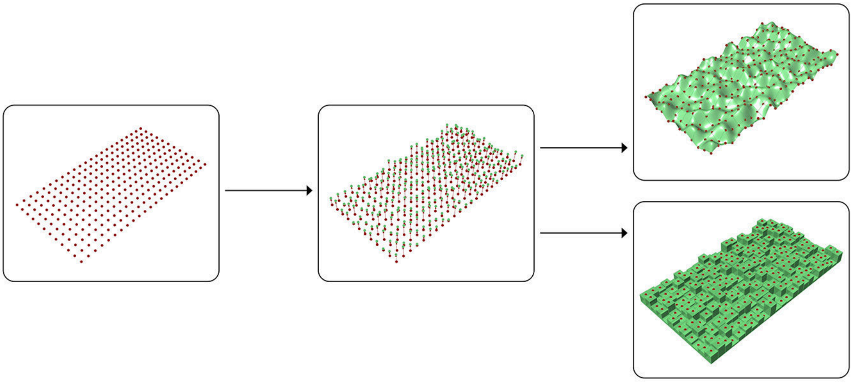

Figure 1. Algorithm for generating sound scattering surface.

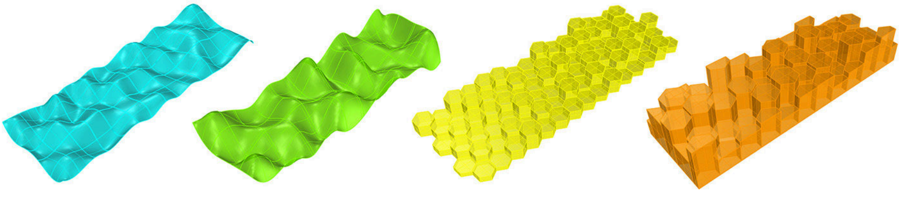

Figure 2. Four options: (1) shallow wave (2) deep wave (3) shallow hex and (4) deep hex.

7. Simulation

This experiment used two different acoustic simulations to predict the performance of the diffusing surface: the BEM software Reflex (developed by AFMG) was used to simulate the sound scattering performance, and a custom FDTD software was used to visualize sound wave propagation and scattering from the diffusing surface. While sound scattering can be measured from scale models or from 1:1 prototypes, there are challenges with getting accurate results from scale models, particularly at all frequencies and the testing of full-scale prototypes requires not only very large prototypes but similarly large testing facilities, which are beyond the means of many building designers and firms. The sound scattering simulation showed that the deeper geometries provided scattering in lower frequencies while still maintaining strong scattering tendencies in the upper frequency ranges. When the simulations were compared to the estimations of scattering frequency (comparing Table 1 to results shown in Figure 3), the surfaces largely performed better than predicted.

Figure 3. BEM simulation using Reflex: 2D sections through generated design options (left) and calculated coefficients (right) showing Scattering coefficient (blue) and Normalized Diffusion Coefficient (red).

The wave surfaces performed as expected with the shallow wave having good scattering (0.7 and higher) from 2 kHz and above, and the deep wave from about 800 Hz and above. The shallow hexagon showed good scattering from 1.25 kHz and above, and the deep hexagon from 630 Hz and above. The reflex software also demonstrated that all of the surfaces had good scattering performance at a variety of different incident angles. The deep hexagon surface is compared to a flat surface in Figure 4. A challenge with the BEM simulation software Reflex is that it does not take in user-defined geometries. It also does not handle curves, therefore the wave surfaces were discretized and laboriously entered point-by-point into the software.

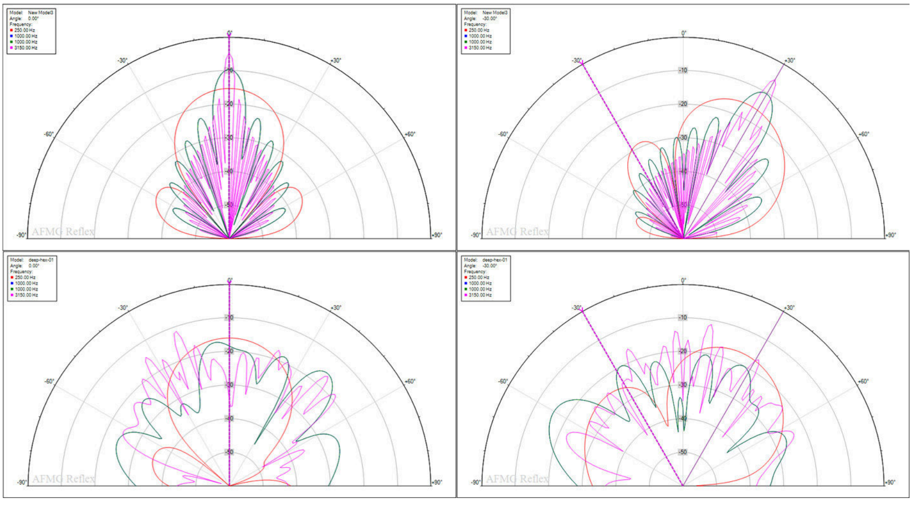

Figure 4. Angular sound reflections (0 degrees and 30 degrees) for a flat panel (top images) compared to the Deep Hex design option (bottom images).

Sound wave visualization is another method of exploring and demonstrating sound scattering performance. Simulations were done using a custom FDTD program that was written in Processing. Animations were created from 2D sections through the four geometric options. These visualizations demonstrate that - critically for sound diffusive performance - that sound energy is dispersed not only spatially, but also temporally. Reflections are spread not only over space, but also arrive at the listening positions at a variety of times, see Figure 5.

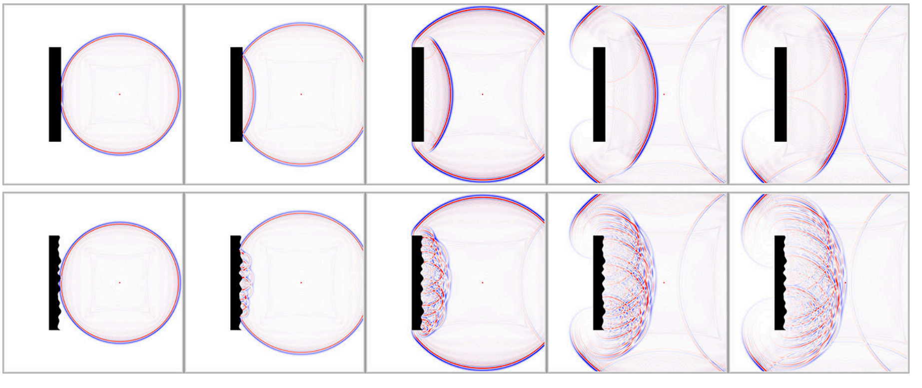

Figure 5. Stills from a sound wave visualization produced using FDTD simulation comparing a flat panel to the Shallow Wave design option.

8. Fabrication

This project arose from a collaboration between the Robotic Prototyping Lab at the John H. Daniels Faculty of Architecture, and Element5, a new mass timber manufacturer based in Ontario, Canada. Element5 donated many test samples and expressed an interest in the acoustic and aesthetic potentials of the complex surfaces made possible with robotic fabrication. To test both the aesthetic look and feel of the proposed mass timber surfaces, as well as test the design-to-simulation-to-fabrication workflow, four 1:1 prototypes were produced using a robotic CNC milling system. The fabrication system consisted of a Kuka KR150 R2700 with KL4000 linear axis with 4500mm travel and a PushCorp 10hp spindle.

From the computer models, the geometry was exported directly to the robotic milling software, Powermill. The milling software generates the required Kuka robot G-code for two sets of tool paths: a roughing pass and a horizontal finishing pass - though the "deep hex" option required only one pass due to the use of a super sweet new endmill. The 1:1 prototypes, see Figures 6 and 7, produced represent different possible scenarios and geometries that can create sound scattering in different ways. These samples are size-limited but are intended to represent the application of these surface geometries on much larger wall or ceiling surfaces.

Figure 6. 1:1 CLT wood prototypes – elevation.

Figure 7. 1:1 CLT wood prototypes perspective.

9. Conclusions

This project investigated the potential for CLT mass timber panels to be enhanced with acoustic performance through the application of CNC-milled geometries. Mass timber as a building material is gaining momentum worldwide as a practical, beautiful, and sustainable material that could be key to the fight against climate change. The architectural strategy of exposing mass timber panels offers an opportunity to prefabricate panels that have built-in acoustic performance. In these experiment different complex geometries were modelled using parametric design. Design options were evaluated and visualized wave-based computer acoustic simulation methods. BEM and FDTD methods were used. These two simulation approaches were fast when compared to scale modelling techniques and provided scattering coefficients that are used in room acoustic simulations, as well as providing dynamic visualizations of the impacts of geometry on reflected sound waves. Further work would be to improve the BEM simulation process to simulate 3D geometries rather than 2D sections, and also to be able to easily input user-defined geometry into the simulation software. Four different geometries were studied and all four surpassed performance predictions. While the wave geometries aesthetically were preferred by researchers and clients, the hexagonal surfaces had improved performance within the same surface depth; however, both wave and hexagon types of surface performed very well. The workflow from parametric model to simulation to fabrication planning software was relatively painless and produced predictable results. In terms of fabrication, next steps are to produce larger prototypes and measure the improvements in room acoustic performance in a particular case study. The results from this combined with the knowledge gained in these experiments in terms of design and simulation workflows can then be combined into a set of guidelines for designing and constructing mass timber panels with sound scattering properties.

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REFORMATIVE CORAL HABITATS

Rethinking Artificial Reef structures through a robotic 3D clay printing method.

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Abstract. In 2018 after Typhoon Mangkhut hit Hong Kong, the city lost around 80% of its existing corals. As a consequence, a team consisting of marine biologists and architects have developed a series of performative structures that will be deployed in Hong Kong waters intending to aid new coral growth over the coming years. This paper describes the present research that focuses on the design and fabrication of artificial reef structures utilizing a robotic 3d clay printing method addressing the specificities of Hong Kong marine ecologies. The paper describes further the algorithmic design methodology, the optimization processes in the generation of the printing path, and the methodology for the fabrication processes during the production cycle to achieve even quality and prevent cracking during the drying process.

Keywords. Digital Fabrication; 3D clay printing; Artificial Coral Reefs; Computational Design.

1. Introduction & background

Coral reefs are some of the most diverse ecologies in the marine world. They are the habitat to tens of thousands of different marine species. However, these wildlife environments are endangered throughout the world. Recent research estimates that around 75 percent of the remaining coral reefs are currently under threat (Burke et al. 2011).

1.1. ARTIFICIAL REEF SYSTEMS

There have been various approaches to the design of artificial reefs to restore the damaged marine flora and fauna. The most common and popular types are based on human-made objects such as discarded subway cars or shipwrecks. The advantage of such structures consists of eliminating the need for fabrication. However, they permit no microstructural development and allow only algae and oyster-type life to form, and have no potential in developing a more abundant marine life. A more target-oriented design to address the problem has been the development of concrete reef balls. Though they are perforated structures, they lack specificity and usually don’t have smaller pocket spaces where corals could

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 465-474.

easily attach and grow. Moreover, the cement used for their production is alkaline, which potentially could damage the local water conditions.

Hong Kong, with its urbanized reef, has some of the most polluted waters in the world, and special attention needs to be allocated to avoid any further pollution. Besides, the subtropical climate provokes a vast amount of underwater sedimentation, which can be detrimental to corals. An assessment of artificial reef performance indicates that only 50% meet their objectives, the remainder having no, little, or limited success (Baine M. 2001). Hence the solution for an artificial coral reef structure must be specific to local conditions to increase the chance of survival for the species.

1.2. 3D PRINTING

In the past decade, 3d printing has become a fabrication methodology in many different professions. The additive manufacturing technique is versatile and can utilize a wide range of materials, such as plastic, resin, bioplastic, concrete, ceramic, and even water-based polymers. It allows a broad range of formal divagations, which can be manipulated to optimize structure, functionality, or amount of material used. 3D printing machinery ranges from traditional printers to robotic arms and continuous feed extruders. The method permits for mass customization (Sabin, J. et al. 2017) or discrete elements with specific needs (Jimenez Garcia, M. et al. 2017).

1.3. 3D PRINTED ARTIFICIAL REEFS

Recently, the Australian design firm Reef Design Lab has developed the 3D Printed Reefs project for the WWF Netherlands Oyster Reef Restauration project in the North Sea. The project consists of 50 units ranging in size from 50cm high to 120cm height using D-shape binder jetting technology. A method that binds sand with a binder based on seawater and magnesium (Goad, A., Lennon, D. 2017).

In France XtreeE and Seaboost (Egis Group), have developed a concrete, artificial 3D printed reef, immersed in the Calanques National Park. The biomimetic yet porous reef is designed to mimic coralligenous habitats in the Mediterranean Sea. It is composed of a structurally complex and dense biogenic substrate, which hosts a plethora of species, such as fish, crustacean, coral, algae, mollusk, and many others (Mallet, A., Guillen, A. 2017).

While these projects present viable solutions to the problem, it is essential to note that the projects are site-specific, and a universal solution could be difficult to calibrate, since there are various types of underwater conditions. However, a common denominator can be considered the use of natural materials, which do not alter underwater flora and fauna and damage it furthermore.

2. Objectives

The research project outlined in this paper seeks to build on these emerging works by developing a solution addressing the specific requirements set out by the marine biologists of the team. These were first that the artificial structures needed to be suitable as microhabitats for the coral fragment of the selected coral species, Acropora, Platygyra, and Pavona corals (Fig.1). Secondly that the structure could provide pocket spaces in which corals could grow in a limited size horizontally, and develop exponentially in the vertical direction, and thirdly prevent sedimentation, a typical subtropical underwater condition. Furthermore, the 3D printed structures had to be based on ceramic material. Clay is similar to the calcium carbonate found in real coral reefs. In preparation for a worst-case scenario, in which the corals would not be able to grow and die, the structures would not pollute the underwater environment.

Figure 1. Platygyra coral (left), Acropora coral (center), Pavona coral (right).

In detail, the following objectives are defined as part of this research. (1) To develop a design strategy that builds on the concept of biomimicry to allow for complex spaces to occur that would provide attributes against the detachment of the inserted coral fragment, hence could enhance a diverse marine life specific to the context of Hong Kong water conditions. (2) To generate an efficient printing path that accommodates the specific morphological design criteria but also ensures structural integrity and the functional aspects of the design. (3) To develop an efficient fabrication process with a DIW 3D printing methodology that takes into consideration aspects of warping, shrinkage, and cracking in the clay material.

3. Methodology

To come up with a solution for the objectives stated above, the research team developed a specific method that combined an algorithmic design approach for the different geometries of the design with a digital additive manufacturing process utilizing 3D robotic clay printing. The method allows for the fabrication of complex and massive pieces while optimizing production time (Rael, R. et al. 2017). The overall fabrication strategy for the complex and large pieces sought to ensure structural longevity, optimize production time, and tackle the involved double-sided printing method.

3.1. OVERALL DESIGN STRATEGY

The overall project consists of 32 units organized in assemblies of 4 tiles each (Fig.2d). Each of the 128 tiles has roughly a size of 0.36 sqm. The tiles will eventually be deployed on the seabed in three different sites in Hong Kong waters.

In order to allow for a manageable underwater assembly through scuba divers, tiles were designed based on a hexagonal assembly strategy with three legs each, making it easier to align the system underwater.

Furthermore, the design needed to be symmetrical or based on similar patterns, because of the use of an ARMS (Autonomous Reef Monitoring Structures), which is a standardized global measuring tool for underwater life behavior. An overly irregular structure could lead to an increasingly difficult means of measuring since it would have to account for formal diversity. For the same reason, each assembly of tiles needed to be identical.

As printing solid clay tiles at this scale turned out to be a challenge since they burst easily during the firing process in the kiln, the team needed to develop a printing strategy that ensured structural integrity, but also avoided any collapse of the tile during firing. Thus, the tiles are organized into three parts. The bottom layer is a porous gridded part, which acts as a structural platform and follows generic grid 3D printing concepts (Fig.2b). The top layer is based on a bio-mimetic approach and serves as the primary surface to attach the coral fragments (Fig.2a). The third part is the footing that is based on three legs. They are printed on the backside of the tile after flipping. They ensure a necessary distance to the seabed for better water circulation and sedimentation prevention (Fig.2c).

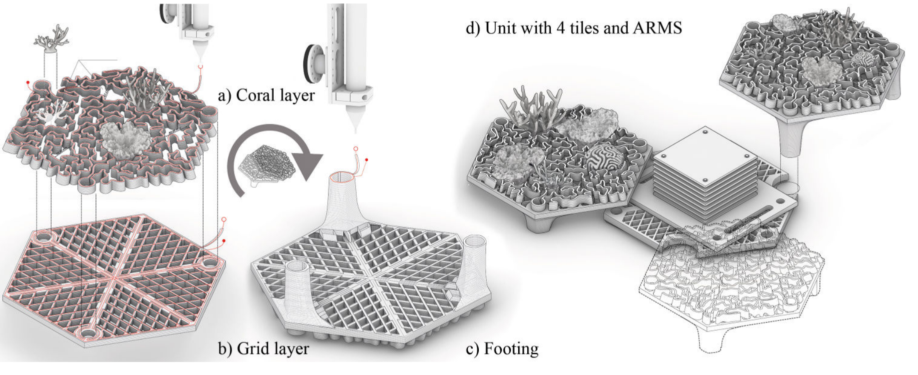


Figure 2. Concept, Manufacturing and Assembly diagram.

3.2. ALGORITHMIC DESIGN STRATEGY

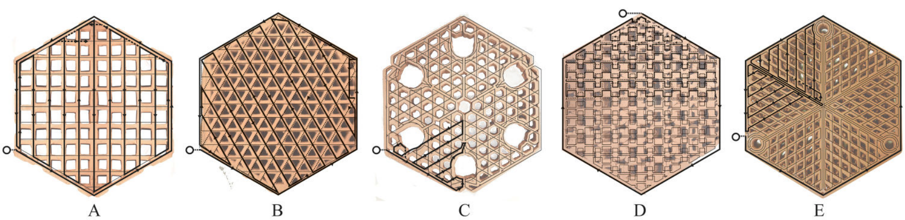
The team used a generative algorithmic design approach for the project. Using Rhino in conjunction with Grasshopper, the focus of this design method was on developing a flexible system that enables an iterative design process, tests different design variants, and generates local specificity within the tile. Custom-made definitions utilizing other plug-ins such as Kangaroo (for form relaxation), Anemone (for periodic and loop generation), Pufferfish (for grid distortion), and LunchBox (for grid generation) were used to create the bio-mimetic layers.

Each of the three composing parts of the tile was computed into a single, continuous line, to optimize printing time. A series of different lines would require more printing time, either because they would require seam calibration (position in which the robot begins a line and commences the other), or the use of an On / Off function of the extruder (extrusion stops while traveling from the end of one line to the beginning of the other). For the code generation of the ABB robot, the research team used the HAL-Plug-in for Grasshopper. This set-up enabled the efficient and accurate transformation of the line geometry into the individual target planes.

3.3. GRID LAYERS

The first set of layers of the tile was based on a traditional grid strategy common to 3D printing. The grid was implemented to prevent sedimentation on the tile's surfaces. Various types of grids were developed and tested for print speed, material minimization, and tendency to crack during the drying process. As 40 sqm of tiles needed to be printed, this set of criteria had to be optimized to reduce production time.

The various types of grids were designed so that a 20 mm diameter circle may fit within the grid's hollow openings to prevent mollusks from developing on the tile and causing potential shattering in the tile base once deployed in the ocean. The tile's size was kept at a constant 650 mm across the hexagon's diameter. Given the tile's large span, crack formation posed a challenge during the air-drying process of all grid types.



GRID	A	B	C	D	E
TIME (minutes)	40-50	60-70	70-80	70-80	50-55
LENGTH (m)	152	181	228	200	170
MATERIAL USAGE (kg, clay density: 3.7 g/cubic cm)	15.1848	18.0819	22.7772	19.98	16.983

Figure 3. Various grid tests with overlaid printing path.

Fig.3A represents a square grid prototype. This grid was generated with intersecting, perpendicular paths, and contained within a hexagonal boundary. Of all the grid types, the square grid used the least material and printed the fastest. It had a total print length of 152 meters divided across 8 layers. However, the grid geometry was eventually dismissed since it did not work well with the coral layer above.

Fig.3B and Fig.3C represent the triangular grid and, respectively, the tri-hexagonal grid. Similar to the square type, these grids were generated with an intersecting path strategy, angled at 30 degrees. The triangular grid had a total print length of 181 meters, while the tri-hexagonal grid had a print length of 228 meters. During the drying process, the former tended to crack and separate at the intersections, while the latter displayed typical s-cracks.

Fig.3D represents a manipulated Peano space-filling curve cropped to the hexagonal tile. This space-filling curve was altered as such that every other member touched or intersected helped breaking the various stresses that occurred during the drying process. The print length of the grid was 200 m. However, since this grid had many sharp turns within the printing path, the printing speed had to be reduced from 70 mm/s to 55 mm/s to ensure that the printed clay adhered to the layer below. Hence, making this strategy less efficient than the other grids described.

Fig.3E represents a diagrid with bracing prototype. The diagrid presents a manipulation of the square grid's geometry as such that its members are parallel to the bracings placed within the tile. The theory behind this strategy was that it would strengthen its structural stability against torsion and create an infill that is symmetrical around its center, which allowed the tiles to dry symmetrically. The total print length of this prototype is 170 meters. The strategy worked best with the geometry developed for the coral mimicry layer and was also the most stable solution for the prevention of cracking.

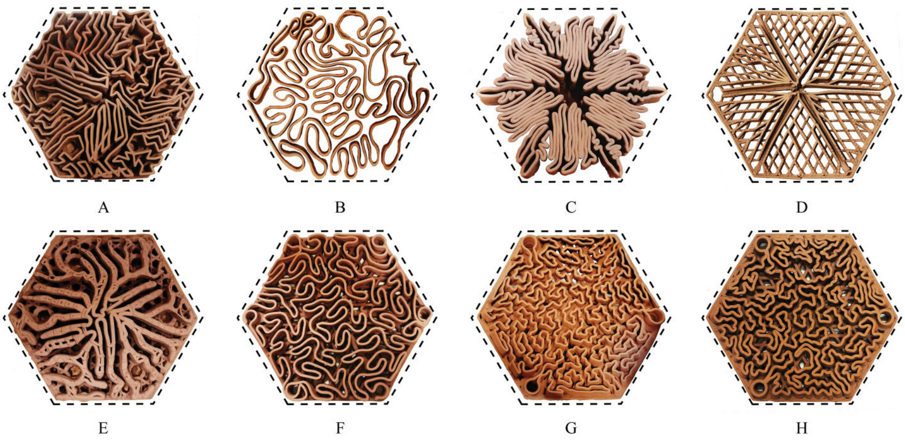


Figure 4. Prototypes of tested coral mimicry strategies.

3.4. CORAL MIMICRY LAYERS

Out of the three species of corals that will eventually be inserted into the artificial reef structure, the Platygyra coral was chosen as a point of departure for the biomimetic form-finding technique. The pattern with its undulating behavior proved to hold the most potential to achieve the ridges that act as anchors for the corals, and the trenches that direct sedimentation. A series of different algorithmic strategies were tested, both in the digital and physical environment, to calibrate the relationship between generative coding, robotic fabrication, material behavior, and ergonomic factors aiding coral growth.

Fig.4A represents a space-filling curve, which is a strategy of mapping multi-dimensional space into 2-dimensional space. It acts as a thread, which passes through every pixel of the space only once (Ventrella, J. 2012). The curve fills the space within the perimeter of the pre-determined hexagon. It proved potential in terms of accounting for the necessary minimum distances between ridges and trenches, and it created a dynamic structure. However, the irregularity of the structure does not perform well with the clay material, leading to breakage.

Fig.4B shows a prototype based on a curve derived as an outline of a circle packing logic. Geometrically, circle packing constitutes the display of circles of various sizes on any surface, ensuring that no circles overlap, but they all touch their neighboring circles (Stephenson, K. 2003). Similarly to the previous test, it had the potential to calibrate distances between print lines according to any given logic but did not perform well as a 3D printed clay prototype.

Fig.4C embodies a particle growth curve, generated in a neuron growth logic, which implies that an original nucleus spreads into branches, developing in a fractal manner. While the distances can be augmented (in the present image, the openings are too narrow), the overall shape lacks structural stability.

Fig.4D exemplifies a logic based on the shortest path. The shortest path is a mathematical concept in which, in a network of curves, the shortest route from a line start point to line endpoints in a network is calculated. Following the diagrid planimetry, the code established a branching methodology according to the shortest path. However, the uninterrupted long lines, which didn't branch, intersect, or deviate from the straight path, are not optimum for 3D printing with paste based materials and do not present structural strength.

Fig.4E represents a merge between the space-filling curve methodology and the shortest path logic. It proved to be structurally stable, but in vertical development, the print started to become inaccurate with a lot of unnecessary material deposition.

Fig.4F and Fig.4G represent prototypes based on a Gosper Fractal curve, which is another type of a space-filling curve, mimicking the fractal development of a snowflake. A generative growth algorithm was applied to the curve (Runion, A. et al. 2005), which then was projected on the underlying diagrid. This strategy allowed the fractal curve to deviate the straight lines only along the diagonal of the diagrid cells, which aided printing. Each fractal subdivision coincides with either the corner of a cell, a diagonal of it, or a middle point of a perimetric curve of the cell. The curve was then relaxed to avoid sharp edges, which can damage coral growth. As the layers are deposited vertically, they start to taper. The curve follows the same logic within its whole geometry, with the exhibition of larger openings in the footing areas, which allows the addition of footing elements. It further was augmented to respect the size limitations of coral growth.

Fig.4H represents the same Gosper Fractal curve, altered to accommodate the use of pockets. The logic for the pockets was done through a folding curve technique, in which the initial curve is subdivided into additional parts, by using more control points. The points were then culled and distanced from an emitter (the center of the pocket), which created additional folds in the curve. This concept also turned out to be the least cracking one and was chosen as the final strategy.

4. Printing methodology and fabrication

The clay tiles were printed with a DIW printing technique (direct ink writing) (Carlos, R. et at 2017), in which the layers are printed one on top of the other. This technique requires no use of scaffolding or molds, which eliminates material waste. As printing set-up, the team utilized a standard ABB 6700 industrial robot with a deltabots linear ram extruder equipped with a 6mm nozzle. The tiles were printed directly onto the kiln shelf made of cordierite, which proofed to be an excellent material for water absorption. The specific clay used was Red Terracotta Clay (P1331, Potterycrafts ltd) mixed with less than 1 % Fine Fraction Crystalline Silica. The printing layer height was set at 2.7 mm to optimize adherence. Extruding speed varied for different parts of the tiles, differing from 10.5 mm/s to 17 mm/s. Layer width fluctuated between 6mm to 11 mm, depending on extrusion speed.

The grid layers were designed with a doubled printing path, to ensure enough mass to prevent cracking, which can happen due to the tension formed within the geometry during the drying process. The infill is only 65% solid, to ease the overall structure and reduce printing time. The width of the grid layers was 11 mm, a thicker structure being able to provide more stability.

The coral-mimicry layers had a width of roughly 6mm since structural stability was established in the grid layers. The geometry was designed in a tapered manner at a 22-degree angle, so that not only the overall ridges prevent sediment deposition, but the overall shape directs outward. The tapering was optimized according to clay behavior.

The tiles were dried in a stable environment for two days before they were flipped for a second printing process that entailed the printing of the legs. The surface was manually roughened up to ensure proper adhesion between the footing and the grid layer. The tiles were then stored vertically and rotated periodically to prevent cracking and to avoid water deposition towards bottom layers. In some prototypes, the layers were dried with a heat gun as printed, but the strategy proved no benefits as opposed to regular drying strategies.

After the tiles had become bone dry during several days of drying, they were fired in a kiln at 1125C. The overall shrinkage after drying and firing was eventually 11%, which is relatively high and could be avoided by using other types of clay with a lesser shrinkage factor.

5. Reflections

The outcome (Fig.5) of the project was successful regarding the design process, algorithmic design strategy, and the robotic 3D printing process. However, the most challenging part of the 3D printing paradigm within the "Reformative Coral Habitats" project was the drying process.

Within that process, the relationship between the horizontal and vertical dimensions of the tiles seems to play an important role. While significant in the horizontal direction, with a diameter of 650mm, the height of 80mm seems not sufficient to counterbalance the tension within the tile during the drying process. While the team had achieved fruitful results, it is not entirely clear how the different parameters involved influence the process. Both the grid, acting as a base-plate, as well as the biomimicry layers, have been subject to a continuous trial-and-error process of optimization. As the team was confronted during this process with much cracking, the design of the printing path and the drying process required calibration that resulted even in the design of devices that enabled the tiles to be dried vertically.

Figure 5. Assembled Prototype.

Hence, it would be desirable in the next iteration of the research to further understand the relationship between scale, dimension, geometry, printing path, and material. Furthermore, it would be beneficial to understand what the relationship between clay-type, cracking, and drying environment is.

Because of the problems mentioned above, the project holds potential not only in terms of aiding coral growth but also in developing a workflow for large-scale 3D printed ceramic tiles. The developed methodology of printing, drying, and assembly can be applied to industrial-scale projects, as currently, there are very few reference projects of 3D printed tiling in the industry.

6. Conclusion

The research presented is in an on-going stage. The prototypes will be deployed in underwater conditions for a period of two years, which is estimated to be the amount of time needed for corals to start being able to form self-supporting structures.

The next phase will focus on measuring the behavior of the corals when interacting with the clay tiles within the specific geometry. While the corals have been tested with the material in a lab environment, the impact of the geometry on the growth of the coral has still not been researched. The results of the measuring within each tile will determine the success of reef growth. However, all tests will be based on identical geometries within the tiles. Further developments could propose a broader range of formal exploration to understand better if geometries play a vital role in the development of coral growth. The testing could either utilize a method of mass customization, in which each tile is unique or use a strategy in which the elements are the same but vary in scale.

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PICA

A Designer Oriented Low-Cost Personal Robotic Fabrication Platform for Sketch Level Prototyping

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Abstract. As digital design and fabrication are becoming increasingly prevalent, it is essential to consider how these technologies can be made more affordable and intuitively introduced to individual designers with limited computing skills. In this paper, we present an affordable personal robotic fabrication platform, PICA, consisting of a 3D printed robotic arm with a set of controller programs. The platform allows designers with limited computational design skills to assemble motors and 3D printed parts easily and to operate it in a code-free environment with direct manipulation through 3D modeling software. With the real-time communication between 3D modeling software and this robotic fabrication platform, PICA also allows designers to efficiently change the topological properties of geometry during the fabrication process. Based on a comparative observation of several application scenarios of using PICA among two groups of architecture students, the research can be summarized as follows: 1.) The project has proved to be an affordable approach to ease the materializing process when converting a designer's initial intent from digital space to a physical prototype. 2.) Designers could be facilitated by utilizing this robotic fabrication platform, especially during the period of conceptual design.

Keywords. Robotic Fabrication; Design and Fabrication; Tool Development; Designer Oriented; Ubiquitous Manufacturing.

1. INTRODUCTION

While the rapid development of digital fabrication tools is expanding the possibility of design space, its complexity reduces the access to the majority of designers who are not equipped with computing skills to take advantage of these technological advancements. Three main contradictions are preventing digital fabrication technologies being more affordable and accessible to designers with limited computational design skills. First, design practice is a process that requires balancing production efficiency and labor input (Arayici et al. 2011). Most of contemporary computational design and fabrication tools hinder their users from mastery by a long-term steep learning curve (Sharma et al. 2011),

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which usually distracts designers from the core content of design tasks to the tool's manipulation (Teng and Johnson 2014). Second, precision and advanced digital fabrication tools are not suitable for the early stages of design that aim to establish the geometric topological relationships of a given design, such as massing study. Digital fabrication tools are mostly expected to be used for final production or late design phases which mainly focus on precise dimensions, positions, and tolerances. However, the physical working model also acts as an intuitive representation during early stages to push a design forward (Knight and Theodora, 2015) in which the precision information is not critical. Utilizing sophisticated fabrication technologies for a physical working model will increase the various costs as well as limit the design possibilities. Third, in the early stage of design, users' demand for consumer-level digital fabrication tools is much higher than industrial-level products. However, consumer-level digital fabrication tools have maintained at a high price, which makes it difficult for independent designers to afford.

Figure 1. PICA, a Designer Oriented Low-Cost Personal Robotic Fabrication Platform.

In this paper, we introduce PICA (Figure 1), a designer oriented low-cost personal robotic fabrication platform that aims to address these sketch-level prototyping issues. This research project is organized at two levels. At the bottom, we aim to develop a reproducible and affordable robotic fabrication platform (including hardware and software) as a foundation, that allows designers to assemble easily and customize upgrades. At the top, by using PICA, we try to design applications that embody direct manipulation with adaptive fabrication processes to aid designers in the conceptual design process. We also aim to liberate designers from complicated machine language coding and operation. We hypothesized that, with a low-cost robotic fabrication system in a coding-free environment, designers with a limited computation background can still conduct a fabrication task to enhance their design experience and smooth the design to fabrication workflow.

2. BACKGROUND

The Design-to-fabrication workflow and increasing popular interest in digital fabrication is frequently obstructed by steep learning curves. Utilizing industrial robots for fabrication demands two learning subjects. On the one hand, robotics is an enormous interdisciplinary subject. Designers and researchers should have essential exposure to various topics, including mechanical design, kinematics, end-effector design, machine language coding, spatial analysis, and sensing technologies (Shahmiri and Ficca 2016). On the other hand, the operation of robots is also equivalently essential. It is worth pointing out that most industrial robots are painted with orange, it indicates that operating an industrial robot is usually restricted and dangerous (Edgar 2008). Learning the robot operation protocol is often time-consuming for beginners ,and getting familiar with the manufacturing procedure and material property also requires designers' input. All the expertise which most designers were not supposed to be equipped with in their career path demands a considerable investment of time and energy.

Second, the architectural design process reflects the designers' imaginative ideas and their materialization procedure. The thinking pattern beneath this process is a transition from abstract to concrete, and flexible to restricted. The majority of contemporary digital fabrication tools are numerically driven, which requires the users to input the precise numbers, even when their design ideas are in the early stage. The precise number is not capable of handling uncertainty, multidimensional complexity, and flexible compromises. Quite the opposite, excellent design inspiration, also known as the ”aha moment”, is often generated in a relationship-oriented adaptive environment rather than in an accuracy driven setting.

In addition, since design is an iterative process, the repetitive work is unavoidable (Simon 1996, Meng 2009). One of the main goals of the repetitive work is to seize and optimize these reiterative insights and inspirations through continuous trials and errors, then push the design concept to the implementation at a more practical stage. The working model plays a critical mediating role in the design process, it is not only a representation and summary of design outcomes but that the tactile and material engagement helps to explore and discover the hidden design potentials (Knight and Theodora 2015). Utilizing robotic fabrication technology to make a working model is not ideal. For instance, to make a model for a massing study by a robotic arm, the designer firstly needs to determinate an exact size of the massing, then set up a toolpath by scripting in the robot controller software. After the robot slowly processes the model, the designer might find a particular size needs modifying, so the designer has to repeat the previous operation until the result is satisfied. Existing robotic fabrication processes are complicated and non-intuitive. Precisely sized geometry is converted–which is likely modified in later phases–to readable machine language and further translated to sophisticated equipment. The designer-oriented fabrication process needs to be more intuitive to encourage designers to focus more on the overall geometric form instead of a specific size. Meanwhile, the robot needs to be controlled in real-time rather than in a one-way execution to take advantage of uncertainty to generate new inspiration. In short, the model should be rapidly made with a more user-friendly means.

The argument above is not to deny the importance of precision fabrication in the later design phases, however, considering the cost of robotic fabrication, it is unnecessary and uneconomical to utilize an industrial robot in the early stages, such as with a massing study. A piece of low-cost consumer-level equipment is sufficiently functional to perform most of the fabrication task.

3. RELATED WORK

The establishment of our project PICA starts from the investigation of direct manipulation and live control of a robot as well as the prototyping process in terms of design. Recently, research has been developed and conducted to operate an industrial robot through an operator's direct behaviors without working in software user interface and to conduct fabrication work. For instance, Andrew Payne (2011) developed a robotic motion controller with 5DOF that can be manually operated by users. The potentiometer reads the rotation angles and sends to an ABB industrial robot. But the controller can't make the industrial robot follow a pre-defined toolpath since the robot is controlled through forward kinematics, and thus restricted the application of this direct manipulator in fabrication tasks. RoMA (Peng et al. 2018), combines robotic fabrication and augmented reality in the same volume to allow the designer to build a model in an AR environment; the robotic arm follows the designer's gesture to print a wireframe model in real-time. FormFab (Mueller et al. 2018) develops a formative fabrication method that changes a closed thermoplastic shape by warming specific areas to adjust internal air pressure. Users' gestures determine where the thermoplastic should be warmed up by the heat gun attached to a robotic arm.

There are other existing research projects explore real-time control of the robotic arm for fabrication. The popular software that has the potential to connect both 3D modeling activity and robot operation is Grasshopper. However, sending real-time data to robot operation software from Grasshopper often requires multiple layers. Some of the famous example that can control robots via Grasshopper are HAL or KUKA. However, the fact is that this program is designed to generate the toolpath and convert the toolpath into robot programming languages such as RAPID and KUKA, which means that operators still need to execute toolpath commands through robot controller software. Besides sending real-time data to change an executing program, some of the research showcases opportunities for sending real-time data to control an end effector, which typically runs as a stand-alone device. Robosense (Rosenwasser and Sabin 2018) is a project that attaches sensors to the robot's end-effector. It uses these sensors to monitor environmental and material factors, then applies these parameters to change the extruding pressure.

4. IMPLEMENTATION

4.1. HARDWARE IMPLEMENTATION

The making of PICA starts from an in-depth investigation of the current 6DOF industrial robotic arm and designers' demand for personal fabrication. To design a new configuration of a robotic arm, we firstly determine the constant motion and structure parameters of the robot, including the maximum movement speed of each axis according to the duration required to complete the task. Hereafter, with the assistance of a robot's parametric kinetics model that we build in Grasshopper, we determine the length of the upper arm and forearm based on the maximum motion range that is capable of carrying the allowable payload to the end effector.

The core components of PICA include the main body, motors, reducer, and controller. The fully 3D printed main body of the robot arm is sufficiently robust for lifting tasks. The main body, similar to industrial robotic arms, is assembled by a base, shoulder, upper arm, forearm, wrist, and a series of grippers. (Figure 1).

Since the primary users of the robot arm are designers, we accomplish a parametric digital model of PICA with Rhinoceros & Grasshopper and make a set of customized components in Grasshopper to control the assembled robot arm directly, which gives easier access to designers and offers opportunities for further development. Since PICA follows the model of "joint-link-joint-link-...-link-end effector," (Figure 2) the parametric model of the robot is mainly determined by the length of links. It establishes the overall relationship between various parts, and defines the size, shape, and position of each component in the entire configuration. In the future, when a designer needs a new robot arm to perform a new fabrication task which requires a broader moving range, he or she can achieve it by setting a new length of arm segment and printing the new replacement (Figure 2). Also, the control signals are updated with the kinetic model accordingly in the Grasshopper definition.

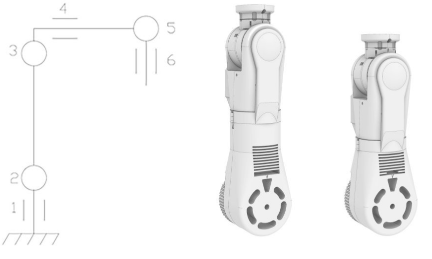


Figure 2. joint-link-joint-link-...- link-end effector model (Left) and the two forearms with different length generated by the parametric model (Right).

Generally, for ensuring precision of movement of the robot arm, servo motors are used in the heavy-duty industrial robot arms. The motor encoder of the closed loop drive system is used to achieve high precision movement. However, as this project aims to develop a lower cost configuration with relatively acceptable accuracy control, seven bipolar stepper motors are used instead of servo motors. According to the configuration of the axes, all six axes can be classified as two types based on its stress situation, every kind of axes have similar calculations. For the axis of 6,4, and 1, it overcomes the inertia force and friction force since the 3D printed parts on these axes are engaging each other. Axis of 5, 3, and 2 is another type that is primarily rotating against inertial forces, friction, plus gravity. Therefore, the calculations of axis 5, 3, and 2 need to consider the impact of gravity. After determining the necessary load and transmission, the primary motor parameters such as holding torque and the rated current can be calculated based on a complete rotation range of the joint. The calculation above helps to determine the stepper motors. In this project, the stepper motor types that are used in PICA are NEMA 23, NEMA 17, and NEMA 14.

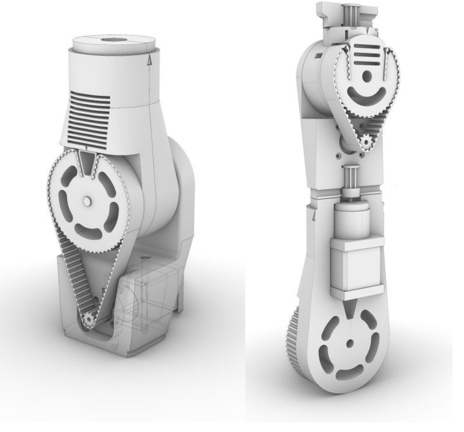


Figure 3. Two types of the joint system: Left, Axis of 5, 3, and 2; Right, Axis of 6,4, and 1.

In terms of the reducer, harmonic drives and Cycloidal drives are commonly used in the industrial robot, which decelerates the motor rotation and increases torque. Deceleration ratio and I/O torque are considered when selecting the reducer. The deceleration ratio of each axis' reducer is determined according to the relationship between the maximum speed of the motor and the required motion speed. For motors that directly connect with the reducer, the maximum reduction ratio can be directly obtained. Moreover, for the motor that connects with the reducer through transmission, it is necessary to determine the maximum reduction ratio according to the design of the transmission and motor speed. In our configuration, for economic considerations, we design a joint system that uses a timing belt to achieve the same purpose of the reducer (Figure 3). Stepper motors at 1,2,3 and 5 axes use this timing belt system to drive remaining joints after the reducer decelerates and amplifies the torque. However, for the 4th axis, as the forearm is very compact, we retain the stepper motor with harmonic reducer as the transmission device.

We also successfully achieve one of our goals as we are aiming to establish a new configuration of a 6DOF robot arm with lower cost comparing with an industrial robot arm. The total cost of PICA, including all necessary components, is less than $800 (table1), making the robot arm affordable for most designers.

4.2. SOFTWARE AND CONTROL

As mentioned above, PICA is a designer-oriented robotic fabrication platform It is developed via a parametric model in Grasshopper that allows designers to define the different lengths of arm segments. Meanwhile, PICA also is operated via Rhinoceros with Grasshopper. A set of customized grasshopper components is made for completing the operation. Fundamentally, there are two approaches to control the robot, and one way is sending rotation degrees on each joint and driving the robot by inputting a number a number directly. This approach is mainly used for moving the robot arm without an expected toolpath. However, since we are conducting a designer-oriented robotic fabrication platform, the robot is required to track toolpaths in most cases. As such, inverse kinematics analysis is significant in the project. The inverse kinematic analysis Grasshopper component allows real-time computer calculations of the rotation degree at each joint. This is based on the position and orientation of the robot's end effector in the spherical coordinate system by applying Denavit-Hartenberg parameters. We set six individual coordination systems along each joint, defining the axis as Z direction and common normal (the link between two joints) as X direction (Figure 4).

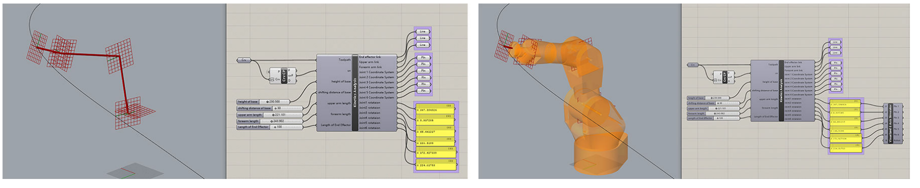


Figure 4. The Kinematics Analysis Component calculating rotation angle and coordination system on each axis, with the input of length of each link and end effector (left) . The filtered solution of inverse kinematic analysis with a visualized robot simulator(right). .

In terms of inverse kinematics calculation, the first step requires obtaining the coordinates and the position of the end effector and to then determine whether the coordinate is in the working range of the arm, and if it is, the inverse kinematic calculation starts. Next, divide the six joints into two groups. First, use the descriptive geometry method to calculate joints 1, 2, and 3. Since the calculation of these three joints are separated from joints 4, 5, and 6, together, they hold the overall posture and positioning of the robot arm. Joint 1 mainly controls the rotation of the whole arm and can be projected to the XY plane for calculation. Joint 2 and joint 3 are separated from the overall rotation of the robot arm and can be projected to the XZ plane or YZ plane for calculation. After completing the calculation of joint 1, 2, and 3, the results are substituted into the D-H matrix of the robot arm to prepare for subsequent calculations.

As most fabrication tasks require a toolpath, which is a 3D curve in digital space, the topological property of this 3D curve as well as the shape of the end effector will define the rotation angle of the rest of the joints. For instance, when conducting a milling task, the direction of the end effector will need to be perpendicular with the tangent vector of the curve at a specific point. This direction, along with the end effector length, determinates joint 4 and 5. According to the constraint conditions, it obtained multiple solutions of arm's posture. We filtered these solutions that are not satisfied with the constraint and select the optimal solution as the final result according to the shortest path principle (Figure 4).

4.3. COMMUNICATION BETWEEN COMPUTER AND PICA

PICA connects with an Arduino Mega board as media to receive data. The host computer generates all joint rotation angles via grasshopper inverse kinematics components. These generated angles need to convert into step numbers to be sent to stepper motors through Arduino to get the robot working. A set of stepper motor drivers (TB6600 in this case) is associated with each stepper motor, which send step and direction information and provide sufficient rated current.

In terms of the communication method between the host computer and Arduino, through case studies, we found that most designers are using Firefly to connect Arduino with a computer. Firefly, as an excellent example of a visual programming tool, provides a more comfortable and intuitive way for designers to operate Arduino and build simple interactive prototypes. However, it is not the best option for us since we are eager to motivate designers to be less dependent on design tool manipulation in order to focus on the design process with the help of PICA. Firefly has a number of limitations. The maximum number of stepper motors is only four, which is not capable of carrying what we need. In addition, we need to save digital pins for end effector development. In this project, we attached an ethernet shield with Arduino Mega board to convert it as a standalone client with an IP address. By locating this IP address with UDP in Grasshopper, all data for 6 or more stepper motors can be sent to Arduino as a string through the ethernet cable (no USB connection required). As such, if the designer needs to further develop an end effector to perform a fabrication task, he or she can have a separate Arduino board connecting with host computer via USB.

Our configuration of PICA allows real-time communication between the robot and host computer. This is because PICA does not have to be operated based on robot programming languages. Grasshopper is capable of streaming data over UDP, but the inverse kinematic analysis software doesn't have to be limited within Grasshopper, as long as the software supports UDP. This streaming approach adds media to help those designers who have limited expertise in robot programming language.

5. APPLICATION of PICA

The design of the end effector primarily determines the Application of PICA. In this case, we aim to examine if direct manipulation and real-time control can facilitate modeling activity at the sketch level to reflect the vision of this research. Firstly, we attached a modified hot glue gun on axis 6 as PICA's end effector and paired it with the other stepper motor to extrude the hot glue filament. Additionally, we also set up a pottery station that allows participants to throw clay on a turntable, and to be scanned by two IR depth scanning device.

The goal is to extract spatial and formal data from real-time analysis of a designer or artist throwing clay on a wheel and to then use these data to shape any form of vase directly by a person's hands. The two IR scanners capture the shape-changing process of this vase from a rough massing to a decent ware. Meanwhile, the dynamic shape is digitized into the Rhinoceros interface in real-time and the PICA plug-in is used to generate a toolpath that wraps around the digitized mesh. As data is captured in real time, PICA starts printing another vase in hot glue following the bespoke changing shape of the clay vase that is being manipulated by the designer or artist. As the printing material is hot-melt adhesive, it offers us the opportunity to change its shape when maintaining a high temperature. While the designer modifies the original clay object directly by his or her hands, the printed geometry is also modified by the robotic arm with its hot end as it is slowly pushing and dragging the vase wall. Since the hot glue sticks have a larger diameter than regular filament, precision is lost. We are still exploring methods to cool down the printed material faster. However, this interactive robotic fabrication process confirms our argument that a low-cost robotic system is capable of conducting a sketch-level modeling task through direct manipulation and real-time control. (Figure 5 and 6)

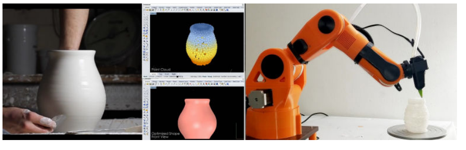


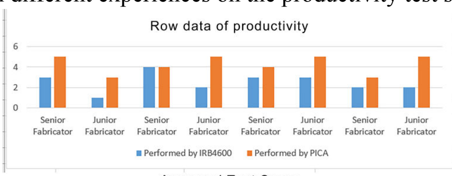
Figure 5. IR scanners are recording the throwing process performed by a designer; Rhino/Grasshopper generates an optimized shape and toolpath for robotic printing, and A tangible vase printed by PICA with hot-melt adhesive.

Figure 6. Vases printed by PICA.

Based on this application, we designed an experiment to evaluate our hypotheses. The experiment was performed in an academic design environment and research lab. The first independent variable is the robot that all participants used to print a vase, whether the use of PICA or an industrial robot (IRB 4600, in this case). The second independent variable is the digital fabrication experience that all participants engaged in. The dependent variable is the productivity that participants had during the study. The techniques that each participant deployed to make a vase is within-subject factors and fabrication experience as the between-subject factor. Participants were from the architecture department at Cornell University. All 8 participants varied with pre-experience and grade; designers with no more than one year experience of digital fabrication were marked as junior fabricators, and the rest are marked as senior fabricators. All 8 participants were familiar with 3D modeling software Rhinoceros to be used in the experiment at different levels.

First, participants were randomly assigned a picture of a vase and were asked to make the clay vase massing by hand according to the picture and to simultaneously 3D print it with PICA within 15 min at the same time. Second, they were randomly assigned a different picture of another vase and were asked to build a 3D massing in Rhinoceros according to the picture and to 3D print the vase with the IRB 4600 (2mm extrude mounted) within 15 min. The dependent variable, productivity, was measured by the completed portion of the vase, printed either by PICA or the IRB 4600. The qualified vase massings should be similar or the same as the picture provided in the experiment. Successfully printing the entire vase would be scored 5, completed printing 80% (measured by finished height) of the vase would be score 4, and so on. After the experiment was complete, the raw data was collected as follows. (Table 1)

Table 1. The raw data collected through the experiment (up) and the Effector of the fabrication method with different experiences on the productivity test score (down).



Averaged Test Score

	Performed by IRB4600	Performed by PICA	Mean
Junior Fabricator	2	4.75	3.375
Senior Fabricator	3	4	3.5
Mean	2.5	4.375	

The results are indicated as follows, a 2 X 2 (fabrication method X digital fabrication experience) factorial analysis of variables (see Table 1). The dichotomous data (low-cost robot arm or industrial robot arm) resulted in highly significant results. As shown in Table 2 and 3, the participants assigned to use the industrial robot for the printing task in the group of junior fabricators reported an average score of 2 on the productivity measure. Meanwhile, an average score of 4.75 was reported when a junior fabricator group printed with PICA with direct manipulation. Participants assigned to use the industrial robot for the printing task in the group of senior fabricators scored an average of 3, and an average of 4 in the printing task with PICA along with direct manipulation. The mean score varied from 2 to 4.75 across the four scenarios. The results suggest that productivity is impacted significantly based on the fabrication method. The average productivity for both groups improved. The productivity measured by PICA (associated with direct manipulation) is significantly higher in comparison to the productivity measured by IRB 4600 (associated with the regular one-way fabrication workflow). The productivity of PICA & direct manipulation approach (mean=4.375) is greater than that of IRB4600 regular one-way fabrication workflow (mean =2.5). The level of a designer's digital fabrication experience also impacts productivity. Generally speaking, designers who have more working experience have higher productivity. The productivity measured in the senior fabricator group (mean= 3.5) is greater than the junior group (mean=3.375).

6. CONCLUSION

The research project PICA provides a practical approach for designers with limited computational design experience to conduct fabrication tasks via a low-cost robotic platform. Designers could benefit from utilizing the described platform, especially during early phases of the architectural design process. PICA allows designers to focus on the topological properties of massing and to fabricate it with a user-friendly interface. Meanwhile, we encourage designers without computing skills, the target group of this project, to build their low-cost robotic platform for personal fabrication by replicating our design. Last but not the least, the realm of designer-oriented low-cost robotic fabrication tool remains partially unexplored. This research sits at the intersection of architecture and Human-Machine interaction, but does not necessarily solely reside in either. Instead, the work we propose resides at the interconnection between multiple areas - an interdisciplinary and collaborative environment is a necessary condition to support further research.

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Theory, Philosophy & Methodology

COMPUTATIONAL PRAGMATISM

Computational design as pragmatist tools for the age of the Anthropocene

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Abstract. The age of Anthropocene describes a geological epoch wherein human action is recognised as a global-scale geophysical force that is reaping devastating consequences for the natural environment. What the Anthropocene and pragmatist thinking share is an understanding of the coevolution of life and the planet (in pragmatism's terminology human-environment relations) through a deeply systemic view. This paper outlines how core methods and theories currently engaged under the rubric of computational design can also be understood to align to key tenets of pragmatism. In so doing, the question this raises is how more recent advancements in computation that include so-called Artificial Intelligence (AI) applications in design might operationalise distributed, shared, and significantly, interactional notions of systemic agency? The argument put forward here is that a neo-pragmatist perspective of computational design must fundamentally engage AI as the age of the Anthropocene necessitates a relinquishing of the privileged view of human-only agency and control over systems towards a more dynamic and interactional model.

Keywords. Computational Design; Pragmatism; Artificial Intelligence; Anthropocene.

1. Introduction

A range of publications over the previous decade have sought to address what it means to engage with digital tools and computing applications in architectural design and in ways of working in the architecture, engineering and construction (AEC) industry (Burry 2011; Burry and Burry 2012; Deutsch 2015, 2019; Gardner et al. 2019; Gerber and Ibañez 2014; Menges and Ahlquist 2011; Leach and Yuan 2018). As opposed to striving for the 'correct' use of technical terms and concepts (Stasiuk 2018) or establishing a 'true' history of digital and computing applications in architecture (Wintour 2018), the aforementioned publications give focus to the practical as well as epistemological and ontological implications of

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 489-498.

engaging digital and computational methods in the design, delivery and production of architecture in the twenty-first century. What draws this body of work together is an effort to shift normative perspectives around the roles and impact of computing in architecture. Here, computing is understood as not merely a tool of representation or machine for making but rather a medium to think and design through (Carpo 2018, p.135). In other words, computing is a process that can operate as an intelligent collaborator in design practice. Of course, these are not wholly new ideas. Conceptualising computing's relationship to architectural design as collaborative echos, builds from, and in many examples, operationalises ideas initially postulated by key American and European figures who explored the earliest forms of digital computing applications in architectural contexts from the 1960s onwards including Ivan Sutherland, Nicholas Negroponte (1969, 1973), William J. Mitchell (1990a), Christopher Alexander, Cedric Price, and Yona Friedman (Vardouli 2016; Wright-Steenson 2017). Through computing, each of these figures speculated on radical new forms of design practice, from testing how architectural concepts and spatial relationships could be given mathematical description to creating participatory design processes, and responsive environments. In so doing, these earlier experiments also critiqued the hierarchical structure of architecture by de-centering the architect as expert, re-engaging end user(s), and prioritising human and environmental data over design decision-making practices rooted in human intuition and empirical generalisation. This thinking, shaped by a different set of cultural logics and realised through a more technically advanced ecology of allied digital and computational technologies, is now reimagined (or re-branded) as computational design. But, and as this article will argue, while the technologies may have evolved and the terminology may have changed, then and now the reimagining of architecture's relationship to computing reflects core philosophical principles of pragmatism.

Accordingly, this paper will discuss how computational design thinking and systems align to key tenets of the philosophical tradition of pragmatism. Particularly, this will argue that evoking a pragmatist perspective of computational design matters as it can open-up more productive understandings of architecture's changing relationship to computing and its implications for design practice, education, and the environment. The following sections of this paper begin with a brief outline of the philosophy of pragmatism. Secondly, this follows with an analysis of the ways pragmatism's key, and sometimes conflicting premises align to computational design. And lastly, the paper will conclude by reflecting on what a pragmatist perspective offers for addressing questions about the role of artificial intelligence (AI) in design practice and the possibilities of realising modes of distributed, shared, and significantly, interactional design agency.

2. Alignments between the Anthropocene and Pragmatism

The concept of the Anthropocene, as popularised by atmospheric chemist Paul J. Crutzen and limnologist Eugene F. Stoermer at the turn of the millennium, describes a geological epoch wherein human action is recognised as a global-scale geophysical force that is reaping devastating consequences for the natural environment (Crutzen and Stoermer 2000). Describing an age of humans in this way intends not to celebrate humanity's innovation and progress, but rather to draw critical focus to the anthropogenic causes of climate change. As a cultural concept the Anthropocene can be engaged historiographically to re-think established histories, stories and narratives (Trischler 2016). Yet, the Anthropocene equally pursues the projective aim to radically shift the anthropocentric worldview that has framed nature as a resource to be expended with little consideration for the longer-term consequences. Given this, the philosophical tradition of pragmatism, that aims to examine and understand human action in the world may seem an incongruous pairing. But as with the Anthropocene, pragmatism adopts an interactional worldview and is concerned with understanding the implications of being in the world towards affecting change. Put another way what the Anthropocene and pragmatist thought have in common is the shared aim of understanding the coevolution of life and the planet (in pragmatism's terminology human-environment relations) through a deeply systemic view.

Pragmatism is a contemporary branch of philosophy originating in America in the late nineteenth century. Pragmatism encompasses several generations of philosophers, numerous philosophical themes and much contestation. Three key figures of twentieth-century pragmatism include Charles Sanders Peirce, William James and John Dewey. A core maxim attributed to Peirce (1839-1914) argues that the meaning of our ideas can be best understood by considering how they guide our actions (Thayer 1981). This links sense-making to the observation of action or phenomena in the world over abstract reasoning. Significantly, this method of philosophising challenged traditional philosophy and offered an alternate and empirical approach to the analytic view. In so doing, pragmatism has advanced what is described as a process ontology or in simpler terms an action-oriented approach to understanding the world and to disclosing the realities of nature (Dewey 1958 [1924], p.x). Of significance to the concept of the Anthropocene, that challenges us to reject the practice of viewing the more-than-human world as simply a container for human action, Dewey advanced the idea that humankind is a part of nature not apart from it. From here, Dewey considered how and what it meant to understand human experience in "naturalistic terms" (p.1). And in this sense, Dewey argued for developing new methods for "...getting at nature, penetrating its secrets, and wherein nature empirically disclosed (by the use of empirical method in natural science) deepens, enriches and directs the further development of experience" (1958, p.2). Given this, Dewey can be seen as an advocate of empiricism, and perhaps by extension technology.

While an extensive discussion of pragmatism is beyond the scope of this paper, key principles are of particular relevance to illuminating the significance of computational design thinking and methods in the age of the Anthropocene. This includes pragmatism's anti-Cartesian or anti-dualist stance that informs a pragmatic account of agency as that which cannot be wholly ascribed to humans or objects and includes action. Equally important here is pragmatism's focus on everyday life, the notion that a process world is dynamic and ever-changing in ways that demands continual re-appraisal, plural knowledge and ways of knowing, and an orientation towards solving practical problems in the real world. That said, Dewey's suggestion that the goal of understanding relationships between actions, implications and consequences is to gain 'control' over situations is argued to be problematic in a contemporary context (McReynolds 2018). On this Philip McReynolds infers Dewey's position reflects a 'residual humanism' in that nature is seen as a "...total set of environmental forces with which humans have to contend...as an opponent that we humans must either overcome or subdue" (2018, p. 80). Despite this aspect of Dewey's position, more generally, pragmatism serves to productively problematise notions of agency and control as wholly human attributes and "conceives instead of the human agent as part of a larger system that acts" (McReynolds 2018, p.85). This recognises that humans are "part of larger systems in which we can make a difference but which we do not control, at least not in the ways envisioned by traditional [modern] models of agency (McReynolds 2018, p.85). This perspective matters because the age of the Anthropocene is characterised by multi-scalar complexities that necessitate an alternate and systemic worldview.

3. Alignments between Pragmatism and Computational design

Contemporary computational design methods, and notably various systems of AI, offer significant opportunities to implement human and non-human scales of thinking simultaneously, also known as multiscalar thinking. More specifically, the computational design method of multi-agent modelling offers the ability to observe a single phenomenon at multiple scales. By encoding the agent at an individual level (local), a complex pattern can be formed at macro-scale (global) and observed. Such patterns, that are often self-organised and complex, may be interpreted as 'swarm intelligence' (Beni and Wang 1993; Hymes and Clemmt 2018; McReynolds 1987). These agents can represent various objects, from abstract particles to a human crowd such as in large-scale urban experiments (Leach 2009). Such methods offer an illeist world view that opens up to the notion that humans are not the only subject of capable thinking and perceiving, and in short, that 'intelligence' can be systemically derived. In examples from the field of computer science, Google's DeepDream (Mordvinstev 2015) and its later implementation as Hallucination Machine (Suzuki et al. 2018) visualises the processes of Deep Convolutional Neural Network's training, in ways that further suggest that the machine is able to perceive and interpret the world. So, while computational methods offer ways to see the world anew, they also force us to confront the fallacy of human subjects as those that play sole and primary roles in observing and shaping the world, and thus normative notions of agency.

In the context of architecture, computational design also refers to systemic methods that seek to establish the conditions for architecture to emerge, as opposed to conditioning and controlling architecture through predetermination. For Christopher Alexander (2011) a holistic way of understanding phenomena as the "product of interaction among parts" constituted a way of seeing capable of shifting entire world views. Alexander further stressed that systemic or holistic understandings were of particular importance for designers of building systems and objects that function as wholes. To paraphrase Alexander, the computational designer has become "the designer of generating systems" whose parts and rules can "create the necessary holistic system properties of their own accord" (2011, p.66). In one sense, this implies computational systems of design can operate autonomously, perhaps removing the risk of being co-opted by agents of control. From another perspective, adopting indeterminate design methods is sometimes seen as a 'relinquishing of (design) control'. This view rests heavily on the assumption of the primacy of human agency and human intelligence to begin with. Systems theory, cybernetic and holistic perspectives however reject the idea of the unilateral control of a system. In a key example described by Gregory Bateson (1972), the thermostat is a cybernetic system as its behaviour is determined by self-regulatory feedback loops, that is, "the behaviour of the other parts of the system, and indirectly by its own behaviour at a previous time" (p.316). Unlike Dewey however, Bateson argued, that the interactional and self-regulating capacities of a system such as the thermostat evidenced of a type of mental action. And as McReynolds further explains, in this way Bateson demonstrates that, "mind" (or mentation or mental action) is not one part of the system or anything that transcends the system. Mind is always immanent to the system itself and includes the action of the environment" (2018, p.88).

So, where computational design operates as generating system it can also be argued as ecologic in that a system inherently includes the action of the environment. Equally in alignment to pragmatist principles, computational design's systemic methods can account for and address the dynamic nature of the world and its ever-changing conditions and problems. Describing design problems as non-deterministic and 'wicked' (Rittel and Webber 1973), William J. Mitchell (1990b) articulated the shortcomings of computerisation alone or computer-aided design systems as those that could not fully account for the entire problem space of architectural design (including its influence in economic, social and cultural aspects). In his view, computerisation could not offer value judgements based on future needs, nor deal with varying situations. Computational design systems, on the other hand could be agile and responsive and continually respond to 'design critics' rather than arriving at a singular conclusion that might be later deemed insufficient. Such views join a chorus of scholars who have imagined intelligent machines as helpful, "mechanical counterparts" and collaborators with human designers (Negroponte, 2011). Yet as increasing computing power draws us closer to Artificial General Intelligence and potentially new types of dynamic, heuristic and non-deterministic computation, with these alternate 'intelligent' systems comes the problem of comprehension. We are confronted with mathematical 'black boxes', that elude explanation using current known approaches.

Concepts of evolution and emergence have become a key focus of computational design discourse over the past decade. Dewey acknowledged a debt to the evolutionary ideas of Darwin and articulated much of his position in terms of biological concepts of growth, organism, and environment from the evolutionary theory of Herbert Spencer (McReynolds 2018, p.85). In a similar belief that nature is acting on a natural selection process of 'optimisation', computational design discourse has engaged with theories of morphogenesis, and biomimicry and explored applications of genetic algorithms. Morphogenesis describes the form generation by genetic code at the cellular level, its architectural implication is mainly for the account of mathematically describing the form emergence and self-organising behaviours inspired by the organic cellular morphogenetic processes. Genetic algorithms are inspired by the natural selection process that involves phenotype being generated by the genome and selected by the environment. Computational design methods aim to mimic this natural selection process to find the best design option out of a set of criteria (Makki et al. 2015). Biomimicry, however, imitates the biological features or behaviours and applies it to algorithms, forms or materials. All of the above accounts accord with the Deweyan naturalist view. With parametric modelling techniques, parameter combinations have enabled the generation of forms not previously possible. A generative process may be described as an iterative process with each steps being parametric. By selectively tuning the input parameters, one may observe the generated characters tend to evolve. Agent-based modelling and swarm intelligence (Hymes and Klemmt 2018) use homogenous or heterogeneous agencies that may have limited action space. By adding flocks of agents, the accumulated behaviours start to form patterns at a macro scale. Significantly, none of the above-mentioned computational systems is deterministic. In fact, it is almost impossible to predict the direct relationship between input and output using mathematical deductions due to its computational complexity. Pragmatism provides the philosophical perspective that emergent and evolutionary behaviour is acceptable; that the black box process can be trusted as long as the practical goals are realised.

On the other hand, we see computational design techniques being put to use in the context of representation/simulation/prediction tools towards the goal of understanding the consequences of practical action in the world. This, however, aligns in some ways to Dewey's problematic residual humanism-that although accepting that humans and non-humans interact to produce an ever-becoming environmental system-equally suggests that it is the role of the human to control this system. From the book, the *Archaeology of the Digital*, early digital technology adopters such as Chuck Hoberman and Frank Gehry enrolled digital tools and computational methods into their design process as a means of controlling the outcomes, whereas Shoei Yoh engaged computational methods to open up the design space and to establish a dialogue with natural phenomena (Lynn 2013). Returning to the present we note an abundance of digital and computational tools that vastly shifts how design can be conceptualised, delivered and produced. From digital modelling tools such as Revit and Archicad, coordination tools such as Solibri, Newforma, rendering tools V-Ray, Enscape, analysis such as Ladybug, architects are increasingly transgressing traditional professional boundaries through computation. Moreover, as data capture is more convenient, from data mining the internet to collecting data through sensors the design space becomes far more extensible well beyond the bounds of the project at hand. Furthermore, technologies of digital fabrication and fast prototyping serve to converge conceptual ideas with analytical and/or physical-material thinking. In this way, computational design-as an ecology of digital and computational tools-allows architects and designers to engage with evidence-based design decision-making over intuition and idealism. But this returns us to a key question, how can these systems, however much they take into account a complex entanglement of conditions meaningfully account for the complexity of the real-world? Are the patterns and insights that contemporary AI systems offer those that can be productively translated into architectural or built environment design contexts? And critically, what are we not seeing when we defer to 'intelligence' in an AI system?

4. Discussion

Reflecting on the impact of computing in architecture in 1989 and in ways that echo the commitments of pragmatism, Mitchell wrote that "...we should think of design systems as open, flexible, constantly evolving knowledge-capture devices rather than static collections of familiar tools and dispensers of established wisdom" (1990b p.8). But it is new and adjunct models of design practice such as WeWork that are doing just this by actively automating office layouts using real-time spatial occupancy data and machine learning techniques (Davis 2019a). Equally, other research collaborations and start-ups such as The Living, Higharc and Australia-based Archistar are deploying similar data-driven strategies in the residential sector (Davis 2019b). In more traditional architectural contexts however, the notion that computation can be employed to generate rather than simply represent architecture remains contentious. Technology innovation in architecture may be outwardly promoted, but it is often put into practice in prescribed territories that reinforce a dichotomous human/non-human divide. (Cardoso Llach 2017; Gardner 2018, 2019; Terzidis 2011). As architect and scholar Kostas Terzidis (2011) points out, this reflects architecture's desire to conserve an image and 'ethos of artistic sensibility and intuitive playfulness' (human) as that which is incompatible with, and indeed irreducible to, the mechanistic and logic-based nature of the computational design as algorithmic procedures (non-human) (p.94). This contradiction is equally reflected in Dewey's residual humanism. As McReynolds (2018) reflects "...in spite of his systemic understanding of individuals as part of and integrally related to their environments, Dewey...locates the source of creative change in the individual human being" (p.86). In other words, Dewey ascribed intelligence and creativity to humans and not the artificial. Yet it is also worth noting that in his lifetime it is unlikely he encountered the concept of AI as anchored to modern computing. Nonetheless, for architecture the human/non-human dichotomy problematically serves to characterise computational design as automation and push innovation to the margins, leaving it to the 'experimental architect or the academic researcher to question...and explore the new architectural possibilities of emerging technologies' (Menges 2015, p.29). And this leaves a space for start-ups to step-in and de-code the logic of architecture and urban planning to service the needs of clients and address local and global conditions and challenges in new ways. And, as the Artificial General Intelligence theory indicates there may be a machine intelligence system that can undertake any tasks that human can in the future, what will then be left for humans to do?

5. Conclusion

This paper has explored how core thinking, theories and methods currently engaged under the rubric of computational design reflect key tenets of the philosophical tradition of pragmatism. Computational design thinking and methods offer systemic and dynamic ways to see the world anew that equally demonstrate a necessary de-centring of the human subject and troubling of normative notions of agency. Where computational design operates as a generating system it can be further argued as ecologic in that a system inherently includes the action of the environment. Yet, the contradiction evident in Dewey's empirically-grounded and naturalist pragmatist perspective, described as a form of 'residual humanism', is also evident in both architecture's conceptualisation and practical application of digital and computational tools. More recently, contemporary computational design methods, and notably various systems of AI, suggest significant opportunities to implement human and non-human scales of multiscalar thinking and to realise distributed, shared, and significantly, interactional notions of systemic agency. The Anthropocene calls for us to relinquish the privileged view of human-only agency and control over the environment and to adopt more dynamic and interactional models towards affecting positive change. A neo-pragmatist perspective of computational design that draws focus to its systemic logic and methods is a way forward to achieve this.

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COMPUTATIONAL TOOLS IN ARCHITECTURE AND THEIR GENESIS: THE DEVELOPMENT OF AGENT-BASED MODELS IN SPATIAL DESIGN

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Abstract. Based on the assumption that socio-technical networks of computation in architecture exist and must be analyzed deeper in order to understand the impact of algorithmic tools on the design process, the present paper offers a foray into it, drawing on science studies methodologies. The research explores in what regard multi-agent systems (MAS) are representative as much from the existence of these socio-technical networks as of how their development influences the tension between tacit and explicit knowledge at play in procedural design processes and of the strategies architectural designers develop to resolve this tension. A methodology of analysis of these phenomena is provided as well as results of the application of this method to MAS, leading to a better understanding of their development and impact in CAAD in the past two decades. Tactics of resolution shaped by early MAS users enable, through a double appropriation, a skillful implementation of architectural practice. Furthermore, their approach partially circumvents the establishment of technical biases tied to this algorithmic typology, at the cost of a lesser massive democratization of the algorithmic tools developed in relation to it.

Keywords. Computational tools; multi-agent system; architectural practice; tacit knowledge; digital heritage.

1. Introduction

The Digital Turn in architecture is a widely accepted notion since the famous AD special issue *The Digital Turn 1992-2012*, edited by Mario Carpo and stating the existence of experimentations around the idea of the digital in architecture as well as popularizing the term (Carpo 2012). The Digital Turn as currently defined encompasses the use of a variety of digital tools. The computational movements in architecture are nevertheless also characterized by a specific socio-historical context of emergence (Gaudillière 2019). Most of its architectural production consists in paper projects, prototypes, pavilions, produced in an academic environment. The computational movements therefore organise around a series of practitioners, of research units and institutions, shaping a network of knowledge transmission. This academic set-up has enabled the field to blossom

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 499-508.

away from most of the usual constraints of the construction industry. This freedom and diversity of explorations make its production a prefiguration of the global computational turn in architectural design currently happening. The computational field as it has developed in the last 50 years forms therefore an ideal set of designers and projects to study programming-based spatial design and the translation of architectural constraints into computational design tools. Furthermore, as computational movements in architecture are characterized as much by the technical aspects of the practice as by the structure of its community of practitioners, they can be identified as a socio-technical network (STN) (Latour 1991), still to be described as such.

The present researches focuses on the analysis of STN of computation in architecture for a specific algorithmic typology, multi-agent systems (MAS), and studies the trade-off happening between the mobilization of tacit knowledge and the explicitation of formal instructions when resorting to it for architectural design purposes, as well as how the structure of programming interfaces of MAS has influenced this trade-off. The study highlights three major dynamics influencing the development of MAS in CAAD: appropriation, democratization, rationalization. The paper will first address the characteristics of the algorithmic typology studied, before presenting the methodology on which the research is based and discussing the findings regarding the three dynamics identified, analyzing to what extent the resort to algorithmic design tools impacts architectural practice.

2. Multi-Agent Systems as a typology

MAS, also referred to as swarms, are object-oriented algorithmic systems modeling the behavior and interactions of sets of agents. Each agent is obeying a series of given laws, and their interactions generate what is known as emergent behavior: a conduct of the set that differs from the specific behavior instructed to each agent. The components of a MAS are the following : an *environment* - usually a measurable space -, *objects* populating this environment - that can be modified by the *agents*, *relations* tying objects and agents together, and *operations* enabling the interactions between objects and agents (Ferber 1995). Amongst the early developments of MAS are the Boids, by Craig Reynolds, in 1986. Craig Reynolds, a computer scientist and graphic designer working at the time on the animation of large numbers of elements for the movie industry, programmed the Boids to simulate the behavior of a bird flock. While being one of the first MAS developed, the flocking algorithm devised by Reynolds also constitutes an example of the type of rules that are applied to agents in swarm algorithms. The Boids obey three rules: separation - respecting a minimal distance from other agents - alignment - head towards the average displacement direction of the flock - and cohesion - respecting a maximal distance from other agents(Reynolds 1987). Following this breakthrough, a large number of frameworks were developed to enable programming with MAS from 1995 on, and those have since been regularly used, mainly in the film and video games industries. In particular, the pioneering development of MASSIVE in 1996 for the animation of crowds of thousands or more in the *Lord of the Rings* films, and the Golaem Crowd Maya plugin, developed in 2011, are nowadays still in use in the industry.

Since MAS can be identified as a specific typology of algorithm, they imply the resort to a predefined typology of instructions, identical for all algorithms (figure 1). The MAS typology as used in CAAD entails three levels of instructions, in the form of rules. First, the rules pertaining to the initial state of the system, such as the position or entry point of the agents and the position of the objects. Secondly, behavior rules for the agents are implemented regarding their movement - direction rules, such as the boids' separation, alignment and cohesion - and their interactions with the objects - attraction or repulsion for example. Finally, rules relating to the geometrical exploitation of the MAS output, in order to convert it in data relevant to the architectural object conceived, by using the final position of the agents, the traces of their displacement or of the operations, and potentially by adding novel geometrical elements.

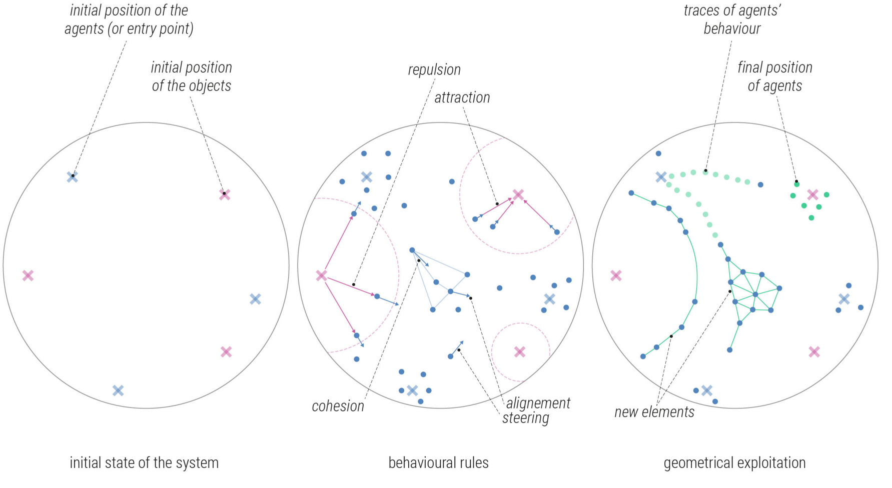

Figure 1. Rule typology for multi-agent systems.

3. Methodology

The research is based on the analysis of a series of case studies by practitioners key to the development of the MAS typology, its related tools and its use for architectural design. In order to outline the computational field as described in the introduction, AD issues have been searched to establish a list of projects and practitioners resorting to digital tools, with a focus on the use of scripting to produce architectural objects or information relevant to the production of an architectural object. The compiled list highlights practices, institutions, projects and tools of the computational movements in architecture, and identifies each project with one or more typologies of algorithms. From this list, the projects associated with MAS were extracted and practices and practitioners appearing more than three times in the list were identified as having made a significant contribution to the development of their use in CAAD. In complement, a literature review of published projects resorting to MAS in the Cumincad database was conducted on 115 papers to assess the contemporary use of MAS, after the creation of a number of algorithmic tools enabling an easier manipulation. The chronological development of major algorithmic tools for MAS modelling has also been examined, for standard frameworks as well as the specific tools involved in the case studies - such as Toxiclibs for Processing and the Flower Power Rhinoceros plugin - as well as for grasshopper plugins - Quelea, Zebra, Nursery, Boid, Physarealm, Culebra - offering an overview of the democratization of this typology through tool-making.

Three aspects are at stake in this study: the constitution of the STN and the chronologic development of MAS use in the computational movement in architecture, the development of ready-made tools and the trade-off between tacit knowledge and programming instructions formalisation. A grid of analysis for the projects themselves has been developed, and each case study has been analyzed following this same grid of criteria, containing four parts. First, the algorithmic specifications and the choices made for the MAS rules are examined. The articulation with other typologies of algorithms is also assessed, in the cases where the MAS is only a part of the complete architectural design algorithm. Secondly, the architectural instantiation of the algorithm is examined. The goals targeted while using the swarm are sorted in four categories: generating an initial state, a space hierarchisation, structural elements and shapes. Architectural specifications such as the ones originating in the brief or the context and their implementation are also recorded. Finally, information pertaining to the technical set-up - type of programming interface, visualization software and programming software - and the organization chart - composition of team, role, background, programming skills - are collected. The sources of information used in the analysis are interviews with practitioners, public documents such as finalized drawings for the projects - including diagrams explaining the algorithmic structure - and documents found in public and private archives, in particular programming scripts, but also complementary sketches and documents throughout the genesis of the project.

4. Multi-Agent Systems as tailored algorithms : tacit-explicit tension and appropriation

As MAS blossomed in the 1990s, architects started resorting to them as well (Krause 1997, Coates & Schmid 1999), and these algorithms gained further momentum in CAAD during the 2000s. The emergent behavior of swarms and their ability to self-organise turned them into popular devices among architects of the computational field, as well as their capacity to handle complexity and the possibility they encapsulate to program matter (Pantic & Hahm, 2015). Users devised various applications based on swarms behaving according to diverse rules, from simple flock algorithms to simulations of magnetic fields (Andrasek 2009) or behavioral data (Schumacher 2018). More complex uses were also developed, such as algorithms combining several swarms together, or with other algorithmic typologies. A few examples of the resort to MAS for architectural design can be given. The project Mesonic Fabrics, by biothing, associates a MAS with cellular automata in order to generate roofing structures. The Cliff House project, by kokkugia, is an experimentation tying MAS to the use of composite fiber architecture to develop a structural shell for a house on a extreme cliff topology. A third example is the Trabeculae / Protosynthesis project by supermanoeuvre, reimagining an office tower and its atrium by implementing two MAS, one shaped by light transmission requirements and the other creating a structural truss network. Finally, Living Morphologies (supermanoeuvre) revisits Le Corbusier's Unité d'Habitation with a MAS retro-engineering the circulation logic devised by the architect. These explorations of the potential of MAS for CAAD where accompanied by the development of tailored algorithms, as well as libraries developed by emblematic practices of the field, in particular supermanoeuvre, Kokkugia and biothing. This first period of appropriation of MAS by architects is characterized by the exploration of multiple architectural issues - structure, light, form, users' movements -, and a small-scale STN, depicted in figure 2. This phase is also marked by the high programming skills of MAS users, resulting in a skillfull negotiation of the tacit-explicit tension.

Practitioners generally draw on a form of subjectiveness and on their expertise to produce a relevant answer, in the form of an architectural object, to a given spatio-temporal context. The expertise built by architects throughout their years of training and practice relies on intuition as well as on tacit knowledge. The latter is a form of knowledge that cannot be formalised or rendered explicit by the person holding it and is therefore hardly transferable (Collins 2010). It cannot be put in writing neither given the shape of a set of instructions. Whereas tacit knowledge is instrumental to the practice of a discipline, given its inability to be formalised, it also renders specific disciplines very hard to automate and specific sets of knowledge very hard to transfer to computer-supported programs. This points out a key issue for architecture: it is first and foremost a practice, and should be analyzed as such, including in the understanding we have of how architects resort to algorithmic design tools. The fact that a computer relies on sets of explicit knowledge, in the form of instructions transmitted through programming languages, to execute series of calculations, not only makes it difficult to automate some practices, it also requires from architects using algorithmic tools to embrace a procedural understanding of the design process. This renewed understanding of the design process is nevertheless at the core of the extensive potential seen in algorithmic design tools and of the renewal and enrichment of architectural production in the last decades. While the superimposition of the practical dimension of architecture and the formal dimension of computation creates a negotiation between tacit and explicit, practitioners of the computational movements have since their dawn developed strategies to tackle it. The core STN associated with the development of MAS is the illustration of one strategy in particular, resulting in the appropriation of the typology.

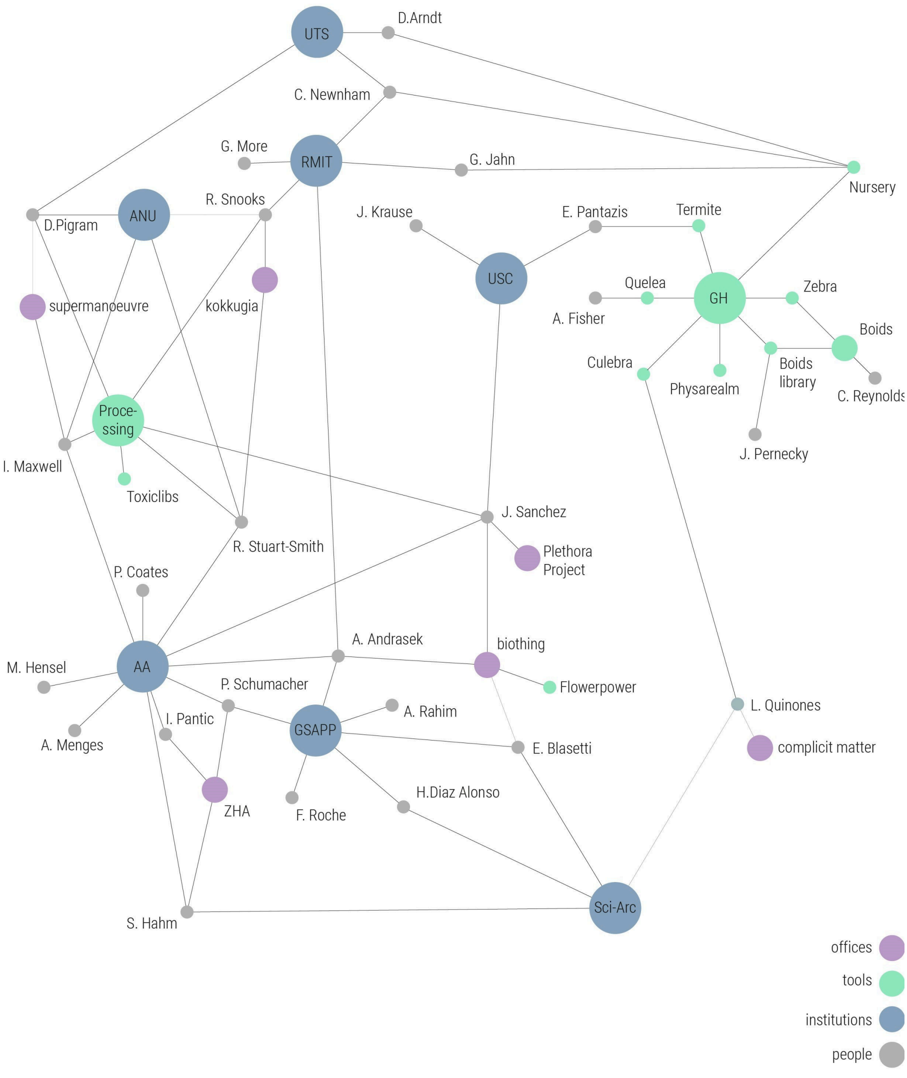

Figure 2. Core socio-technical network for multi-agent systems.

The assessment of the organization chart of each project, as well as the skills and areas of specialization of the participants and the role they played in the project, has highlighted an especially high level of mastery of programming skills for architectural practitioners. Furthermore, the practitioners also belong mostly in tools developing and algorithms scripting categories, rather than in ready-made algorithms using. In other typologies, such as evolutionary tools, the discrepancy existing between the knowledge profile of the tool developers and of the tool user results, because not accounted for, in the appearance of technical biases

(Gaudillière 2020). This can be the result of a resort to complex algorithmic typologies originating in other disciplines - such as biology for evolutionary tools - with a rapid democratization and the lack of an appropriation period through the development of tailored algorithmic design tools by and for users in the field of architecture. In the case of MAS, however, the practitioners of this first phase represent precisely this appropriation period, and despite the typology originating in other disciplines, algorithmic tools currently in use have been mostly devised by the practitioners themselves, resulting in the overlapping of developers and users competences.

The programming skills observed also ensue in a strong bias awareness. The combination of programming mastery and bias awareness results in a fully grasped negotiation between tacit knowledge and explicit instructions. Both the interviews and the analysis of the scripts attest to the mastery and understanding of technical set-ups and typological rules, enabling a conscient mobilization both of tacit knowledge and of these technical aspects in architectural implementation. Nevertheless, while the mobilization of MAS through both the genesis of libraries and the scripting of tailored algorithms relying on these libraries for each project confirms the appropriation of this algorithmic typology, the segmentation of project specific algorithms hints to a delineation of the process. The early version of the Flower Power plugin, relying on the previous and separated drawing of the plan, is an example. Another example is the description of the kokkugia libraries and their two-steps use in the practice : first devising MAS behavior libraries by expliciting instructions and secondly, choosing the library based on known - formal - results of the behavior and on a intuition regarding a specific project, to build a tailored script based on it. The practitioners observed thus recreate a classic mobilization of tacit knowledge, therefore demonstrating an appropriation of this algorithmic typology for architectural design.

5. Multi-Agent Systems as ready-made tools : interfaces for democratization

More recently, a second phase of MAS development in spatial design has begun, as this typology, alongside many algorithmic design tools, has initiated a massive democratization, with the appearance of numerous new tools designed for an easy manipulation of the typology (figure 3). The resort to MAS currently addresses three major fields: behavioral simulation for urban planning, self-organizing workflows and decision steering, and complex shape generation for architectural objects. While the first phase is characterized by one major category of users, the second phase, given its democratization dynamic, shows new types of users, with distinctive ways of mobilizing this algorithmic typology. The six Grasshopper plugins allowing for the use of swarms show a cumulated number of 56 636 downloads, an average of 8090 per plugin - Kangaroo Physics, the most downloaded Grasshopper plugin, displays a total of 443 415 downloads. While this already hints to a small community of users, active members of corresponding Grasshopper groups only represent less than 2% of this number, as well as published papers on the topic. Despite the difficulty to assess properly the number of regular users of such algorithmic typologies, these figures outline a key element regarding the field of MAS for CAAD in academia: the differentiation between superficial and extensive uses. These elements suggest that, while the presence of Grasshopper plugins hints to attempts at democratising MAS through easier interfaces, the pool of both types of users remains small, in particular when compared to other typologies such as evolutionary tools, currently much more widespread (Gaudillière 2020).

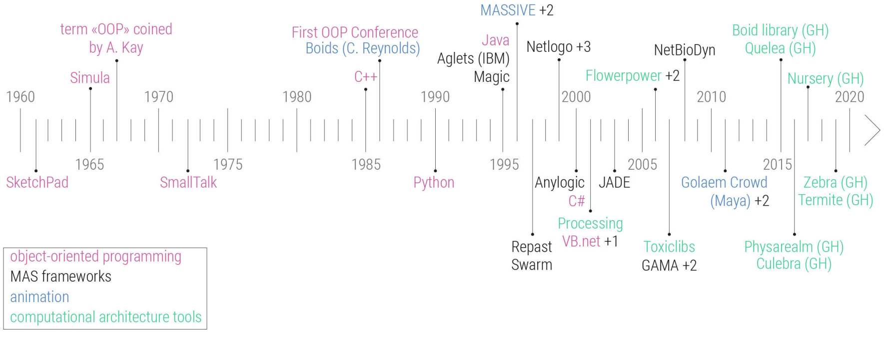

Figure 3. Chronology of multi-agent systems programming principles, frameworks, and tools.

To understand the mechanism of democratization for algorithmic design tools in architecture, a key element to study is the interface of tools, and its thickness. The notion of thickness of the interface acknowledges the varying distance existing between the initial architectural intention and the final representation that is the output of the algorithm, and is similar to the multiples *layers* of an interface that UX designers refer to (Masure 2014). The variation of thickness of the interface is intricately connected to the ability of the user to access rules and details of the mathematical model on which the algorithm is based and to the similarity of knowledge profile of users and developers. Therefore, in the first phase, as users are in their majority capable of scripting a tailored algorithm and to devise their own libraries and interfaces, the knowledge profile overlaps, as previously highlighted, thus providing almost zero-thickness interfaces of MAS. Interfaces and the layers forming them for both tailored algorithms and ready-made algorithmic tools, each typical from one phase, are depicted in figure 4. While tailored algorithms enable an access to rules in upper layers, and are composed of a small number of layers, ready-made tools are composed of many layers and the access to the programming of specific rules is located in lower layers, harder to access for users with little programming skills and leaving upper layers with only predetermined behaviors. Thus, the second phase of development of MAS is characterized by interfaces with high thickness, hardly enabling a detailed manipulation of the typology and hindering appropriation through tacit implementation, a step crucial to the use of MAS given the complexity of this typology, and therefore to their democratization.

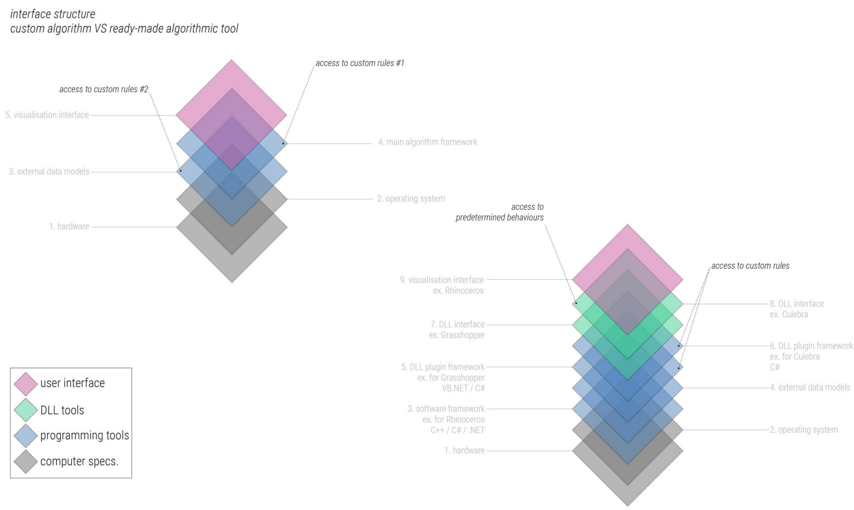

Figure 4. Interface layers for ready-made and tailored algorithms.

Of aforementioned strategies of negotiation between tacit and explicit depends the becoming or not black boxes of algorithmic design tools. By providing an easier resort to algorithmic design tools, interfaces display a black box mechanism (Latour 1987) : they become standard tools of architectural design, and users do not need any longer to question in detail their functioning and relevance, no need to scratch beyond the interface to fully grasp the complex mathematical, physical and informational models they are based on. While the simplification through an interface easier to manipulate is key to the democratization of algorithmic design tools in architecture, tactics of negotiation depend in a large part of the understanding of tools by their users, and on biases enabled by the structuration of algorithmic typologies, of tools and of interfaces.

6. Conclusion

Based on the assumption that socio-technical networks of computation in architecture exist and must be analyzed deeper in order to understand the impact of algorithmic tools on the design process, the present paper offers a foray into it, drawing on science studies methodologies. The research explores in what regard MAS are representative as much from the existence of these STN as from how their development influences the negotiation between tacit and explicit knowledge at play in procedural design processes. A methodology of analysis of these phenomena is provided as well as results of the application of this method to MAS, leading to a better understanding of their development and impact in CAAD in the past two decades. Tactics of negotiation shaped by early MAS users enable a double appropriation - borrowing an algorithmic typology from other fields to create tailored tools from it and managing to implement a classical architectural practice by mobilizing tacit knowledge. Furthermore, their approach partially circumvents the establishment of technical biases tied to this algorithmic typology, at the cost of a lesser massive democratisation of the algorithmic tools developed in relation to this typology, displaying especially thick interfaces. MAS are an algorithmic typology that necessitates technical mastery, but in returns pushes a sensible use of computation in architectural design, as well as a diminution of epistemological and technical biases. These characteristics clash with the global contemporary trends of architects pulling away from technical issues (Picon 1989, Carpo 2011) and of computation tools as vectors of rationalization of architectural practice for the industry (Gaudillière 2020), further explaining the difficult democratization of this typology, despite what it has to offer.

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DESIGNING WITH UNCERTAINTY

Objectile vibrancy in the TOROO bamboo pavilion

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Abstract. This paper challenges digital preoccupations with precision and control and questions the status of tolerance, allowance and error in post-digital, human-centred architectural production. It uses the participatory action research design-and-build project TOROO, a light-weight bending-active bamboo shell structure, built in Hsinchu, Taiwan, in June 2019, as a demonstrator project to discuss how protean digital design diagrams, named 'vibrant objectiles,' are capable of productively absorbing serendipity throughout project crystallisation processes, increasing designer agency in challenging construction contexts with high degrees of unpredictability. The demonstrator project is then used to discuss future research directions that were exposed by the project. Finally, the applicability of working with 'vibrant objectiles' is discussed beyond its local project use. Common characteristics and requirements are extracted, highlighting project setup preconditions for which the scope covered by the architect needs to be both broadened and relaxed to allow for feedback from design implementation phases.

Keywords. Post-digital; Bamboo; Bending-active shell structures; Uncertainty; Objectile.

1. Introduction: Post-Digital Architecture Practice

The research discussed in this paper is situated within 'Post-digital Architecture,' defined as architecture that *"[...] address the humanisation of digital technologies through interplay between digital and analogue cultural and material systems, between virtual and physical reality, between high-tech and high-touch experiences, between the local and the global"* (Crolla, 2018). This field focusses on computation-based architecture practice that seeks to locate itself back into the physical world of praxis while being informed by decades of working with computers, and that is typified by "output created using alternative embodied media and notational systems and through participation, interaction, and collaboration".

This paper uses the bamboo pavilion installation TOROO as a demonstrator project to illustrate the extent and flexibility of its approach to digital means

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 509-518.

and methods (see Fig. 1, 6 and 7). This project was built in Hsinchu, Taiwan, in June 2019 in a construction context typified by great uncertainty throughout the design and implementation process. The project's design approach centred on working through what we called 'vibrant objectiles' (Crolla, 2018). These are conceptual, holistic, computation-driven, associative design models that are procedural in nature, cover both project design and delivery, and are capable of robustly harnessing the variabilities, unpredictabilities and slippages that typify project implementation in contexts of challenging means.

The paper argues that this modus operandi allows for a substantial expansion of the locally practically available design solution space associated with specific materials and crafts - a solution space which is less restricted by the commonly assumed limitations of construction practices encoded in local building cultures.

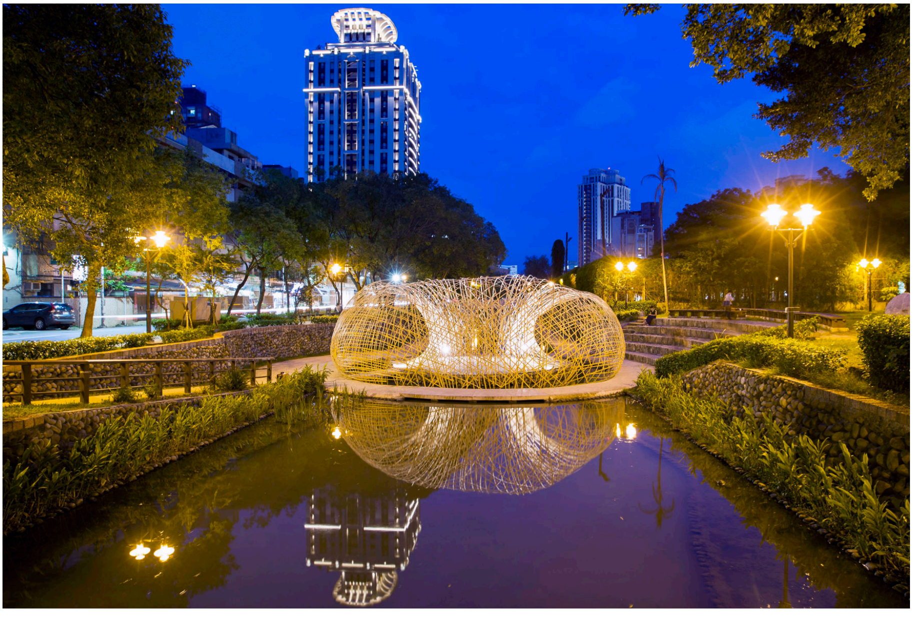

Figure 1. TOROO by night (Hsinchu, Taiwan, 2019).

2. Research Methodology

The demonstrator project is part of a larger design-and-build study on bending-active bamboo shell structures. Its methodology is based on 'Participatory Action Research' (PAR) and 'Reflective Practice' (RP). 'Action Research' (AR) is the construction of knowledge through the process of change, with a focus on developing practical results by improving specific situations (Groat and Wang, 2002; Herr, 2015). PAR adds to this that the researcher engages personally in this action process and actively participates in the change situation while simultaneously conducting research (Walker et al., 2008). The action process is a cyclical, heuristic process that fundamentally embraces 'trial and error' and is guided by RP, being the use of self-analysis to understand, evaluate and interpret events and experiences in which we are/were involved (Schön, 1983). RP seeks to enable insights and develop personal understanding, knowledge, and action. This knowledge is then linked to earlier developed higher-order knowledge and theoretical positions, whose explanation to others becomes clearer through the demonstrator project.

3. Background: Bamboo's Unpredictability

3.1. BENDING-ACTIVE BAMBOO SHELL STRUCTURES

Bamboo is the most ecologically sustainable construction material currently available. Certain species have tensile strength properties like steel, grow over a meter a day, and can be used in construction within 3 to 5 years, making bamboo one of the fastest biological carbon absorbing materials (Hidalgo-Lopez, 2003). Working with bamboo impacts socially too, as it creates local craftsmanship opportunities often rooted in regional culture. Bamboo's impact can be further pushed into the realm of spatial design through structural performance driven design approaches: By incorporation bamboo as structural material in high-performative applications, like light-weight bending-active shell structures, a wide variation of non-standard architectural spatial designs becomes possible.

Yet, bamboo is a notoriously difficult material to incorporate in modern modes of construction due to the large natural dimensional and structural performance variations found within and in between individual culms. Typically, no building codes exist for bamboo applications in construction nor for structural performance calculation of its use in a non-processed natural form. As the material doesn't succumb well to the material control and predictability typically found in and expected from contemporary construction materials, like steel, concrete, and even wood, current modes of architecture implementation struggle to benefit from its inclusion.

3.2. VIBRANT OBJECTILES

Contemporary digital design tools, however, due to their procedural nature, are in principle capable of harnessing variation and variability. In the nineties, the definition of a designed object was expanded by Deleuze, who introduced the term 'objectile' as a generic open-ended notation that includes both solutions and the associative system that enables them (Deleuze, 1993). This definition can be productively expanded to 'vibrant objectiles' by proactively including open-ended, non-digital components related to design materiality, material systems, and materialisation (Crolla, 2018).

'Vibrant' objectiles are conceptual, holistic, computation-driven, associative design models that are procedural in nature, cover both project design and delivery, and are capable of robustly harnessing the variabilities that typify this process. They are built from a select number of tried-and-tested interdependent components that are optimised for local implementation. These components can incorporate context-specific idiosyncrasies and have potentially high levels of volatility or uncertainty, termed 'vibrancy', which are managed throughout the project development, rather than locked down from the start. These 'vibrant' components are placed in and communicate across a hierarchy of scale and influence, permitting and enabling the emergence of larger-scale impacts and complexities beyond the author's complete control. From early on, the extensibility of these uncertainties, i.e. the components' vibrancy, is managed and harnessed within the developing objectile through incorporated feedback from continuous rigorous prototyping. This gives robustness to the setup, rather than exact predictability of the outcome, allowing uncertainties room to feed back into the system until project completion.

Measures for project success thus shifts from precise, predictable design materialisation towards a more relaxed yet practical project realisation: Rather than seeing the act of design materialisation as the literal, real-world translation of a digital design, an objectile's ability for mass-variation is used to embrace implementation fluctuations while designs gradually develop into their final singular site-specific solution.

3.3. TOROO'S UNPREDICTABILITY

TOROO was realised as part of a series of bamboo design and build workshops in 2019 in Hsinchu, Taiwan, in which local volunteers with no prior construction experience assisted in the construction. From the onset, this setup meant there would be no control over the available craftsmanship nor over material dimensional stability, and substantial tolerances and allowances would need to be permitted during implementation. What was not anticipated, however, was that due to sudden changes in available resources the final construction material was changed one week before construction from thin bamboo culms of 25mm diameter to 30mm-wide bamboo splits with a thickness of ±5mm. This sectional change meant a reduction in inertia, and with that an increase in deflection, of factor 60, challenging the design's implementation viability. Yet, the robustness and flexibility of the procedural workflow, set up to be a digital 'vibrant objectile', allowed absorbing these parameters through design adaptations during construction, bringing the project to a successful end.

4. Main Components

4.1. PROJECT DESIGN

TOROO intended to study how one can expand the design solution space for bending-active shell structures produced by deforming prefabricated, repetitive grids, made from equidistant quads. Such designs, the best example of which is Frei Otto's 1974 Mannheim Multihalle (Bächer et al., 1978), can today easily be digitally generated with common architectural design softwares like McNeel's Rhinoceros®, its procedural modeller plug-in Grasshopper®, and the physical force simulation engine add-on Kangaroo®. With those, material bending forces can be abstracted into corresponding vector forces applied onto discretised curve networks represented by a spring-particle system. In such setups, macro-level behaviours can be perceived like those found in physical prototype or full-scale construction setups in which initial grid setups are deformed and pushed into subsequent equilibrium geometries (Crolla, 2018).

The design of TOROO intended to take advantage of the ease of construction of such flatbed grid structures to create a novel structure from bamboo. The objective was to avoid the typical ‘bubble-shaped designs’ associated with the popped-up flatbed grid typology. This was done by introducing four ‘singularities’ into the continuous equilateral quad-shaped grid topology: In four locations, five equilateral pentagons were incorporated into the quad-shaped grids, allowing the overall equilibrium geometry to include a column-like structure (see Fig. 2). This initial topology setup was then deformed through external forces and anchored at its perimeter to become a torus-like shape. This torus was opened up on one side in response to the site conditions - a concrete island placed inside a river with small bridges to allow entry and passage.

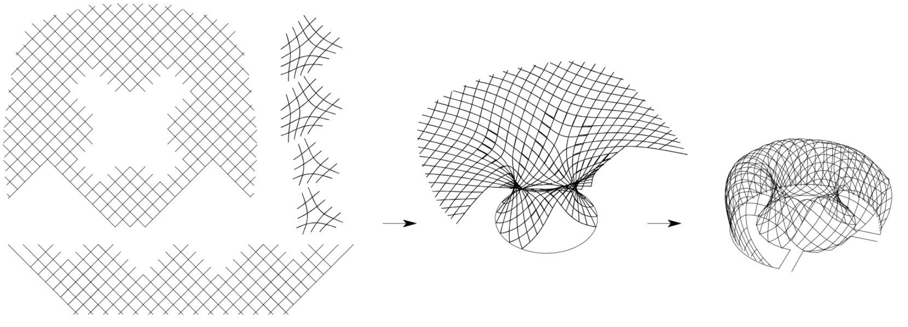

Figure 2. TOROO’s topology diagram and installation sequence.

4.2. FINETUNING THROUGH PROTOTYPING

A possible outcome from the vibrant objectile model setup was tested through a 1:15 scale physical prototype made from 3mm diameter bamboo sticks (see Fig. 3). For this, the repetitive nature of the equidistant grid allowed for straightforward production. The model prefabrication was split up into a top grid, a column grid, and five singularities, all of whose topological data was extracted from the digital files (see Fig. 2). The parts were fixed with standard zip ties, interconnected to one another, deformed and pulled down, and then anchored in place at the perimeter. Then, the structure was further densified at will with bamboo sticks until a final design was achieved. This densification was done in response to onsite view lines and spatial properties of the pavilion and aimed at creating a play of varying density, opacity, enclosure, and surface definition in which the original grid was visually absorbed. Visitors approaching and entering the pavilion would perceive its space definition as constantly changing. The densification implementation strategy was not prescribed in detail but intentionally left open-ended to allow ad hoc onsite input from the construction team.

4.3. ONSITE CONSTRUCTION MODEL CHANGE

Tests demonstrated we would be able to follow an onsite sequence like the one applied in the scale model, only with larger zip ties and thin bamboo culms. The last-minute material change did not leave sufficient time to fully redesign the project in response to the increased deflections. Onsite trials with the available bamboo splits revealed a far floppier material system than anticipated in the digital simulations or witnessed in the 1:15 scale model where the grids required force to be 'pulled down'. Instead, the use of splits resulted in the torus' arch spans to collapse onto themselves, requiring propping-up from underneath.

Figure 3. 1:15 scale physical prototype.

With the original grid already prefabricated, the choice was made not to change the material system. Instead, the top grid's outer edge was trimmed short prior to fixing it onto the column, thus reducing the torus' arch heights from 6.5m to 4.5m This meant an increase in the surface's double curvature, improving its resistance to buckling. All separately prefabricated components were interconnected following the original topological system into a floppy whole that was then gradually densified until a stable, self-supporting overall shape was reached from which the support structure could be removed (see Fig. 4, 5). The densification pattern now directly related to structural stability issues, rather than responding to originally planned visual elements, giving the final product a rather transparent top and a densified base (see Fig. 6, 7).

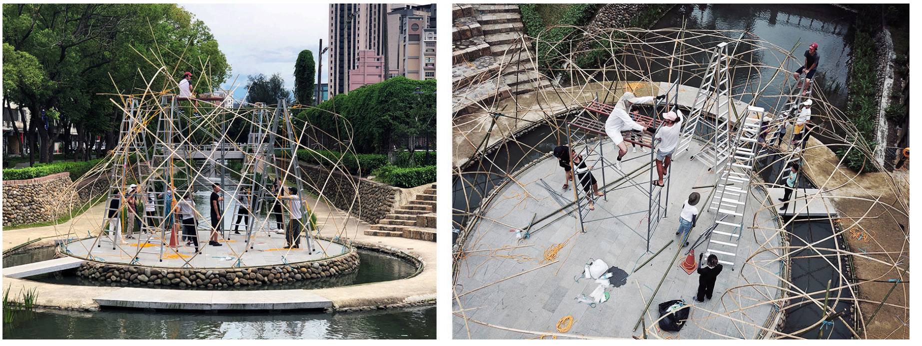

Figure 4. Under construction: central column installation (left), connection of top grid (right).

Figure 5. Under construction: grid densification.

5. Discussion

While the overall design difference between the original digital model and the final as-built structure is significant in terms of dimensions and densification strategy, the project's design concept, being its topological setup, spatial response to site, construction sequence and intended material effects, remained intact. The onsite acceptance of differences was not a forced subjection to errors in material or craftsmanship nor a post-rationalisation: as a conceptual design strategy, this was managed from the beginning as an inevitable aspect of project development in a context that would not allow full planning or controll ahead of time. Whereas the level of component vibrancy was admittedly larger than originally hoped, the protean nature of the objectile allowed its incorporation. Typically, such forced dramatic last-minute change of structural materials would cancel a project, but here, the approach allowed the design and construction team to maintain its agency.

The inherent variability of bamboo and bamboo-related craftsmanship requires an alternative design approach to typical architectural planning in which maximum levels of control are sought, often with the help of digital design and implementation tools or extensive building information models. As shown, when working with bending-active structures, especially material properties related to elasticity and inertia can have a major impact: careful calibration of implementation strategies and details is needed in response to onsite conditions.

Local craftsmen, with a deeper understanding of local materials and their properties, can assist in finding solutions within the extent of the design system's solution space. For example, overly stiff culms can be replaced with bundles of elements with smaller diameter or even through the layering of bamboo splits. But often such knowledge is not available. Each of these locally specific solutions comes with its own details, required skills and visual impact, and they can all be seen as singular expressions of the same vibrant objectile model setup. Rather than aiming to control each of these aspects ahead of time, architects can productively increase their agency by creating room for these conditions to inform the final. As demonstrated by TOROO, today's digital toolbox has inherent qualities that can assist in overcoming unknowns, and a surprisingly large practical design solution space exists for architecture that is receptive to inevitable qualities of working with natural, temperamental materials and their associated craftsmanship. Further design methodological research with similar aims for other materials, building systems, and crafts has the potential to increase digital design and construction technology impact in construction contexts of limited means.

In discussions on the architecture industry's obsessions with control of error and precision, recent trends in 'digital architecture' have been criticised for drawing masonry walls with software packages designed to cut lenses or map brain tumours (Hughes, 2015). But rather than these tools' capacity for hyper precision, it is the procedural nature of the digital realm altogether that opens doors to transcend limitations of common praxis, especially in contexts where generic design solutions proliferate allegedly due to lack of available means and resources. Working through more open-ended design model setups that productively respond to local conditions and their possible benefits, be it ecological, economical or socio-cultural, allows benefits from design computation to impact far beyond the avant-garde or the academic research lab. Through a process of managed rather than precisely controlled implementation, materialisation processes can contribute to give valuable rigour and animus to final outcomes.

Figure 6. Aerial view.

Figure 7. Interior perspective by night.

6. Conclusion

When a value shift takes place from focus on exact design production towards a model system's ability to harness variation during implementation, opportunities open up to push the impact of recent digital design tools further, especially into developing construction contexts typified by limited means. The procedural nature of working with ‘vibrant objectiles’ allows prolonging the navigation through the expanse of a project’s design solution space until all onsite unpredictabilities are incorporated. TOROO demonstrates how development of a robust design framework that allows for such incorporation becomes a priority, and the in-situ goal becomes the production of a highly bespoke outcome as site-specific singular expression thereof. TOROO illustrates how the inclusion of onsite serendipity into digital design workflows has the potential to enable radically unique and spatially versatile architectural solutions rooted in local culture and sustainable building practices.

Acknowledgements

This research by the Chinese University of Hong Kong was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region China: Project No. CUHK 14604618, Project Title: Bending-active bamboo shell structures: methods and guidelines for best architectural design practice. The design and build workshop was organised in collaboration with the National Chiao Tung University Graduate Institute of Architecture (NCTU), the Association of Humanitarian Architecture (AHA), and the Hsinchu City Government. The workshop and construction team included Kristof Crolla, Garvin Goepel, Nichol Long-Hin Wong, Shuk-Man Lo, Jae Sok Surh, Tong Chen, Victor Wei-Chung Chien, Hui-Ting Hsu, Yen Lun Huang, Nicky Chung-Yu Hwang, Yu Chuan Lai, Tsung-I Lee, Mu-Huai Liu, Hang Yu Peng, Carol Yu-Jung Shen, Wa Bowe, Xin-Yu Wang.

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AFTER ABSTRACTION, BEFORE FIGURATION

Exploring the Potential Development of Form Re-topology and Evolution Reapplication with Three-dimensional Point Cloud Model Generation Logic.

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Abstract. In the era of three-dimensional (3D) informatics, the 3D point cloud modeling algorithm has the potential to further develop. In this study, we attempt to eliminate the limitations of the traditional reverse modeling method and directly turn point cloud data into the material for innovative architectural design by integrating 3D point cloud modeling into the CAD/CAM platform(Rhino/Grasshopper) most widely used by parametric designers. In this way, the randomly ordered point cloud model can be regenerated and reordered according to the designer's requirements. In addition, point cloud data can be spatially segmented and morphologically evolved according to the designer's preferences to construct a 3D model with higher efficiency and more dynamic real-time adjustment compared with the triangular mesh model. Moreover, when a computer vision technique is integrated into the point cloud design process, the point cloud model can be further used to more efficiently achieve rapid visualization, artisticization, and form adjustment. Therefore, point cloud modeling can not only be applied to the spatial structure presentation of building information modeling(BIM) but also can provide further opportunities for creative architectural design.

Keywords. Three-dimensional Point-cloud Model; Computer Vision; Point Set Registration; Topology Optimization; Regeneration.

1. Introduction

The point cloud is a relatively new geometrical class, which is only introduced in the 2000s (Rusinkiewicz and Levoy 2000). Along with the advent of the era of popular photography and the mature development of photogrammetry, the way of capturing physical objects and space into the three-dimensional(3D) data set is limited to high-end devices such as the laser scanners. To date, digital photos taken by ordinary cameras and mobile phones can be used to obtained 3D point cloud data through photogrammetry software with multi-perspective 3D reconstruction principle. At the same time, the textures in images can also be

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 519-528.

merged into point cloud. As a result, the three-dimensional point cloud data has become a design material that anyone can afford. Nonetheless, Rhino 3D modeling software collaborating with Grasshopper plug-in is now the most widely used parametric design platform in the field of architectural design. This methodology utilizes NURBS(Non-Uniform Rational B-splines) curves as a core technology to generate smooth and flowing curve architecture. However, when using the mesh model that can present convex/concave surfaces and textures' details on this platform, it is not only difficult to edit but also significantly reduce the computing performance. Conversely, the point cloud model not only does not need to record point-to-point sequence relation when generating surface of mesh model, nor does need to calculate the data of huge triangular surface. By storing specific data such as coordinate, time, intensity, scan angle in a single point, highly complex forms in the real world can be realized in Rhino 3D and the result is a faster and more detailed expression. Subsequently, this study endeavors to make point cloud as one of materials for topology and optimization of an early stage of parametric design. We explore how the point cloud data can collaborate directly with python in Grasshopper according to user requirements and design strategies. Different methods of data simplification, data extraction, range selection, and other big data processing are carried out.

This paper incorporates the design logic that architectural designers often used to transform a two-dimensional(2D) plannar models and three-dimensional(3D) stereoscopic model back and forth into point cloud model analysis process. Through the establishment of depth images and conversion of red-green-blue values based on depth data, we can quickly generate 2D images from 3D scenes. Additionally, feature extraction is performed by directly using the highly developed 2D images technique and packages(OpenCV and scikit-image). After that, the 2D images are returned to the 3D coordinates after the morphological transition by using the relationship of indexing and point set registration between pixels and 3D coordinates, and the point cloud model is constructed in terms of stylization, abstraction and morphological evolution. Therefore, the real space or object can be reinterpreted and stimulate more possibilities for development. It also allows design to incorporate both aesthetic and practical requirements simultaneously, making it be quickly customized according to the physical models and objects in the modern industrial era. It has also developed into a potential design material for diverse applications.

2. Discussion

Color is an integral element of our world, not just in the natural environment but also in the man-made architectural environment. Color always played a role in the human evolutionary process(Frank H. Mahnke). Point cloud data are obtained from immense databases of 3D coordinates and specific image attributes (e.g., color, intensity, and brightness) produced through 3D scanning and photogrammetry. Thus, designs via point cloud can more comprehensively analyze spatial contexts and can incorporate diverse space-time factors such as color and lighting instead of focusing only on the architectural modeling in XYZ space. 3D point cloud applications have increased rapidly in recent years.

From the perspective of the cross-platform Open Source Computer Vision Library (OpenCV), the trend of relevant modules being utilized for the processing of 3D point cloud data has grown gradually, especially in the translation of 2D imagery to 3D vision. Notably, the use of Rhino/Grasshopper makes the form of editing geometries computationally simple and easy to automate through mesh vertices, especially when modeling an irregular shape or designing a project consist of many complex elements in the site. Moreover, the program performs well even when the surface of the mesh model is removed and only color-coded vertices are retained. Therefore, we have explored the additional possibilities and innovative potential of integrating related open-source python libraries and sending required data to the CAD/CAM platform (Rhino/Grasshopper).

2.1. LIMITATIONS AND IDIOSYNCRASIES OF MESHLAB

MeshLab, an open-source 3D mesh-processing software, is used to develop multiple filters and regenerative methods. However, for designers, it is difficult to master this program without a strong computer-science background. When considering the colors of a 3D model, there are two options for visualizing and controlling MeshLab's encoding. One method requires the use of a color vertex. The other requires the use of texture mapping. The color vertex method is much easier to use. However, to retain color detail, a model comprising very small triangles must be saved. This comes with huge computational costs. Thus, most users prefer texture mapping. However, color data are not encoded in a geometrical context via this method and are instead included in an external file. Thus, users must clearly understand parameterization. Otherwise, when deleting invisible layers or re-meshing, the color information can be lost.

2.2. POTENTIAL OF THE DURABLE ARCHITECTURAL KNOWLEDGE (DURAARK) PROJECT

DURAARK was funded through the European Commision's FP7 Programme from 02/2013 to 01/2016. CloudCompare, a 3D point cloud processing software based on OpenGL, was used for development. It relies on an octree structure that is highly optimized for huge point clouds using color information. It also performs many simple analyses. It does well visualizing large point cloud data, and it provides a strong data analysis function. In terms of design, it lacks adjustment flexibility with editing points in defined regions having irregular boundaries. Furthermore, the point picking function of CloudCompare is quite slow. However, CloudCompare has performed very well in popular model analyses, but it has been weak for detailed designs or form evolution platforms. Therefore, this project develops an excellent plug-in volvox for Grasshopper to solve multiple problems of point cloud integration for architectural modeling programs, including reading and writing various file formats of point cloud data and merging or subsampling point cloud models. However, the entire project focuses more on form regeneration and evolution of the overall model. Thus, meshing the point cloud via voxelization is the only way to achieve form re-typology. Therefore, this project examines the potential of using point cloud data as design material and uses color and the change in normal vectors as reference data to discover new and creative approaches for re-typology. It is expected that the form evolutions and the detailed editing of specific areas of the point cloud will be flexible for both models for the highly popular Rhino/Grasshopper visual programming environments.

2.3. ENHANCING THE DIVERSITY AND CREATIVITY OF THE POINT CLOUD MODEL DESIGN BY INTEGRATING THE OPEN SOURCE LIBRARY OF RHINO / GRASSHOPPER

Point clouds are sources of realistic scenes and virtual objects that can be used in creative ways. Thus, we have attempted to incorporate 2D planes, which designers often use during the design stage for point cloud analysis and design. During this process, the point cloud model generated by professional photogrammetry software is used to create depth images through plane projection. The depth information is then converted to red-blue-green values to quickly support image ranges. Image processing techniques (e.g., OpenCV and scikit-images) are well developed used to complete edge extraction, key-point detection, material replacement, object merging, and adjustment. Point set registration is used to convert an image pixel to back to 3D. Thus, we can retrieve results with high efficiency and accuracy. This process also provides designers point cloud design concepts so that they can build a smoother communication platform between designers and customers.

3. Methods

Point cloud data enable media to accurately present information regarding material and spatial relationships in the real world and substances on a virtual platform. Since there is no sequential relation between points and they are not related to each other, we attempted to eliminate the complex processes and massive calculation memory required for editing the high-poly mesh model in Rhino/Grasshopper. Moreover, OpenCV(open-source computer vision) is one of the most popular, and powerful libraries in image processing. Using python-remote-control(a plug-in for Grasshopper) to transmit the required data from Python IDE to Grasshopper, the issue of cross-platform data transfer can be easily resolved. Therefore, we aimed to develop a design process for the 3D point cloud model's morphology analysis, generation, and optimization based on the open-source library(OpenCV), and CAD/CAM platform(Rhino/Grasshopper). In doing so, the difficulties of disordered point cloud re-typology, such as selecting/deleting a specific range of points, feature detection, texture adjustment/replacement, and form evolution, can be efficiently resolved, and the process of point cloud editing will become more designer-friendly. So, that point cloud model is used directly for re-topology, morphogenesis, which meets the requirements of customized and refined design. The processes are detailed in the following sections.

3.1. DATA CAPTURING: EXPLORING EFFICIENT METHODS TO OBTAIN A 3D POINT CLOUD MODEL FROM DIFFERENT FORM AND SCALE OBJECTS

Photogrammetry and 3D scanning are the two primary methods of reverse modeling from a real object. This project attempts to utilize red-green-blue values and normal vectors from the point cloud to investigate the potential of the evolution of the form of the 3D model. Therefore, the two methods mentioned above are employed for the reconstruction of the digital 3D model, and the obtained results are analyzed to ascertain efficient means of attaining superior modeling outcomes in discrete situations to allow compliance to the requirements of subsequent design processes. The results(see figure 1) of the study are as follows:

- Photogrammetry reconstructs models by comparing pixel colors and defining the anchor points of 2D images. The lack of restrictions in terms of the object scale is an advantage of this method, and its disadvantage is that a completely closed mesh model cannot be obtained, because the object is not allowed to move during the photo-taking process. Errors are also common with smooth objects that do not evince obvious edge features.
- The use of the non-contact optical laser scanner (Artec Space Spider) is based on the structured-light method of 3D reconstruction, and Artec Studio utilizes features in overlapping areas to automatically align captured frames. Therefore, the position and angle of the object can be changed arbitrarily before each scan to obtain completely closed mesh models with details. However, a focus problem causes the 3D laser scanner to be unsuitable for the reconstruction of objects that are too large or too small.

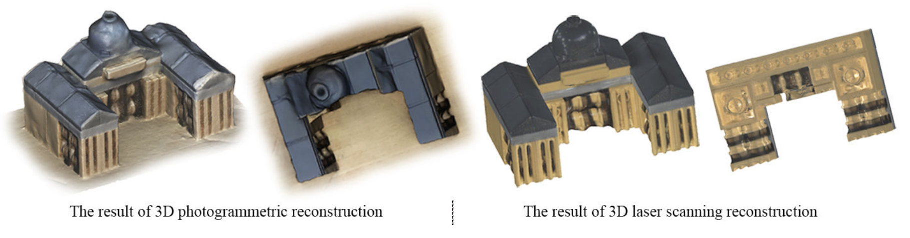

Figure 1. Comparing photogrammetry and 3D laser scanning methods.

3.2. DATA REGENERATION: USING VOLVOX (A PLUG-IN FOR GRASSHOPPER) AND PYTHON-PCL TO IMPORT AND RESAMPLE POINT CLOUD DATA

The resample module, which is based on the moving least squares function(MLS) in the point cloud library (PCL), was used to estimate the normal vector of points, and improve issues such as broken, and rough surfaces caused by shadows or light reflection. Then, we proposed the use of RANSAC (Random Sample Consensus) through the sample consensus module in the PCL to remove outliers and noise near ground. Thus, the data obtained using photogrammetry can be regenerated without noise(see Figure 2).

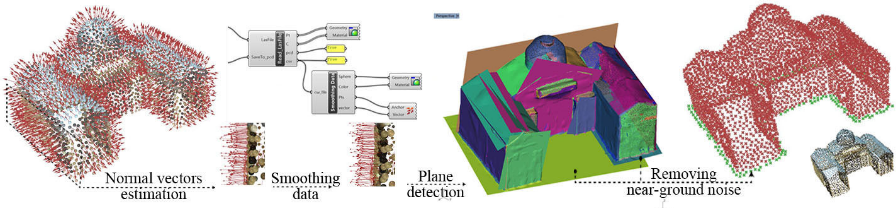

Figure 2. The process of point cloud model regeneration in Rhino/Grasshopper.

3.3. DATA INDEXING: TRANSFORMATION FROM 3D WORLD COORDINATES TO TWO-DIMENSIONAL (2D) PIXEL COORDINATES FOR INTEGRATING COMPUTER VISION TECHNIQUES INTO POINT CLOUD PROCESSING

First, we indexed the point cloud and selected the number and location of the necessary projection planes according to form and features. Next, we projected points onto multiple selected planes, and the shortest distance between each point and its projection point was considered the depth data. Therefore, when two or more points were projected in the same position, only the point with the smallest value in the depth data was selected to be projected onto the plane. Moreover, we used the module in OpenCV to establish depth images based on the depth data and the obtained projection result. Finally, we converted depth images to range images(see Figure 3) according to the values in the alpha channel to ensure that the point selection and feature detection in the next step can occur without interference from different materials or surfaces.

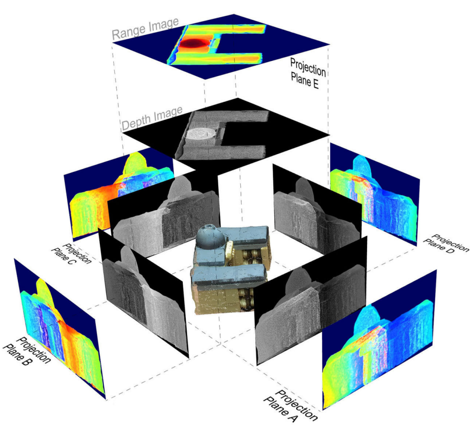

Figure 3. Spatial relation diagram and projection results.

3.4. DATA ABSTRACTING: USING POINT SET REGISTRATION AND A COMPUTER VISION TECHNIQUE TO IMPROVE THE ADJUSTMENT FLEXIBILITY OF THE 3D POINT CLOUD MODEL

We indexed each pixel in the projection image and stored red-green-blue and depth data sequentially in accordance with the image coordinate system. By this approach, we utilized the index relationship between the 3D point cloud and each of the pixels to complete the point set registration process and minimize the data. Furthermore, by combining computer vision and image synthesis technology, we were able to efficiently adjust the projection planes by regenerating the feature points/edges and replacing the material and then returning the results to the 3D point cloud model using the point set registration method. For example, we can use the “Sobel edge detection” function in scikit-image library o extract edges and pixel coordinates with an alpha value higher than 200 and use the index relationship that we have established previously to select points near the edges in the 3D point cloud model. Finally, after completion of the registration, we used the “voxelgrid filter” function in python-pcl to voxelize the edges‘ points to accurately locate the positions of the edges’ lines in the model(see Figure 4).

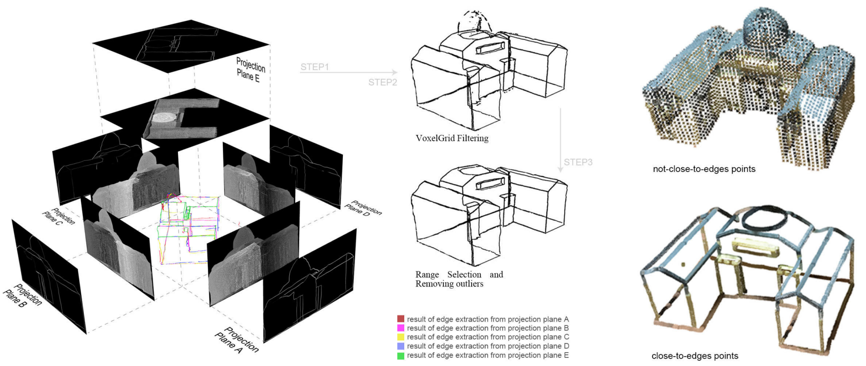

Figure 4. The result after superimposing each projection plane for Canny edge detection and registration.

4. Experiment

The main purpose of this study is to explore how point cloud data with high spatial dimensions can be used as a creative design material and be flexibly applied to diversified design fields. Therefore, we tested the above-mentioned approaches in diversified design fields. For example, we constructed a point cloud model with artistic visual effects, evoluted the form from a cube to furniture, and optimized the detail after form re-topology. The test results are as follows:

4.1. ARTISTICIZATION OF POINT CLOUD MODEL

We re-sampled the data from the projection results to ensure that each of the points in the 3D model was only projected on the specific projection plane with the shortest perpendicular distance from the projection plane. We then imported the results to Photoshop, created replacement materials, and filtered special effects processing. Finally, the results were returned to the 3D model using the point set registration method. Furthermore, material replacement and special visual effect presentation of the point cloud model (see Figure 5) were carried out. By these processes, a design concept can be quickly simulated and visualized in Rhino/Grasshopper, so that rational analysis and logic can be combined with perceptual design thinking and more innovative design results can be presented.

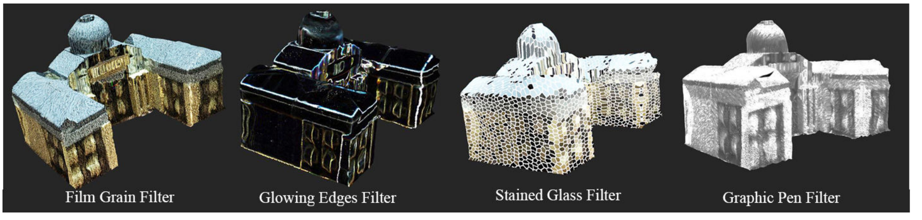

Figure 5. Artisticization of point cloud model.

4.2. APPLICATION OF POINT CLOUDS TO THE FORM EVOLUTION

In this stage, we used a simple cube to explore the potential of the 3D point cloud model typology using the hybrid modeling approach that we proposed in order to prove that making a combination between the 3D models in Rhino/Grasshopper can be creative and at the same time efficient as the 2D image collage of the different elements in Photoshop. The results are as follows:

4.2.1. Selecting an irregular boundary area of points for replacing red-green-blue values and translation of points

First, we projected all the points in the 3D model onto the nearest projection planes and attached the patterns with highly complex shape onto the projection images(see Figure 6: step 1). We then used the point set registration approach to select the points which were covered by the patterns in the projection images by the index relation that has been established previously. Finally, each selected point's red-green-blue value was substituted(see Figure 6: step 2), and the position was moved to a certain distance along the normal vector according to the alpha value of the corresponding pixel on the pattern(see Figure 6: step 3 to step 5), so that we can prove that the 3D point cloud model can promptly and comprehensively select a specific area and regenerate using the selected index of pixels in the projection images.

4.2.2. Form evolution through depth images

Each point in the point cloud model is independent and is not affected by the neighbors, In this context, the point cloud model requires the attachment of the depth image of the object to be combined with the original model in the most suitable projection image, and it uses the module in OpenCV to extract the alpha channel value in the area. As a result, the value will be directly projected onto the corresponding point in the 3D point cloud model. The depth images can also be used to extend or copy the existing points to produce smooth curves/surfaces and other effects(see Figure 6: step 7 to step 9). Thus, the design can meet the functional requirements and demonstrate modeling aesthetics accordingly.

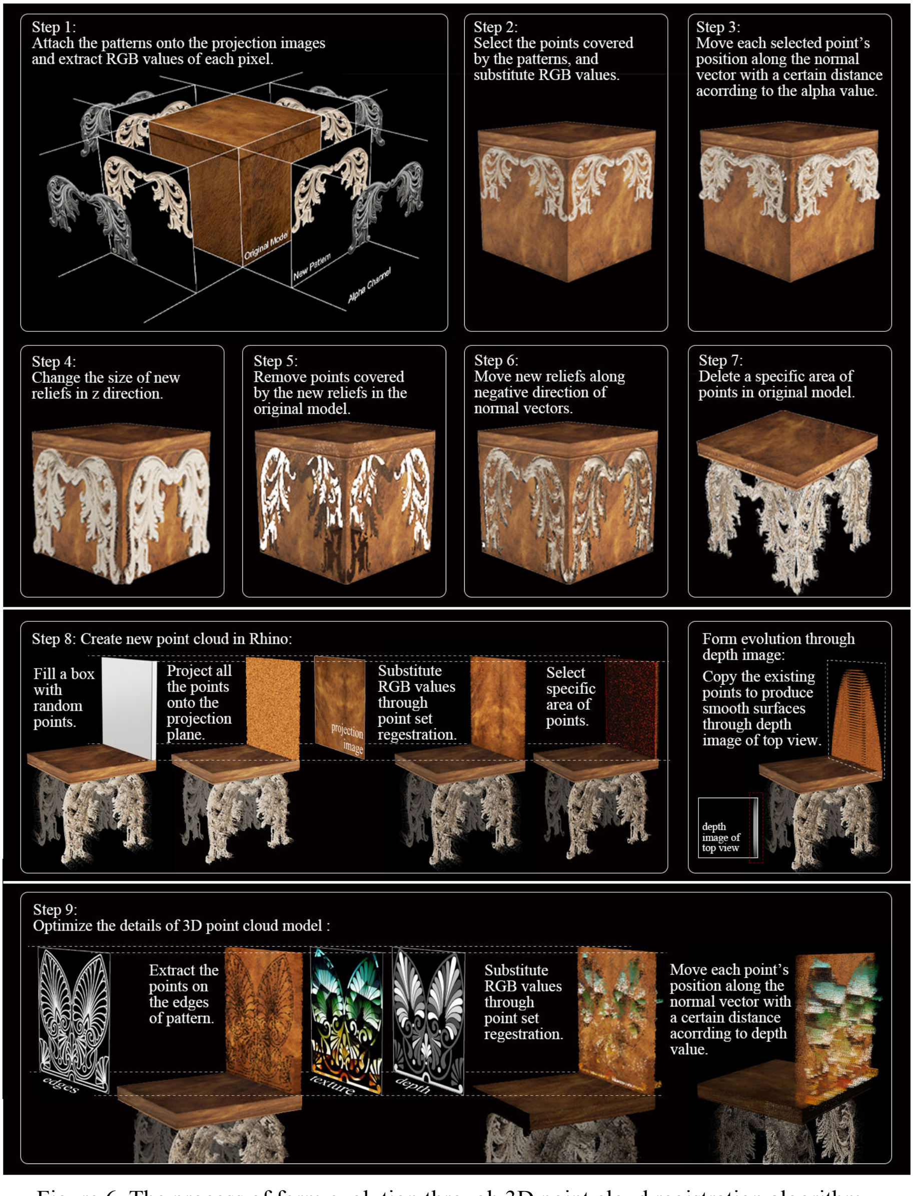

Figure 6. The process of form evolution through 3D point cloud registration algorithm.

5. Conclusion

We integrated multiple open-source python libraries into our pre-design process and sent the required data to CAD/CAM platform(Rhino/Grasshopper) with the aim of representing point cloud data analysis techniques and algorithms that have already been well developed from the designer's perspective. The application of rapid modeling will not only be pursued for the practical expression of realistic senses in virtual scenarios, but the said models will also be equipped with human-specific perceptual thinking, and creativity capabilities. By re-analyzing those techniques and mathematical rules, creative inspiration beyond rational logic might be induced and thus allow architectures to not only impart and inherit history but also create future opportunities to march toward a better living experience.

6. Further Steps

Rhino/Grasshopper, despite being an excellent platform for fast testing and rapid visualization, is inferior to game engines in overall computational efficiency in terms of point cloud processing of extremely big data. In contrast, the design of the overall analysis demonstrated in this study allows the integration into Blender with C-Python as a platform. This technique should not only be applied in preliminary architectural design and analysis, but it should also be used in design simulation and art with even bigger data derived from drone photogrammetry. Moreover, regarding the planar projection that we used in this research, there are relevant problems of anamorphosis or distortion when using the original model; the surfaces of which are not flat and edges not bent. Therefore, the UV mapping coordinate setting rules in OpenGL can also be adopted in the future to flatten the point cloud model, which can further improve the accuracy of optimization, and re-typology models using computer vision technologies.

Acknowledgment

This research was supported by the Ministry of Science and Technology under Grant Number 109-2634-F-009-015, and was managed by the Pervasive Artificial Intelligence Research (PAIR) Labs, Taiwan.

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MASS-TAILORISATION - THROUGH THREE ANALOGIES

Resolving the paradox of choice in the architecture design process through the digital continuum of mass-tailorisation

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Abstract. The advent of digital tools and technologies has provided designers with the ability to create in complexities and volumes of unprecedented scale. Thus, perhaps the designer has also become prone to the paradox of choice than ever before, at a time which the decision-making process of the designer is increasing in its significance due to the near-limitless possibilities of design. Mass-tailorisation aims to aid the decision-making process of the designer in a world of unprecedented possibilities but of limited practicalities of reality by narrowing the viable solutions through non-critical design contexts and biases. Mass-tailorisation begins as a reaction to mass-customisation, however, through the aid of digital continuum and the pursuit of the Move 37 phenomenon, mass-tailorisation aims to aid the designer of the modern times.

Keywords. Mass-tailorisation; Paradox of Choice; Artificial Intelligence; Decision-making; Mass-customisation.

1. Introduction.

Mass-tailorisation, as opposed to mass-customisation, can be used as a tool to aid the decision-making process within the computational design process. Since the 20th-century, the advancement of digital tools and environments has laid paths for new digital methodologies in how designers approach the architectural design process. More recently, it has become more efficient and effective than ever before to generate numerous viable design solutions that all satisfy the single design problem in question through the aid of computational and digital design methodologies. However, the practicalities of many architectural projects cannot accommodate for numerous solutions. It is often the case that only a select few, if not a single solution, is realised at the end of the process. Therefore, the responsibility of the designer as a decision-maker is significant in the choice for a viable solution from the pool of options. It is at this point that the designer is prone to experiencing the paradox of choice - the difficulty in selecting the 'best' solution due to the numerous possibilities.

Learning from the shortfalls of mass-customisation and utilising artificial intelligence, the research proposes the idea of mass-tailorisation - the reduction

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 529-538.

of viable solutions through non-critical biases. The research aims to develop a mass-tailorisation process established upon a digital continuum of design, fabrication, and assembly in an attempt to aid in the decision-making process of the designer and avoid the paradox of choice. More specifically, the Burr puzzle is used as an evaluative case-study unit for design-led research of mass-tailorisation. The research discusses that the computational capability to produce numerous viable solutions creates a scope of opportunities that is too broad to allow for the effective and efficient decision-making process. Hence, the scope of solutions is in-fact only ‘possibilities’ to the designer. The development of mass-tailorisation allows for an effective and efficient decision-making process that will transform the mass ‘possibilities’ to a select, often intentionally bias ‘solutions’ that respond to specific design contexts in question.

2. An introduction to mass-tailorisation - through the Ford Model T.

2.1. MASS-PRODUCTION

The Fordist paradigm of mass-production is an economic concept birthed by the progressive development of standardisation, mechanisation, and automation that spanned the 19th and the 20th-century industrial revolution (Smith. 2019). The concept revolves around the idea of economies of scale - a cyclical process of greater production of standardised, mechanised, and automated units increasing repetition of manufacture, thus increasing the efficiency of the manufacturing system and reducing the cost per unit, which in turn encourages higher consumption that drives greater production yet again.

An example of mass-production in its full envisioned potential was the Ford Model T - the first affordable car. Henry Ford - considered to be a pioneer in mass-production - has explained the car as: “You can have it in any colour, as long as it’s black” (1923, p.73). Ford’s explanation is an iconic statement that describes the spirit of mass-production. By continually focusing on the repetition of the same output (black paint), the efficiency of the manufacturing system increases thus, decreasing the unit prices to an affordable level.

The advantage of mass-production was evident. Approximately 15 million cars were sold between 1908 and 1927, solidifying the automotive as an essential part of the American middle-class life.

Although mass-production was an innovation that changed economics, it was not without its faults. In mass-production systems, due to the nature of the limited variety of outputs in exchange for low-cost prices, the user essentially has to meet the characteristics of the output to satisfy their design needs. The user can either decide not to acquire the product deeming that its predetermined characteristics do not sufficiently meet their needs or, acquire the output even if it does not fully meet their requirements, potentially compromising some of their needs (eg. “Even though I want a red Model T, a black one is good enough”). This notion of compromise - labelled as ‘customer sacrifice’ - can determine the efficiency and effectiveness of a mass-produced output (Pine, 2019).

2.2. MASS-CUSTOMISATION

Mass-customisation aims to increase the number of viable outputs while maintaining the efficiency established in the Mass-production system. First delineated by Tuffler (1970) and coined by Davis (1996), the economic concept of Mass-customisation began its emergence in the late 20th century as an advanced technological progression to mass-production. Pine described mass-customisation as "the new frontier in business competition for both manufacturing and service industries. At its core is a tremendous increase in variety and customisation without a corresponding increase in costs." (1993, pg.xiii). If mass-production is achieved through economies of scale, mass-customisation is achieved through economies of scope - "the application of a single process to produce a greater variety of products or services more cheaply and more quickly" (Pine, 1993, p.48). The focus shifts from the output to the manufacturing process.

Applying the concept of mass-customisation to the Ford Model T, mass-customisation relieves the condition that Ford has put on the user. Unlike mass-production, mass-customisation explains to the user that "You can have it in any colour". This statement is viable because mass-customisation at its best can increase the variety of outputs while retaining the efficiency of mass-production to keep unit costs down. Customer-sacrifice is significantly reduced.

While mass-customisation allows the increase in the variety of the output, the very concept of mass-customisation can also bring about a duality of opportunity and a problem. In the example of the Ford Model T, due to the potentially infinite possibilities of colour combinations the user is faced with the 'Paradox of Choice' - too many options leading to the difficulty of making a single choice (Schwartz, 2016). Schwartz explains this phenomenon as: "learning to choose is hard. Learning to choose well is harder. And learning to choose well in a world of unlimited possibilities is harder still, perhaps too hard" (Schwartz, 2016, p.148).

2.3. MASS-TAILORISATION

Mass-tailorisation aims to resolve this Paradox of Choice. If mass-customisation enlarged the output of a mass-produced system to allow numerous varieties, mass-tailorisation narrows the output of the mass-customised system to a select few that best represent the user's needs or desires. In the context of the Ford Model T, mass-tailorisation explains to the user that "You can have it in any colour - but if you are after a family car, a blue, green, or red car will be the best. So which one would you like to choose?". Like mass-customisation, mass-tailorisation can create a potentially near-infinite number of outputs, however, by incorporating a specific design context - a family car for example - mass-tailorisation narrows the outputs to a select few that best meets the specified design context. The user is still able to make a choice, even outside the tailorised outputs. As such, the ultimate aim of mass-tailorisation is to allow the user to have more control over their own decisions in a world of complexities while ensuring that those decisions are beneficial to the design context in question.

Architecturally, the need of mass-tailorisation is evident. The advancement of tools and technologies available to architects has increased the capacity of the designer to create more with fewer resources. Such developments provide great variety, however, often than not, the practicalities of architecture only allow for a select few to be realised to completion. Thus, the decision-making of the architect becomes ever-important in a world of unlimited possibilities but of limited realities. With such responsibility in context, the next section aims to establish a positive relationship between the current advancement of tools and technologies, and mass-tailorisation.

3. The Relationship between mass-tailorisation & the digital continuum - through the Burr puzzle.

3.1. THE DIGITAL CONTINUUM AND ITS RELATION TO MASS-TAILORISATION.

In the beginning of the 21st century, as the digital environment started to develop to a level that was accessible to the mass public, a new notion of architectural methodology was proposed. The notion of "a new digital continuum, a direct link from design through to construction, [that] is established through digital technologies" was implied (Kolarevic, 2003, pg.3). Kolarevic later coins this idea as the "Information Master Builder" (2003). In its essence, the Information Master Builder aims to create a digital continuum from design to fabrication and to assembly, with the information of the creation transferred and used in the digital environment throughout the process.

The incorporation of such a design-fabricate-assemble digital continuum proves to be an important factor in the development of architectural mass-tailorisation systems. As more of the information of human-made environments transition into the digital, in the field of architecture: "the ultimate goal becomes to construct a four-dimensional model encoded with all qualitative and quantitative dimensional information necessary for design, analysis, fabrication, and construction, plus time-based information necessary for assembly sequencing." (Kolarevic, 2003, pg.8)

Consequently, the act of designing, fabricating, and assembling is becoming more unified. The close relationship between design, fabrication and assembly, and the possibility of complete unification results in every architectural decision becoming more extensive in its influence within the digital continuum. More than ever before, the act of building is becoming a closed system, where decisions for design will have to consider fabrication and assembly, decisions for fabrication will have to consider design and assembly, and decisions for assembly will have to consider design and fabrication. Furthermore, the capability of the digital continuum to produce unprecedented volumes of design possibilities pose complex implications in the decision-making process of the designer. In this context, mass-tailorisation will play an important role in providing more focused decisions for the designer and the client.

3.2. THE BURR PUZZLE

Due to the complexity of the unlimited possibilities in architecture, the research of the potential for mass-tailorisation within the digital continuum of architecture needs to begin at a smaller, definable scale. In order to test these ideas, the Burr puzzle was chosen as the first case study.

The six-piece Burr puzzle is regarded as the most familiar three-dimensional puzzle, consisting of various combinations of six interlocking assemblies of notched pieces arranged symmetrically in three mutually perpendicular intersecting pairs (Coffin, 1991). Each piece of the puzzle must be of equal length and must not be less than three times its width. The complexity of the Burr puzzle gained significant interest among mathematicians and computer scientists in the late 20th century, resulting in significant findings in regards to the puzzle (Coffin, 1991).

In the six-piece Burr puzzle, every piece of the puzzle can consist of up to 24 cuboids in a 6(L)x2x2 proportion. Of the 24 cuboids, every piece will always consist of 12 cuboids, six on each end of the piece forming an ‘L’ shape. The remaining central 12 cuboids become the variables; each piece may have none to all of the 12 cuboids, or any permutation in between.

Applying the permutation logic results in 4096 various pieces. However, to ensure that each puzzle consists of only six pieces, any piece that was split into two or more parts were eliminated to reduce the number of valid pieces to 2225. Eliminating symmetrical pieces further reduces the pool to 837 (Coffin, 1991).

3.3. THE DESIGN-FABRICATION-ASSEMBLY DIGITAL CONTINUUM OF THE SIX-PIECE BURR PUZZLE.

3.3.1. Design

Working with the remaining pieces, an algorithm selects six pieces to determine whether the selected pieces in their defined sequential order and location can form the Burr. Once the algorithm has found six pieces in a specific order and location that can form the Burr, it has designed an iteration of the Burr puzzle. Many studies have been conducted to calculate how many iterations of the Burr puzzle are possible. While the exact number of solutions is yet to be calculated, it has been estimated that there are up to 71.3 billion iterations of Burr Puzzles (Cutler, 1994). The aim of this research is not to design all the possible iterations of the puzzle, instead, develop a mass-tailorisation system that reduces the possible outcomes through weighted biases based on defined criteria (by various factors such as the designer or the laws of physics) in relation to the digital continuum.

3.3.2. Fabrication

Once the algorithm has designed an iteration of the Burr puzzle, this digital information can be linked to digital fabrication using CNC milling machines or industrial robots. Digital fabrication allows for greater freedom in the fabrication of Burr puzzles. Traditionally, only a pool of 59 pieces labelled as ‘notched pieces’ was preferred as these were the only pieces that could be easily notched using a saw or a dado blade. Other pieces that included blind corners and edges required additional labour such as chiselling or joining several sections together to form a single piece (Coffin, 1991). This process required greater intricacy in the craft as functional and aesthetical deficiencies were more likely, hence these pieces were less preferred. However, the use of digital fabrication technologies provide more control and hence removes these fabrication limitations, allowing more pieces to be considered of equal preference and produced with more efficiency. The preferred pieces are no longer unwillingly limited to 59 pieces but expands to 2225, consequently unlocking the potential to fabricate all of the 71.3 billion possible puzzle iterations.

3.3.3. Assembly

Once the Burr puzzle pieces have been digitally fabricated, the same digital information can be used for digital assembly. While the purpose of puzzles is to challenge the users in the assembly of the pieces, the goal in this research is to allow for quick and easy assembly, simulating the complexities of architectural assembly and construction on a small scale, and testing whether digital assembly is able to efficiently and effectively aid in its process. The Microsoft Hololens, an augmented reality headset, along with Fologram, an augmented reality plugin for Grasshopper, is used for the assembly section of the digital continuum. Using the Hololens, the user is able to see a step-by-step interactive holographic demonstration alongside the physical puzzle pieces. Without the aid of digital assembly, the assembly of an unfamiliar iteration of the Burr puzzle could take several hours or even longer. However, through the use of augmented reality, the assembly time reduces to under ten minutes.

3.4. MASS-PRODUCTION, MASS-CUSTOMISATION, AND MASS-TAILORISATION OF THE SIX-PIECE BURR PUZZLE.

When the digital continuum is able to repeatedly generate one iteration of the Burr puzzle, a mass-production system is established. Likewise, when the continuum is able to generate variations of the Burr puzzle using the pool of pieces, a mass-customisation system is established. One can design, fabricate, and assemble different variations of the Burr puzzle without compromising the efficiency and effectiveness of the process because every variation satisfies the requirements for the Burr puzzle. However, it is at this point that the shortfall of mass-customisation can be seen.

Should the digital continuum be able to create all of the estimated 71.3 billion iterations, there is no clear and logical method for the user to select one output over another. This is because each of the puzzle pieces did not have specific design contexts beyond its role as a burr puzzle piece. Due to the context-less nature of the pieces, the designed puzzles become context-less beyond its Burr design. Thus, no puzzle can become more ‘valuable’ than the other as all designed puzzles are now ‘only’ Burr puzzles. This leaves the selection of a single Burr puzzle to a near-random selection based on inefficient, ineffective, and illogical probability of chance. In other words, the user has no control over the selected output. The user has experienced the paradox of choice and has lost control of the decision-making process of the design.

To help address this problem, mass-tailorisation aims to add additional layers of specific design context to the Burr puzzles. Through this process, the outputs can be ranked in their 'value' against its response to the given design context. For example, a mass-tailorised algorithm will be able to apply specific design contexts such as 'the easiest to assemble', or, 'the easiest to fabricate'. Through these additional layers, the outputs can be evaluated in its relative degree of response to the specified design contexts. The designer and the client become more engaged and gain an added understanding of the properties of each output, helping them gain greater control over their decisions to best respond to the design context.

3.5. THE MORE SOLUTION SPACE THERE IS, THE MORE SPECIFIC THE TAILORISATION CAN OCCUR.

An interesting relationship exists between mass-customisation and mass-tailorisation. As mass-tailorisation is a reaction to mass-customisation, the more comprehensive the mass-customisation system is, the more comprehensive the reacting mass-tailorisation can be.

Simply put, the larger the variety of outputs created by mass-customisation - otherwise known as solution space - the better the select number of outputs can be tailorised in mass-tailorisation, reducing customer sacrifice. Hence, ironically, while the paradox of choice is not welcomed, an increased solution space is appreciated.

In light of such a relationship, the next section speculates on a possibility for increasing the solution space for mass-tailorisation through the aid of digital tools and artificial intelligence.

4. The relationship between mass-tailorisation and the Move 37 phenomenon - through a series of lines.

4.1. ALPHAGO AND MOVE 37

The ancient game of Go is considered to be one of the most complex two-player games in the world - it is estimated that the possible moves in Go outnumber the number of atoms in the universe. Due to these complexities, Go has often been described as 'hypnotic', 'most abstract', 'intuitive', and 'creative'. In the ancient east-Asian countries, Go was considered to be one of the four noble arts alongside music, poetry, and painting (Kohs, 2017). In March 2016, a computer programme by the name AlphaGo challenged Lee Se Dol, an 18-time world champion, in a five-game match of Go. Due to the perceived-qualitative qualities of the game, very few expected AlphaGo to pose a serious threat to Lee Se Dol. In fact, many experts claimed that such technology was at least another decade away.

To the surprise of the majority, AlphaGo won the match four games to one. However, the result of the match was not the single biggest news of the event. In Game Two, on the 37th move of the game, Alpha Go made a move that only 0.01% of Go professionals would make. It consequently became the critical move in winning the game and the move has since been labelled as Move 37.

4.2. THE RELATIONSHIP BETWEEN THE MOVE 37 PHENOMENON AND OUR CAPABILITY OF DRAWING A LINE.

We suggest that phenomena such as Move 37 could be possible in the field of architecture. We have conducted a simple experiment to illustrate an analogy for the possibility of Move 37.

The experiment asks for participants to draw a single line on a white canvas. It is then followed with the instruction to draw as many different lines on the white canvas as they deemed possible and suit. Expectedly, both instructions were completed with relative ease. In the case of the first instruction, individuals were able to quickly draw a line on a white canvas without much trouble. In the case of the second instruction, there were differences in the number of lines being drawn. However, most were able to draw multiple iterations of a line.

In light of the completion of the second instruction, the first gains much greater significance. The second instruction exemplifies that individuals can cognitively generate multiple variations of single lines. However, when the individual was tasked with drawing a single line on the canvas, they were able to avoid the paradox of choice and draw a single line that was deemed the best fit for this particular task - they have performed mass-tailorisation.

The figure below illustrates some iterations of a single line on a white square canvas (Figure 1).

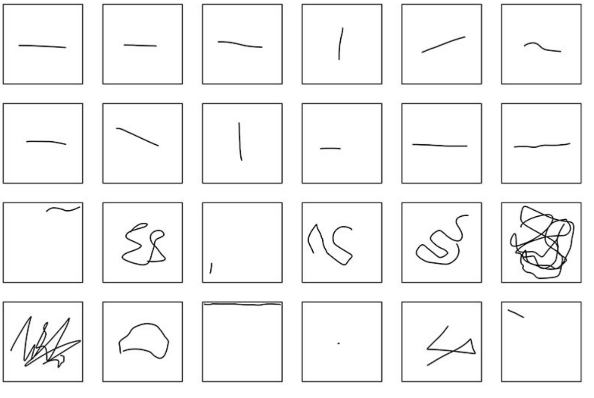

Figure 1. Iterations of a line.

We suggest that these lines are simple analogies to explain the phenomenon and significance of Move 37, and why digital tools will be able to help us in the decision-making process. While the participants of the experiment were able to generate multiple lines, through the use of digital tools, ‘drawing’ every single possible iteration of a line within a given canvas is not an impossible feat. Such action expands the solution space for a ‘line’ on a canvas, providing an improved basis for mass-tailorisation.

4.3. WHAT IS A LINE? - A SHORT DISCUSSION ON SEMANTICS

The reader might suggest that the examples of lines provided are in fact, not lines. Validity exists in such observation, encouraging a discussion on the semantics of a line. In fact, as a vital element of the architectural design process, the semantics of a line in architectural context is worthy of a paper in itself at the least. Therefore, in this paper, we simply suggest that the call for the discussion on the semantics of a line in itself provides for the case that designers could be framed within their own biases and preconception of thinking. The validity for one to claim that a drawing may or may not be considered as a line frames them within their perceived understanding of what a line is. Therefore, through the use of digital tools, we may be able to break these boundaries and possibly discover the undiscovered lines - the Move 37's in the drawing of a line - and perhaps more broadly, in architectural design also.

4.4. THE IMPORTANCE OF MOVE 37 PHENOMENON IN MASS-TAILORISATION

The Move 37 phenomenon is an important part of the mass-tailorisation system as it will expand the solution space on which mass-tailorisation will occur. Should digital tools and artificial intelligence able to aid the designer in the discovery of undiscovered abundance, the solution space of the designer will expand. As explained earlier, a large solution space will provide finer mass-tailorisation. Customer sacrifice is reduced in a finer mass-tailorisation system, hence higher the likelihood that the designed intent of the output is satisfactory, leading to a better decision-making process.

5. Conclusion - Mass-tailorisation, Digital Continuum, and the Search for the Move 37 phenomenon

Mass-tailorisation can aid the designer in the decision-making process by resolving the paradox of choice - the paradox of choice being an indication that the designer is troubled in identifying correct design decisions. Meanwhile, in establishing mass-tailorisation, the digital continuum and the search for Move 37 phenomenon serve the same purpose - to increase the solution space to allow for refined tailorisation. The digital continuum establishes an inherent mass-customisation system that unlocks the viability of possibilities within our cognitive comprehension. The search for Move 37 phenomenon then, is tasked with discovering the possibilities that might yet be waiting to be discovered. In the age of the digital, through the digital continuum and the Move 37 phenomenon, mass-tailorisation will be able to increase our capabilities as a designer in a world of unlimited possibilities as well as aid in the decision-making process in the world of practical realities.

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ONTOLOGY-DRIVEN ANALYTICS FOR INDOOR POINT CLOUDS

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Abstract. Automated processing, semantic enrichment and visual analytics methods for point clouds are often use-case specific for a given domain (e.g, for Facility Management (FM) applications). Currently, this means that applicable processing techniques, semantics and visual analytics methods need to be selected, generated or implemented by human domain experts, which is an error-prone, subjective and non-interoperable process. An ontology-driven analytics approach can be used to solve this problem by creating and maintaining a Knowledge Base, and utilizing an ontology for automatically suggesting optimal selection of processing and analytics techniques for point clouds. We present an approach of an ontology-driven analytics concept and system design, which supports smart representation, exploration, and processing of indoor point clouds. We present and provide an overview of high-level concept and architecture for such a system, along with related key technologies and approaches based on previously published case studies. We also describe key requirements for system components, and discuss the feasibility of their implementation within a Service-Oriented Architecture (SOA).

Keywords. Knowledge Base; Point Clouds; Semantic Enrichment; Service-Oriented Architecture; Ontology.

1. INTRODUCTION

An ontology can be used to define the relationships between entities, methods, data, semantics, and processes for a given domain. An ontology can also be used to set up and maintain a Knowledge Base, and for performing related inferencing operations. A Knowledge Base contains all of the semantics, rules and facts used to infer a decision based on provided ontology (usually with ontological metadata). As such, a Knowledge Base employs a given ontology to structure its data. When the ontology is updated by various process results and inputs (e.g., domain expertise, computed semantics, etc.), so is the Knowledge Base with new rules, facts and associated semantics. Thus an interdependent relationship exists between the two concepts, as they are both used to contribute to the definition, creation and updating of knowledge within a given domain. Indoor point clouds, once

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 539-548.

processed and analyzed, have the potential to provide insights into the structure, state, and dynamics of buildings and other constructions, and, by that, to support decision making, e.g., in Facility Management (FM).

1.1. PROBLEM STATEMENT

However, since point clouds are ambiguous by nature, they impose constraints for being applied due to phenomena such as visual clutter and self shadowing. Even more crucial is the lack of any semantics or even ontology within their context (e.g., ontology of a typical office building). An ontology-driven approach would enable automated selection of optimal processing and analysis techniques of point clouds for indoor environment representations, and also enhance decision making through insightful analytics within the subdomain of Operations and Maintenance (O&M) in FM (e.g., for space and inventory management as well as for the optimization of room utilization, occupant comfort, emergency routes, etc). Even when point clouds are semantically enriched, they seldom contribute to the ontology of a building and are only used for single-use decision making cases. Therefore, an ontology needs to be formed that relates to the digital representation and associated O&M processes for the operation of a building. There is a paucity for an ontology-driven analytics,where users can simply query such a system in order for it to generate, associate and present useful semantics for FM decision making tasks (using point clouds as the main representation of the physical environment). In turn, the knowledge of such a “smart” system would be expended when performing any subsequent tasks.

1.2. RESEARCH CONTRIBUTIONS

We present and discuss conceptual system and process designs for each of the key components for an ontology-driven analytics system. We propose an ontology-driven approach that can adapt specific algorithms for segmentation and classification of point cloud clusters, perform such processing operations, and make use of visualization methods to present the resulting semantics to FM stakeholders.

2. FOUNDATIONS AND RELATED WORK

Point clouds can be used to visually inspect and assess the current state of the built environment, can help to track construction-related or refurbishment-related changes over time, and can be used as base-data for the generation of as-is and as-built Building Information Models (BIM) (Qu and Sun 2015). A point-cloud based representation of indoor environments within the context of interactive 3D visualization enables enhanced stakeholder engagement and communication (Xu et al. 2018). Since point clouds do not contain any other information besides spatial distribution in 3D space and possibly color and/or intensity values, they need to be enriched with semantics to effectively support the various FM-related tasks. This process can be error-prone and time-consuming when performed manually (e.g., introducing errors in decisions due to incorrect observations). Generation and injection of semantics into point clouds is based on associating each segmented point cluster with either metric (Armeni et al. 2017), domain expertise (Sacks et al. 2018), or probabilistic deep-learning-based processes and their outputs (Che et al. 2019).

A particular challenge is dynamically assigning semantics or adapting processing algorithms for generalized use-cases when using point clouds. The process of semantic enrichment of point clouds is in most current situations unidirectional (e.g., point clouds are semantically enriched at a single time for a single purpose, with the semantics remaining valid only for the current version of the point cloud). Therefore, in order to be able to dynamically generate and query semantics for point clouds, a feedback system using a Knowledge Base for semantics generation and updating is required. Cursi et al. (2017) describe the development of a prototypical BIM Semantic Bridge system, that can map Industry Foundation Classes (IFC) semantics to an ontology representation using OWL (Web Ontology Language). They state that the main advantage developing a knowledge base using an ontology-drive approach is that is allows experts from different AEC domains to access and exchange knowledge during the design phase of a building (as BIM by default focuses on geometric representation of a building or structure).

Poux et al. (2017) advocate the use of a multi-level semantics framework, in which the first level of semantics represents the point cloud data structure, the second represents the connection elements between the point cloud data structure and the spatial context, while the third level connects specific ontologies with the point cloud that is used by domain experts for performing various semantic queries. All three semantic levels are connected within a feedback loop to a Knowledge Base. The Knowledge Base is updated through inputs from analytic results, devices and domain expertise. Ponciano et al. (2019) describe a fully semantically guided approach for the detection of objects in indoor point clouds. They propose the use of a constantly updated knowledge base that, in turn, is used to select and adapt the most appropriate processing algorithm based on the observed ontologies. Sadeghineko et al. (2018) describe the generation of semantically rich BIM models from point cloud data, where each segmented region of a point cloud is given a unique annotation using the Resource Description Framework (RDF) schema specification, thus enabling relationships between BIM elements to be captured and queried.

The use of visualization for enhancing stakeholder decision making can be accomplished using various annotation methods, and plays an important role for focusing the viewers attention to the semantics of a 3D point cloud scene. Florio et al. (2019) describe different visualization techniques for exploring BIM models using semantically-driven representation configurations. Savva et al. (2017) describe a context-driven annotation approach for 3D indoor scenes, which automatically suggests and presents possible object semantics to the user while they are exploring the scene. A similar approach is described by Zhang et al. (2016), using statistical inference based on user-guided image annotations of indoor environments and their potential spatial arrangements. Another important point is that approaches for semantic enrichment, ontology generation and visual analytics can be implemented using an Service-Oriented Architecture (SOA), which can help for e.g., decoupling of hardware and software requirements between the user and the processing system (Döllner et al. 2012).

3. CONCEPTUAL SYSTEM DESIGN

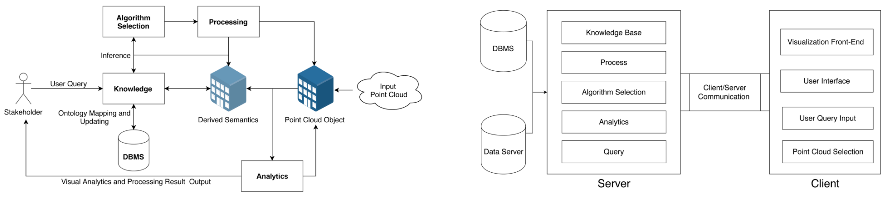

Figure 1. A high-level overview of the main architecture and components of the ontology-driven analytics system for indoor point clouds. The stakeholders interact with the point cloud and are provided with analysis outputs. User tasks such as spatial or inventory queries are inferred from the Knowledge Base component, which is derived and updated using the ontology-driven approach. Conceptual design of an SOA that satisfies the integration requirements of the conceptual system components is shown on the right diagram. The server is responsible for the processing, inference, DBMS operations, and ontology updating tasks, while the client enables the users to select the initial point cloud they want to perform semantic queries on, to visualize the result of the query, as well as to use and update the ontology. .

Fig. 1 illustrates the overall high-level design for the ontology-driven analytics system. The proposed system design is made up of six key components: (1) the Knowledge Base component, (2) DBMS (Database Management System) component, (3) Algorithm Library, (4) Analytics, the (5) the Processing component and (6) the Query component. The six components work together in order to update ontologies, generate semantics and parameter values for selected processing algorithms. It is assumed that a core ontology is defined, which is then subsequently updated through the introduction of new semantics, expert knowledge and existing digital documentation. Initially, the Processing component would be used to filter the input point cloud (e.g., generate normal vectors, remove duplicate points, or sub-sample). The user can enter a new analysis task - a semantic query, that would be interpreted by the Query component. The Query component uses this query (translated into a machine-readable format), to infer a decision using the ontology represented by Knowledge Base component. In turn, the Knowledge Base component then utilizes the existing semantics objects accessed by the DBMS component to form a decision. In this case the selected decision is based on matching the algorithm for the required task from the Algorithm Library component.

The selected algorithm would then be sent back to Processing component, which would apply it along with specific parameters to the point cloud. The result of the processing would be semantics that can be injected into the point cloud for further semantic enrichment. These associated semantics would then be sent to the DBMS component in the form of standardised semantics description object, where they would be once again utilized by the Knowledge Base component next time a new task is initiated by the user. In such a scenario the Knowledge Base acts as an inferencing component of the system. In an example scenario, a user wants to take an inventory of all types of specific chairs in a given office room (Fig. 2). The point cloud is first processed by the Processing component (e.g., for normals compuation, planar surface segmentation, etc). Next, the user's semantic query for selecting all chairs will be sent to the Knowledge Base component that will compare all existing semantics obtained from semantics objects in the DBMS component, in order to select a specific algorithm for detecting the objects via the Algorithm Library component. For example, it is known that chairs are often found in rooms with desks, and that each office has at least one computer desk, which in turn has specific dimensions for the room object that is evaluated from segmented planar clusters obtained from the initial processing of the point cloud. It would also be known that the point cloud has RGB values, and that it was captured using commodity mobile hardware (so it is a coarse representation of the real-world with a lot of noise). Based on this ontology, the Knowledge Base component could formulate an algorithm suggestion and request the Algorithm Library component for a multiview classification algorithm with specifically tuned parameters (based on the derived semantic relations). Once the selected classification algorithm detects and classifies the chairs, the associated resulting semantics that are injected and presented to the user via the Analytics component would also be sent to the DBMS component. This would make the whole ontology-driven system "smarter", as new semantics are introduced with each new user query, and new relations are used to update the ontology that is inferred by the Knowledge Base component for future use.

Visualization of the semantically-enriched clusters of a point cloud scene is vital for highlighting their location in 3D space, and bringing them to the attention of the user for further inspection and assessment. Often, indoor point clouds may contain visual clutter that requires the user to manually navigate and select regions-of-interest for inspection, semantic enrichment and further annotation. In order to draw the users attention to areas of interest in a point cloud that may contain a lot of visual clutter, we can consider the use of visualization idioms (Haber and McNabb, 1990) for highlighting and possibly abstracting, through visualization, the spatial areas of interest in the point cloud. The Analytics component fulfils the role of generating the visual representation of the 3D point cloud, specific point cloud clusters and their associated semantics. We propose the use of specific visualization styles for representing the semantics that were injected into specific point clusters as a result of the ontology-driven scene analysis. These could, e.g., include cluster color coding, floating boxes, abstracted geometry, and manipulation of opacity values (Fig. 3). We also propose the concept of a "smart scene annotation" sub-system as part of the Analytics component, using a probability-based recommendation approach (Fig. 4). Such a component would take into account the currently visible point clusters and would automatically provide suggestions to the user of the object that is currently in view, based on the probabilities derived from the associated semantics of that point cluster (essentially a semi-automated semantics-annotation process).

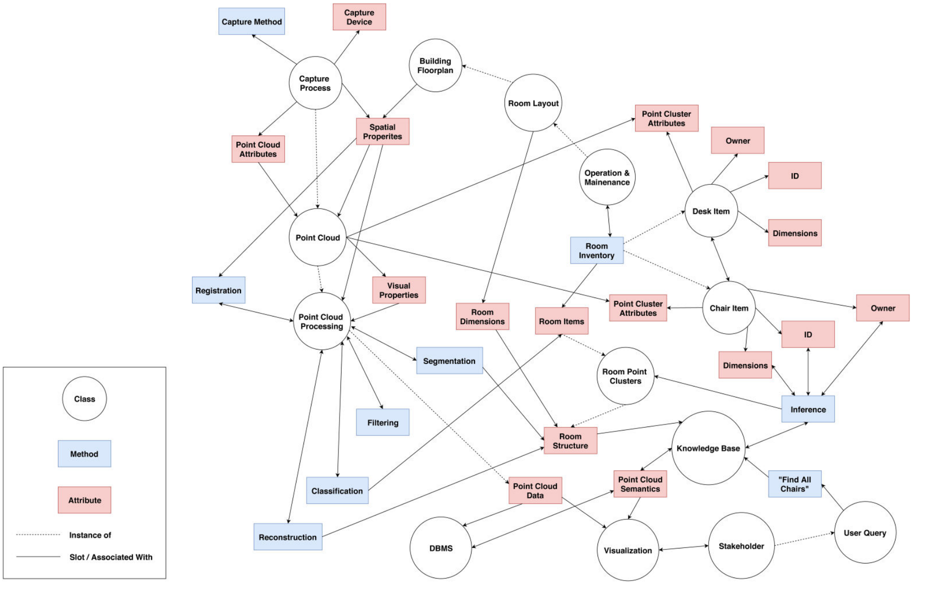

Figure 2. A core ontology example for using a point cloud representation for an O&M task.

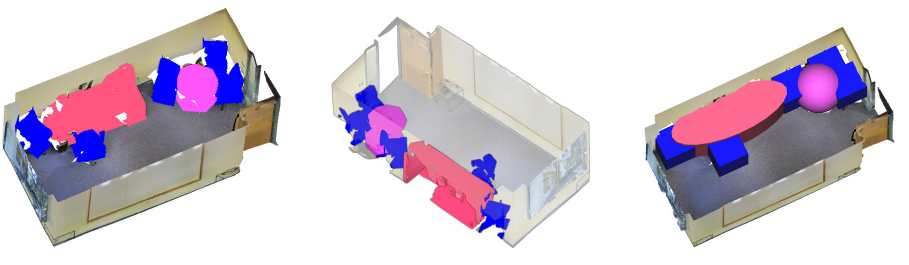

Figure 3. Examples of different visualization idioms used to highlight semantics in a typically cluttered point cloud of an office (from the Stanford dataset by Armeni et al. 2016). The examples feature simple color coding of different object-type point clusters (left), opacity-based visualization in order to avoid visual occlusion (center), and use of abstracted 3D geometry in place of the point clusters in order to simplify the visualization and draw more visual attention from the viewer (right).

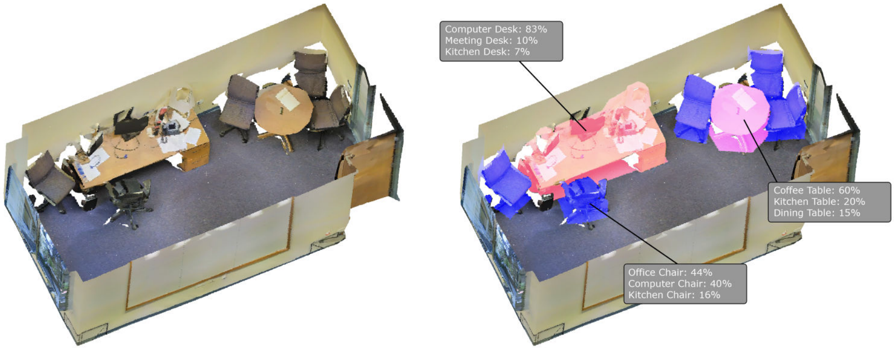

Figure 4. Example of the proposed smart scene annotation, based on the derived probabilities introduced with the classification of point clusters as specific furniture objects. The user is presented with the top three possible semantics for each of the point clusters that are highlighted as "office furniture" objects. The user would, in turn, be able to select the correct semantic for each cluster, and this selection would then be sent to the Knowledge Base component in order to update relations, semantics and processes between the related room and building. Furthermore, a user could manually add semantics that is not already offered and, by that, could extend or refine the underlying ontology itself.

In the context of visualisation and analytics systems, the use of a SOA can help to decouple the often complex image generation process (e.g., on a dedicated high-performance rendering server) from the display of and interaction with those images on clients of various classes (i.e., running various hardware configurations, such as smartphones and tablets), which may be of an older generation, and may not have the hardware and software capabilities to process and render data in real-time and in high quality. Other services could implement and advertise other complex computation tasks including, e.g., deep-learning-based classification of point clouds. The proposed Algorithm Library and Processing components will contain all of the related algorithms used for processing, reconstructing, classifying and evaluating point clouds. Additionally, the design of the Knowledge Base and DBMS components as separate services allows for running the generation and association of semantics as well as ontology management, on dedicated workstation computers with high-performance computing and storage capabilities, whilst rather lightweight clients can access this functionality through the service interfaces.

4. DISCUSSION

In terms of feasibility of implementing the conceptual ontology-driven analytics system, four specific system design requirements and tasks need to be considered. Firstly, a key requirement for the proposed system is an existing and suitable ontology for buildings and indoor spaces. This ontology could then be interpreted and used as the default ontology by the Knowledge Base component when formulating the Algorithm Library component selection response based on the user's initial semantic query. For actual implementations of an ontology, it can be defined essentially as a schema (e.g., RDF). Attempts at defining a formal ontology for buildings and using it to derive semantic relationship for FM-related applications, in most cases those based on BIM requirements, have been discussed by Iskidag et al. (2013), Emgård and Zlatanova (2007) and Nagel et al. (2009). Valid topologies can be derived form BIM-based representations of indoor spaces (e.g., office building related), though this is dependent on using and parsing IFC, CityGML or other related BIM and GIS files. In most cases relationships between specific entities, e.g., in the IFC file representation, can be used to generate connectivity graphs between spaces in a building representation. However, the building and indoor space ontologies are often derived for a single use-case, and therefore difficult to generalize. There is specific paucity for forming any sort of ontologies based on point clouds, which has no standardized semantic file format that is comparable to that of IFC or CityGML (unless an extension is used to embedded point clouds into those file formats, though important semantics and reconstructed geometry are generally not preserved).

Secondly, the task to evaluate and select a suitable DBMS that can handle the parsing, updating and querying of semantic objects would need to be undertaken. Such a database system could be a relational or non-relations DBMS oriented towards semantics and spatial queries. Borrmann (2010) propose an octree-based spatial query database system for retrieval of VRML digital building and city models, implemented and tested using extended versions of relational and object-oriented SQL for custom spatial queries. Ma and Sacks (2016) describe a NoSQL cloud-based database for storage, sharing and retrieval of BIM models (in addition to allowing further semantic enrichment by supporting custom IFC-complaint mapping and representation using the Binary JavaScript Object Notation (BSON) format). Solihin et al. (2017) define and test a BIM-based rule language and describe a system for transforming BIM-data into SQL-based representation for allowing simplified access to FM-related data for stakeholders. The authors note that while relational (also known as SQL-based) DBMSs can be easily extended without rewriting interfaces from scratch, there are still issues concerning the speed of access to data from user queries, as well as enriching such data with custom information due to having to parse and convert IFC-related schematics.

Thirdly, the specific algorithms to be included in the Algorithm Library and used by the Processing components need to be selected and evaluated. While there is a wealth of algorithms available for specific processing tasks of point clouds, certain algorithms are, e.g., better suited towards outdoor point clouds. We have found that certain classification and clustering algorithms provide promising results for classifying indoor point clouds (Stojanovic et al. 2019a).

Fourthly, it is important to define if a specific system is developed only for observation-based analysis and decision making, or if the results from semantic enrichment will be used to infer specific condition-based rules within e.g., Building Management System (BMS), Computer Aided Facilities Management (CAFM), Integrated Workplace Management System (IWMS) or Environmental

Management Systems (EMS). In such a case it would be necessary to introduce more safeguards, and perhaps restrict the system to non-critical O&M monitoring and forecasting tasks.

5. CONCLUSIONS

Based on the provided literature review and discussion of related and influential work, it can be concluded that there is currently no straightforward implementable software solution for ontology-driven analysis of indoor point clouds. While there are promising research results and prototypical implementations showing how ontologies can be formed and integrated with point clouds in principle, using semantics derived through various classification and processing algorithms, the design and end-to-end implementation of a use-case oriented expert system as described in this work is still an open issue. This is especially the case when using domain expertise from FM stakeholders as most current ontology-driven software prototypes for BIM and FM applications are not user-centered (e.g., no focus on user interfaces, qualitative analysis of user input and feedback, etc) The feasibility of implementing an ontology-driven approach is also supported by the authors previously published research for semantic enrichment and visualization (Stojanovic et al. 2019b). Additionally, previous work by the authors has also demonstrated the feasibility of integrating various processing and representation components for visualization of spatio-temporal data as well as point cloud data (Stojanovic et al. 2019c). Based on this and the resulting prototypical implementations and testing of core components, we conclude that a user-oriented, analytics-focused and ontology-driven system can be designed, implemented, and deployed, provided that a suitable ontology of buildings and indoor spaces can be established. After the service-based implementation and successful testing of these key components, we are currently working towards developing a working prototype of the full concept proposed in this paper.

ACKNOWLEDGMENTS

This work has been partially funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) as part of the ZIM program, and the Research School on Service-Oriented Systems Engineering of the Hasso Plattner Institute, Faculty of Digital Engineering, University of Potsdam, Germany.

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INVESTIGATING SITE SURVEY PROCESS WITH PROTOCOL ANALYSIS AND AN EXTENDED FBS FRAMEWORK

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Abstract. In this paper, we try to investigate architectural site survey process by conducting experiment and quantitative analysis. 17 student volunteers were asked to practice site survey for a fixed design objective. With site survey process recorded along with sketching and utterance, we adopt protocol analysis and FBS ontology, which are widely used and discussed in design process research, as the basis of our analysis. Since site survey is a preliminary stage of architectural design, it differs from actual design process in many aspects. In this case, we extended the original FBS framework by adding two extra activities-Objective Processor and Subjective Processor- to better describe site survey process.

Keywords. Site Survey; Protocol Analysis; FBS Ontology; Architecture Education.

1. Introduction

Architecture students and professional architects conduct site survey as an important source of information and inspiration. However, there're very little research about the site survey, telling us what actually happens and how it affects following stages of design activity. With development in quantitative methods of evaluating design process, a natural idea is to conduct site survey experiments to yield results of analysis. In this paper, we introduce a quantitative research of architectural site survey based on experiment, protocol analysis and FBS ontology (J. Gero,1990). Additionally, since FBS ontology, which means function, behavior and structure, was initially put forward to analyze design activity, there is a lack of branches and connections for more specific design moves in site survey process. Our observation and understanding is that, during site survey process, designers process the features of site with their objective knowledge or subjective experiences. To help understand the design moves in the site survey process, we made extension to the FBS framework by adding two extra activities. With protocol analysis and the extended FBS framework we investigate our site survey experiment data and conduct multiple analysis.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 549-558.

2. Background

2.1. SITE SURVEY

Site survey is a preliminary activity for architectural design which inspects site where design is proposed. By conducting site survey, designer could look into site in detail and have immersive experience to find out potentials in actual design stage. Although enjoyed limited attention in traditional design process, site survey is considered to be a more critical step architect will take in the modern age. Having a more and more blurred ambit with the first draft, it is recognized as the fundamental activity for being aware of the basic disposition of the site, and also considered as the very first step where the design take place. Although site survey is a common and important practice among architects and architecture students, the process is rarely looked into. There are few related researches that inspects site survey process.

2.2. FBS ONTOLOGY

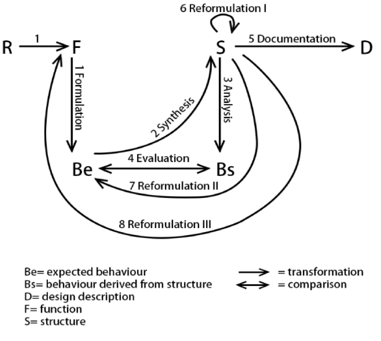

Figure 1. The FBS Ontology (J. Kan, J. Gero 2017).

FBS ontology (J. Gero,1990) is one of the most commonly used ontology in design process research which concludes design activities into 8 processes between 6 variables: F(function), Be (expected behavior), Bs (structure behavior), S(structure),R(requirement),D(documentation). Function (F) of design refers to its intention and purpose. Structure (S) refers to components and relationships of design. Behavior, including Be and Bs, refers to the performance, either the expected performance (Be), or the performance of Structure (Bs). By linking and transferring between these variables, FBS ontology could then describe design process with 8 processes, which is shown in Figure 1. The FBS ontology has been applied on many design fields and was shown effective as protocol analysis coding scheme.

3. Experiment Setting

In order to investigate the process of site survey, we adopt protocol analysis as our major research method. We set up a site survey experiment involving 17 volunteers and record the whole experiment process for further analysis. Considering the compactness between the site survey and the actual architectural design as well as the clear end of the experiment sign, subjects of our experiment are given a fixed design objective, which is locating a campus café in a certain area in a university campus. The site map is shown in Fig. 2. To investigate the possible correlation between architectural design experience and site survey activity pattern, we recruited 17 volunteers, among which 8 are architecture student ranging from senior to junior and 9 are from various other majors. All participants finished the site survey process independently in 10-15 minutes following "Thinking Aloud" principle.

Figure 2. Site map of experiment.

Experimental process:

1. The subjects are guided to the starting position (shown in the red dot in figure 2), and receive the architectural design assignment, site map, paper, pen and other materials and tools.

2. The subjects confirm the experimental content:site investigation for the design of coffee shop in this red dashed area. The objective is to select a specific location for the coffee shop and briefly explain the reasons for such selection: A. Observation and analysis of the objective environment B. subjective feelings in the venue and the reasons for these feelings. In the process of experiment, subjects need to reflect the thinking in the form of language (Think Aloud)

3. The subjects and the recorder go to the research site together to record the detailed image of the research process. The experiment can be ended after the subjects determine the location of the coffee shop and explain the reasons briefly. Over 15 minutes, the experiment will be ended, too.

4. After the experiment, the subjects return the materials and tools.

The entire experiment process is recorded, segmented and analyzed. Segmentation is conducted by separating design process into “design moves”, which are the smallest coherent operation detectable in design activity (Goldschmidt 1992). We then coded the design moves under an extended FBS framework of which the details are discussed in the next chapter.

4. Modifications and Adaptive Updates of FBS framework

Since site survey is a preliminary stage of design process, the focus and distribution of activity differs from the setting of original FBS ontology. Based on our observation from experiments, volunteers tend to focus mostly on the Requirement code, which include their thinking about both task document and site features. In this way, much of our concerned process would be unified under the R code if we proceed the analysis using the original FBS ontology. In this case, we propose additions and extensions to meet our demand.(Shown in Figure 3)

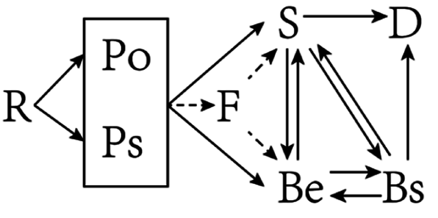

Figure 3. Diagram of the extended FBS framework.

We believe that the Requirement code here is uniform and not convenient for further classification, and the link between Requirement coding to Structure is not perfected. Between them, we added a coded box (Po and Ps codes in figure 3), which we call “processor”. “Processor” is the step where the analysis begins after the subjects have accepted the objective information from the outside world. They process the existing data in two modes of the processors - based on objective knowledge (Processor Objective) or based on subjective experience (Processor Subjective)-to derive different kinds of basic conclusions. Meanwhile in the original FBS coding, this part of the information is also classified as Requirement.

Table 1. Example of extended FBS codes.

FBS Code	Content
Requirement	So, I think we can check on the other side of the river directly.
Requirement	Um … let me see, this way is north, and that's south (looking at the picture).
Requirement	This way is west, and that's east.
Expected Behavior	So if … the café faces east rather than west
Structure	Maybe the west bank will be a better choice.
Requirement	Then … (looking at the picture) what are *Renjiantianshi* and *Fengwuqingtong*?
Requirement	I can see that there is a path along this side of the river.
Requirement	This way is … Zhishan Road.
Objective Processor	It is a main road of Tsinghua campus.
Requirement	Um … this way … I know this square.
Objective Processor	They have the ruin of the Summer Palace here.
Requirement	Here is the Lover Field.
Objective Processor	That's a brilliant work of Prof. Wang Lifang.
Structure Behavior	I think this place … is very suitable for constructing a café.
Subjective Processor	One fact is that it's relatively quiet.
Requirement	And it's also near to the Lover Field.
Requirement	Then there are some libraries next to it.
Requirement	But these trees are arranged in rows.
Structure Behavior	That's a little hard.
Structure Behavior	I think this piece of open land is nice.

In Table 1 we can see an example of segmented and coded site survey experiment. "It is a main road of Tsinghua campus" (line 9, row 2) is the conclusion that the subject personally derived from the objective condition (R code) "This side is the Zhishan road". It is from the basic knowledge "The Zhishan road is a main road in Tsinghua campus", which is not the knowledge that the tester provided to the subject. So this sentence is categorized not as the Requirement code, but as the conclusion derived from the objective knowledge processor (objective processor), coded as Po.

And "One is that it's relatively quiet." (line 15, row 2) is classified to the Ps code (subjective processor). Although its predecessor in the context is "I think this place ... is very suitable for constructing a cafe." (line 14, row 2), coded as Bs, is a seemingly summative judgment of the design behavior coded as S (line 5, row 1)in the previous part of article, we actually think that the R coding and Ps coding the subject added (line 16-19, row 1) are the predecessors of the logical chain of the subject. They play the same explanatory role as the R and Ps codes while in the positive sequence. “Quiet” as the subjective feeling of the subject is classified to be the conclusion derived from “analysis based on subjective experience”, which belongs to the new analysis code we have invented, namely Ps coding. Figure 4 shows the stacked bar graphs of a recorded and segmented site survey process with sliding window sized 14, showing the distribution of different design moves. The left graph adopts the original FBS ontology as coding scheme while the right graph adopts our extended FBS ontology. These graphs visually show how our extended framework differs from and outperform the original one. With the extended ontology, site survey process is better analyzed.

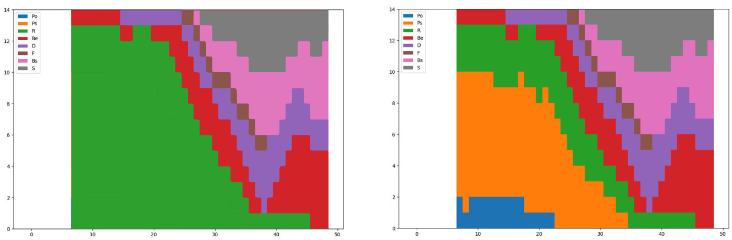

Figure 4. Comparation of previous and current process diagrams.

5. Analysis Results

Multiple analysis was conducted based on the the preprocessed data, including statistical analysis, process visualization, Markov chain analysis (J. Kan, J. Gero 2009), information entropy measurement (J. Kan, J. Gero 2018), Key Move, Ineffective Move, etc.

5.1. FBS ISSUE DISTRIBUTION

The participants’ process visualization of FBS issue distribution is generated with sliding windows. The diagrams (shown in Fig. 5) show that all the 8 codes in the extended FBS on the timeline, indicating that the design moves in site survey process deal most often with Requirement(R), then objective analysis (Po) or subjective analysis (Ps) derived from requirement observation. Additionally, we notice how diverse peaks appear to be generated by the design moves that focus on Requirement(R), and further strengthened by design moves of ’Processer’(P). Compared with Students who have not received architectural education, architectural students have more obvious peaks and troughs in the dynamic issues diagram, which means they tend to concentrate on a single kind of design behavior over a period of time.

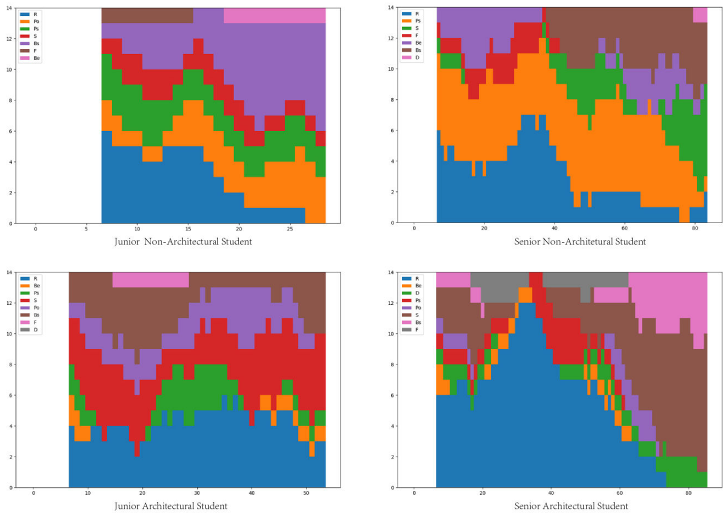

Figure 5. Example diagrams of process visualization.

When looking specifically at the design moves that focus on only external information collection(R) and processing of them (Po & Ps), we can find that some tend to collect external information, then perform specific design behavior(S) and make certain evaluations and analyses (Be & Bs). While others prefer to spread these two codes(R&P) throughout the experimental period. Through the analysis above, it can be concluded that there are two different types of information collection in site survey- centralized and distributed collection. Although non-architectural students also showed similar differentiation tendencies, the difference in the appearance of peaks and the amplitude of a single peak is more pronounced among architectural students.(Shown in Fig.6) From this observation, one can conclude that the designing mode of non-architectural students is more divergent and more average through the whole site survey process.

Another analysis of FBS coding is based on the dynamic process of switching between different codes. The Dynamic Process shows the coherence and efficiency of different design behaviors of volunteers. As shown in Fig. 6, there are almost a few peaks of different sizes in the charts of the architecture students, indicating that they have a concentrated code conversion during the design process. When we further analyze the categories of conversions, we can see that architectural students have more obvious peaks of ‘R-P’ type during the experiment, indicating that they accept external information and process it. In the middle or late stages, a main ‘S-S’ peak appears in their chart, showing that they are working in a centralized and coherent design. In general, this peak can also be found in the corresponding entropy map. In addition to the number and amplitude of peaks, architecture students generally have more conversion types than non-architectural students, which is reflected in the more complex color blocks in their charts. In summary, it can be inferred that the positive impact of architectural education on design thinking efficiency, proficiency and flexibility.

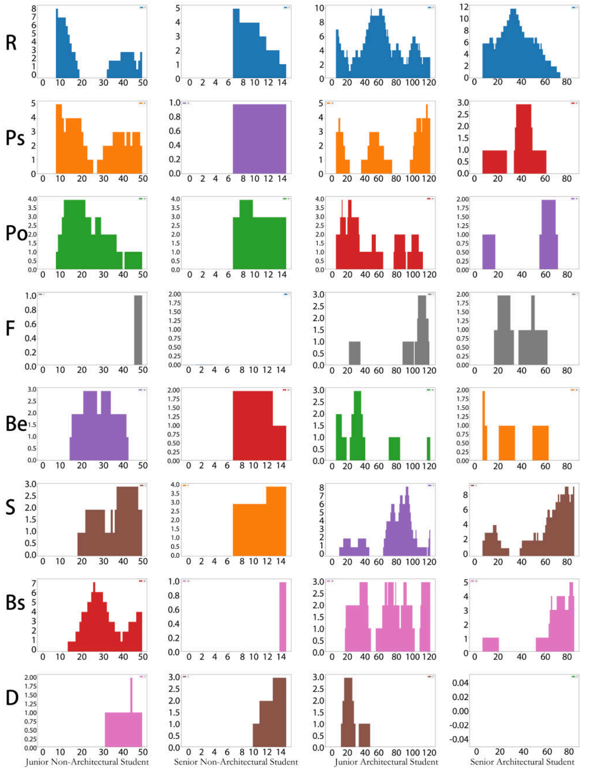

Figure 6. Example diagrams of dynamic issues.

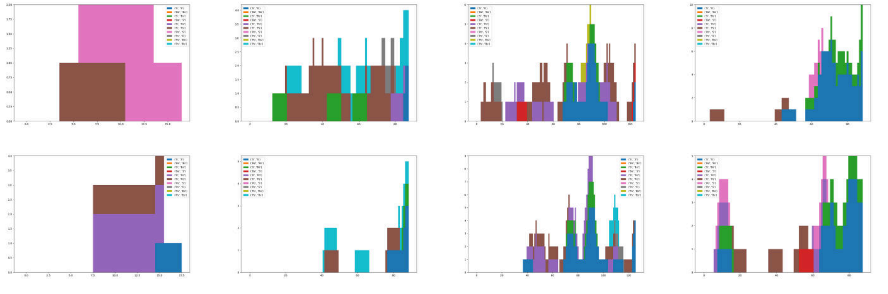

Figure 7. Example diagrams of Dynamic Process.

5.2. ENTROPY ANALYSIS

Information entropy is introduced by Shannon (1948) to measure the amount of information carried by messages. The related theory has dramatically influenced or even shaped today's information technology. In recent years, researchers have transferred entropy into the field of design research. (Krus 2013, Gero 2011)... Specifically, Kan and Gero (J. Kan, J. Gero 2018) used it in analysis of design protocol to show the innovative potential of design processes. Here we also carried out entropy analysis using LINKODER (M. Pourmohamadi, J. Gero 2011), which is a protocol analysis software tool with FBS framework as basis. As shown in Table 1, the entropy value, which is positively related to the productivity of the design, of junior non-architecture students is lower than that of senior non-architecture students, also lower than that of junior architecture students. Moreover, the senior architecture students maintained high entropy values in the entire experiment. (Table 2.)

Table 2. Statistics of Average Entropy over the Linkograph.

Specialist subjects	Educational Level	Average Entropy		
		Forelink	Backlink	Horizontal link
Non-Architecture	Junior	1.632	1.743	1.234
	Senior	2.629	2.777	1.445
Architecture	Junior	2.132	2.333	1.263
	Senior	2.895	3.548	2.156

5.3. KEY MOVES AND INEFFECTIVE MOVES

A more detailed understanding can be found by looking at key moves and ineffective moves over the site survey process, using the linkograph visualization (shown in Fig.7). Key Moves can be distinguished using the number of backlinks and forelinks starting at specific design moves, showing that these more critical design moves actually correspond to design ideas or intentions. Positive correlation between the number of key moves and the level of architecture education is observed. Design moves that don't contribute to key moves and are only linked to neighboring moves are defined as Ineffective Moves. We find out that architecture student volunteers clearly have fewer invalid threads. This fact shows from another aspect that the volunteers who have received architectural education are more efficient in site survey process.

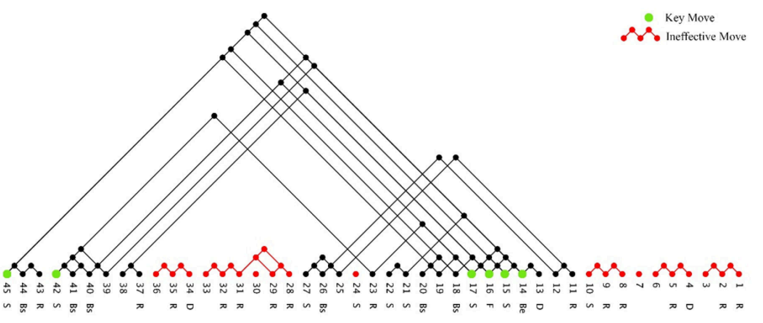

Figure 8. Example diagrams of Key Moves and Ineffective Move.

6. Conclusion

This paper presents analysis of site survey process based on experiment, protocol analysis and an extended FBS ontology. Our contribution is three-fold: Firstly, we novelly adopt quantitative analysis methods to investigate site survey process. Secondly, we extended the original FBS ontology to better fit site survey process. The extended ontology could possibly work on other preliminary design stages as well. Thirdly, we conduct multiple analysis based on experiment data and observe evident difference between two groups of volunteers, showing the effect of architecture education. From the analysis above, we can tell that in site survey process, architectural education provides a more efficient, proficient and flexible mind, followed with a more precise logic to get a designed result, which indicates that architectural education provides an enhanced capability in obtaining useful information from environment as well as in giving accurate descriptions.

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SHAPE GRAMMARS IN COMPUTATIONAL GENERATIVE DESIGN FOR ORIGAMI

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Abstract. This article presents a method to introduce the concept of computer-generated design into origami design through shape grammar. In the previous origami design method, rigorous and complicated mathematical calculations takes a lot of energy from the designers. This research simplifies the design process of crease pattern into the generating and applying shape grammar rules. As a blank space in the current design field, the generative design of origami greatly expands the possibility of origami design and also provides the basis for the further use of computer technology in origami design

Keywords. Shape Grammars; Generative Design; Origami.

1. Introduction

Origami, this ancient Japanese traditional art has been greatly developed in the last two decades(Debnath et al. 2013). With the further exploration of the mathematical principles inherent in origami, people began to use the computer to design origami, creating origami that has never been seen before(Demaine and Tachi 2017). In the fields of engineering, medical and robotics, Origami has become one of the most prospective directions(Felton et al. 2013)(Lang 1996). In the field of architecture, from the mechanical nature of origami to the aesthetic value, many architects have proposed their own understanding and application of origami(Mitani and Suzuki 2004).

A crease pattern is an origami diagram that consists of all the creases in the final model, rendered into one image. It acts as the most important bridge in the transformation from flat paper to a three-dimensional origami structure. Since the design of the crease pattern follows strict mathematical principles, many scientists have used the computer to generate crease patterns(Lang 1996). But such approaches still require users to have a fairly profound mathematical knowledge which is quite difficult for most people.

This research gets inspiration from computational generative design and shape grammar, transforming the action of folding into the rules of shape grammar. In this way, the computer can simulate and generate a large number of foldable crease pattern in a short period of time. In the next sections, we will start with the basic theorems of crease pattern design, then the analysis of classical origami skills, and finally define the shape grammar rules for origami.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 559-568.

2. Basic Concepts in Origami

Computer-aided design technology has great potential in origami design by simulating and further analyzing the characteristics of origami. Crease pattern as a drawing standard that is widely used in origami design and communication. its abstraction and legibility make it indispensable in the process of computational design. However, unlike folding an origami artwork by hand, which emphasizes inspiration and experimentation, the design of the crease pattern needs to follow strict mathematical principles(Lang 2017). For example:

Maekawa-Justin Theorem: For any flat-foldable vertex, let M be the number of mountain folds at the vertex and V be the number of valley folds. Then

$$M - V = \pm 2 \quad (1)$$

Kawasaki-Justin Theorem: Let v be a vertex in an origami crease pattern, and let θ1,θ2,...,θN be the angles between consecutive creases going around the vertex (N must be even). Then the vertex can fold flat if any and only if:

$$\theta 1 - \theta 2 + \theta 3 - \theta 4 + \ldots - \theta N = 0 \quad (2)$$

Justin Isometry Theorem: For any Justin path C (a simple closed path on the crease pattern that doesn't pass through any vertices), let F1,...Fn be the sequence of folds crossed as one traverses the crease Fi. Then the composition of refections show below is the identity operation,

$$\sigma 1 \circ \sigma 2 \circ \ldots \circ \sigma N \quad (3)$$

Justin Non-Twist Theorem: Let C be a Justin path that visits n creases and no crease more than once. Let θi be the angle between successive creases, M be the number of mountain folds encountered along the path, and V be the number of valley folds. Then

$$\theta 1 + \theta 3 + \ldots + \theta(n-1) = \theta 2 + \theta 4 + \ldots + \theta n = \frac{M - V}{2} \cdot 180^\circ (\text{mod} 360^\circ) \quad (4)$$

The discovery of these theorems allows people to use computers to design origami. One of them is the algorithm proposed by Erik Demaine and Tomo Tachi in the software Origamizer, which can transform any model into origami(Demaine and Tachi 2017). Besides, Erik Demaine and Martine Demaine and Jason Ku proposed an algorithm for the Origami maze puzzle font(Demaine et al. 2011). But these algorithms also have limitations: most of these algorithms are based on a fixed pattern, which is more like using origami to express an existing form. Also, the use of these algorithms can only be achieved with a deep understanding of the mathematical basis of origami: which would limit the widespread use of the computational design in the field of origami.

3. The analysis of origami folding skills

Before the advent of computers, people invented many origami skills to create origami arts. The most basic origami skills include mountain fold and valley fold. Then simple compound folds which include inside reverse fold, outside reverse fold, and rabbit-ear fold. After that, there are more complicated skills such as twist fold and closed unsink. These origami skills are characterized in that all complex skills can be achieved by the combination of simple skills. For example, the combination of two reverse folds can form a waterbomb base. The combination of the waterbomb base and four reverse folds can form an open sink fold. All the above skills are composed of the most basic mountain and valley folds. In this chapter, we will analyze the basic origami skills in detail, they will form the basis of subsequent shape grammar for origami.

3.1. BASIC FOLDS

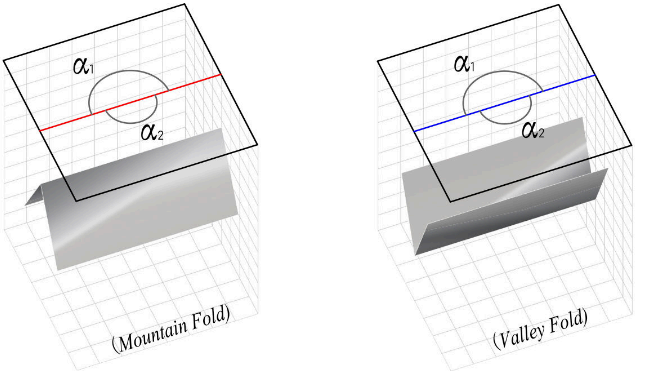

Figure 1. Basic Folds.

Mountain fold and valley fold is the most important and basic skills in origami. People have also invented many different ways to represent mountain and valley folds in the crease pattern. For example, a solid line indicates a mountain fold, and a dotted line indicates a valley fold. This paper uses the red line to represent the mountain fold, and the blue line to represent the valley fold. From the observations of mountain fold and valley fold, we can see that they are the same in a sense: if we flip a mountain fold, we will get a valley fold. Besides, we can think of any point in the mountain/valley fold crease line as a vertex. This vertex is formed by the intersection of two mountain folds or valley fold lines, and the angle between the two lines always satisfies such conditions:

$$\alpha 1 = \alpha 2 = 180° \qquad (5)$$

At this time, the vertices also satisfy the condition in Maekawa-Justin Theorem: in the mountain fold line, M = 2 and V = 0, and in the valley fold line, M = 0 and V = 2. The equation M−V=±2 is still valid.

3.2. SIMPLE COMPOUND FOLDS

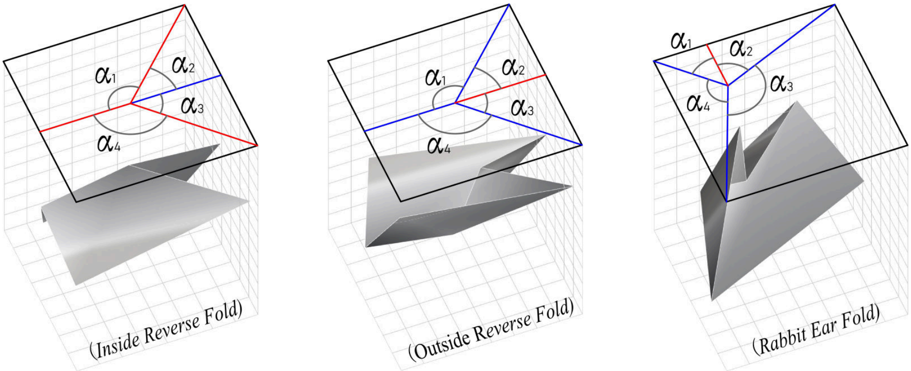

Figure 2. Simple compound folds.

People have different standards for the definition of simple compound folds, *folds.net* defines simple folds as inside/outside reverse fold and prayer fold (know as waterbomb base)(Paulsen 2014). However, *en.wikibooks.org* defines the simple compound folds just as inside and outside reverse fold(Origami/Techniques/Practice 2018). In this paper, in order to reflect their nature more clearly, we classify origami skills that cannot be composed of origami skills other than mountain/valley fold as simple compound folds. So, the prayer fold although the folding process is pretty simple, it is not classified as simple folds (because it can be composed of two reverse folds) and rabbit-ear fold is classified as simple fold.

In this article we focus on these three simple folds: inside/outside reverse fold and rabbit-ear fold. Just like the relationship between mountain and valley fold, Inside reverse fold and outside reverse fold are essentially the same origami skill. There are four crease lines connect to the vertex in inside/outside reverse fold, and the angle between each crease line meet such conditions:

$$\alpha 1 = \alpha 4, \alpha 2 = \alpha 3 \tag{6}$$

$$\alpha 1 + \alpha 2 = \alpha 3 + \alpha 4 = 180° \tag{7}$$

$$\alpha 2 \in (0, 90°] \tag{8}$$

For the rabbit-ear fold, it also has four crease lines connect to the vertex. However, these crease lines form a different relationship. In a rabbit-ear fold:

$$\alpha 1 + \alpha 2 = \alpha 4 \tag{9}$$

$$\alpha 2 = \frac{\alpha 3}{2} \tag{10}$$

$$\alpha 3 \in (0, 180°) \tag{11}$$

3.3. THE COMBINATION OF SIMPLE FOLDS

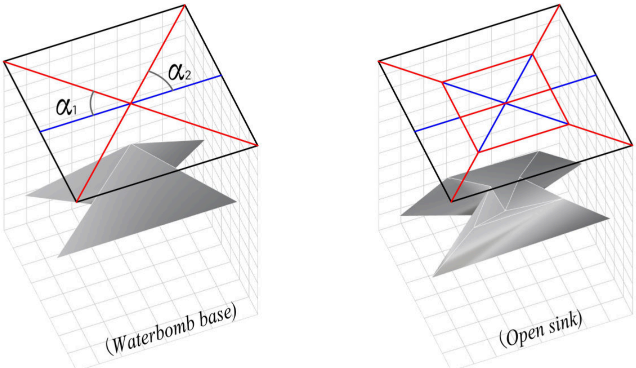

Figure 3. Combination folds.

The characteristics of origami allow us to achieve complex origami by combining simple origami skills. For example, the waterbomb base can be composed of two inside reverse folds. And the variables in these two reverse folds, α1 and α2 can take different values, as long as they meet the following conditions:

$$\alpha 1 + \alpha 2 < 90° \quad (12)$$

$$\alpha 1 \in (0, 90°) \quad (13)$$

$$\alpha 2 \in (0, 90° \square \quad (14)$$

At the same time, we can continue to develop based on the waterbomb base. For example, applying inside reverse fold on each mountain crease line of the waterbomb base, we can get the open sink fold: a typical High-intermediate origami skill. This paper will discuss such operations in detail in subsequent chapters. The flexibility of origami skills is the foundation of applying shape grammar in origami.

3.4. THE COMPLEXITY OF ORIGAMI CREASE PATTERN

In origami, the degree of each vertex is defined by the number of crease lines connected to it. For example, rabbit ear fold has a vertex of degree 4. The number of vertices and their degrees also the number of crease lines in the origami crease pattern are a reflection of the complexity of origami. In this article, we use a matrix to describe the complexity of an origami crease pattern:

$$[V, C, M] \quad (15)$$

In this matrix, V represents the number of vertices, C represents the number of crease lines and M represents the maximum degrees in this pattern. For example, the complexity of the crease pattern for rabbit-ear fold is [1,4,4], and the complexity of open sink is [7,12,6]. The folding operation is essentially increasing the complexity of crease pattern.

4. Shape Grammar for Origami

The advantage of shape grammar is that it could directly manipulate the shape without the consideration of the mathematical principles behind it. This means we can hide complex mathematical principles in shape grammar rules and users could use shape grammar based design tools even if they don't know the origami principles. This will greatly reduce the threshold of origami design, allowing more designers to play with origami.

In this research, we are trying to find a balance between the manual origami design and the computer origami design. The folding action in the manual origami is transformed into the shape grammar operation on the crease pattern. Firstly, extracting the key folding action through the analysis of the origami. Then, different shape grammar rules are designed to express the change of the crease pattern on each vertice. Finally, according to the theorems of origami, further improve the syntax and set the termination situations of the origami shape grammar.

4.1. TRANSFORMATION FROM FOLDING ACTING TO SHAPE GRAMMAR RULES

From the above analysis, we can see that compared to the shape enclosed by crease lines, the vertex is the key element of origami crease pattern. The essence of the crease pattern is a combination of different vertices and the crease lines that connect each vertex. Therefore, the setting of shape grammar for origami is different from the usual shape grammar based on shapes(Stiny 1980). Shape grammar for origami is based on different states of the vertex. The role of each shape grammar rule is to increase the degree of the vertex based on satisfying the origami principle, thereby obtaining more complex origami design by continuously applying shape grammar on the crease pattern. What's more, the start, transformation and termination rules for origami also have their unique characteristics due to the special nature of origami.

4.2. THE START RULES IN ORIGAMI SHAPE GRAMMAR

In origami designs, people often design from origami bases such as bird base and waterbomb base, fish base and so on. The initial state of origami could be a piece of unfold paper or an origami base. We can also complicate an existing origami by continuing to apply shape grammar rules on it. What they have in common is that when we started using shape grammar, the crease pattern was foldable (think of unfold paper as foldable). In this article, we define the initial rules for shape grammar as:

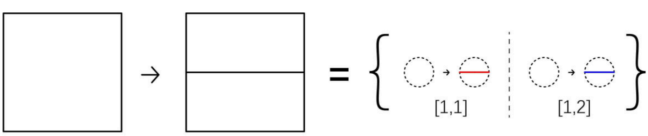

Figure 4. Rule Series 1.

Rules that change the degree of the vertex from 0 to 2: This series of rules is based on the analysis of basic mountain/valley fold. The *Left-Hand Side*(LHS) is an unfold paper so the degree of the vertex is 0. The *Right-Hand Side*(RHS) is a mountain fold or valley fold. The essence of these rules is to generate a mountain/valley fold on the paper. So the crease line can be at any angle, just make sure that it does not intersect the existing crease line. Considering the two different cases of mountain/valley fold and labeling different crease lines with red or blue, we get two rules: [1,1] and [1,2].

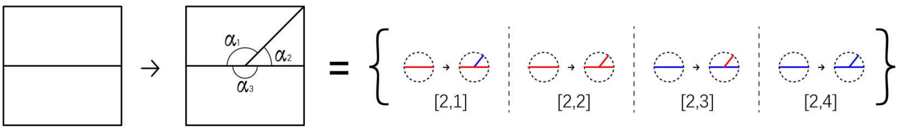

Figure 5. Rule Series 2.

Rules that change the degree of the vertex from 2 to 3: When the generated crease line intersects the existing crease line, we are equivalent to generating a new vertex that has a degree of 3 at the intersection of these two lines. In order to deal with this situation, we define this series of rules. For the angles between crease lines, they meet this requirement:

$$\alpha 1 + \alpha 2 = \alpha 3 = 180° \tag{16}$$

$$\alpha 1 \in (0, 180°) \tag{17}$$

Then, considering the different combination of mountain and valley lines, we get these rules from [2,1] to [2,4]

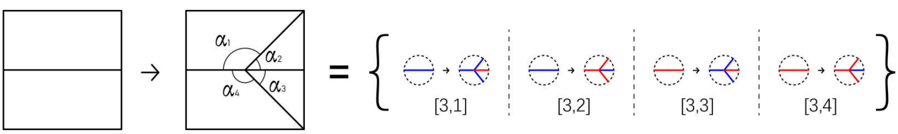

Figure 6. Rule Series 3.

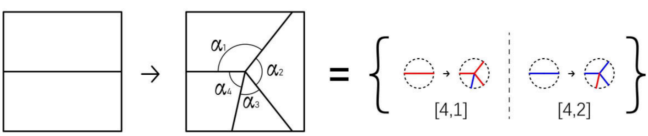

Figure 7. Rule Series 4.

Rules that change the degree of the vertex from 2 to 4: Based on the analysis of inside/outside reverse fold, we defined this series of shape grammar rules in *Figure 6*. It would generate a reverse fold based on an existing mountain or valley line. We treat $\alpha2$ as the parameter in these rules and $\alpha2$□(0,90°]. These angles in the rule are valid for the formula(6) and (7). The same for the analysis of rabbit-ear fold, we defined the series of rules in *Figure 7*. The difference is that it generates a rabbit-ear fold rather than reverse fold. The parameter for this rule $\alpha 2$□$(0,180°)$ and the angles are valid for the formula(9) and (10). Considering the combination of mountain/valley lines, we get the rules from [3,1] to [3,4] and also [4,1] [4,2].

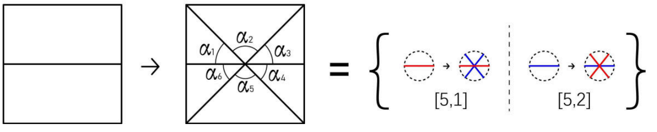

Figure 8. Rule Series 5.

Rules that change the degree of the vertex from 2 to 6: Deriving from waterbomb base, rule series 5 has two parameter $\alpha 1$ and $\alpha 3$. They both range from 0 to 90° and the sum of them is less than 90°. We get the rules [5,1] and [5,2] by considering the properties of the crease line.

4.3. THE INTERMEDIATE RULES IN ORIGAMI SHAPE GRAMMAR

In the process of using shape grammar, not all *Right-Hand Side* is a foldable crease pattern. For example, it forms a new vertex, but this vertex is not foldable. In this case, there is a special type of rules that transforms an unfoldable vertex into a foldable vertex by extending the previous folding action. This also includes an increase in vertex's degree. In this article, we define such shape grammar rules as transformation rules or intermediate rules. These rules are mainly as follows:

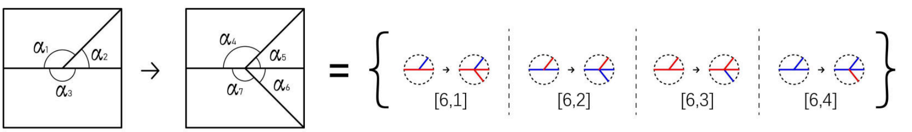

Figure 9. Rule Series 6.

Rules that change the degree of the vertex from 3 to 4: These rules would change an unfoldable degree-3 vertex into a foldable degree-4 vertex. The *Right-Hand Side* is actually a reverse fold, so the angles in this rule are valid for formula(6),(7) and (8).

4.4. TERMINATION SITUATIONS IN ORIGAMI SHAPE GRAMMAR

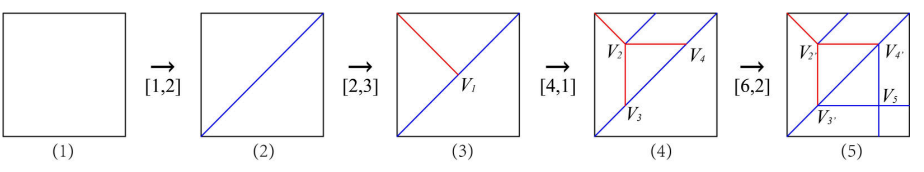

Figure 10. Example of termination situation.

The final crease pattern needs to satisfy all the mathematical theorems to form a foldable crease pattern and an unfoldable crease pattern is meaningless in origami design. This is reflected in the setting of our termination rule: when a vertex that is not foldable (which means it does not meet the requirements of theorems in chapter 2) and is not included in the *Left-Hand Side* of all shape grammar rules, this situation is defined as the origami shape grammar termination situation. At this time we will undo the shape grammar operation in this step and try different rules in that crease pattern. In the example above, we finally get vertex V5 after a series of shape grammar operations. However, V5 is composed of four valley lines which don't meet the requirements for Maekawa-Justin Theorem. What's more, the degree of V5 changes from 0 to 4, which does not exist in our shape grammar rules. So we can only undo one step and return to the state in step 4.

4.5. GENERATION OF ORIGAMI DESIGN

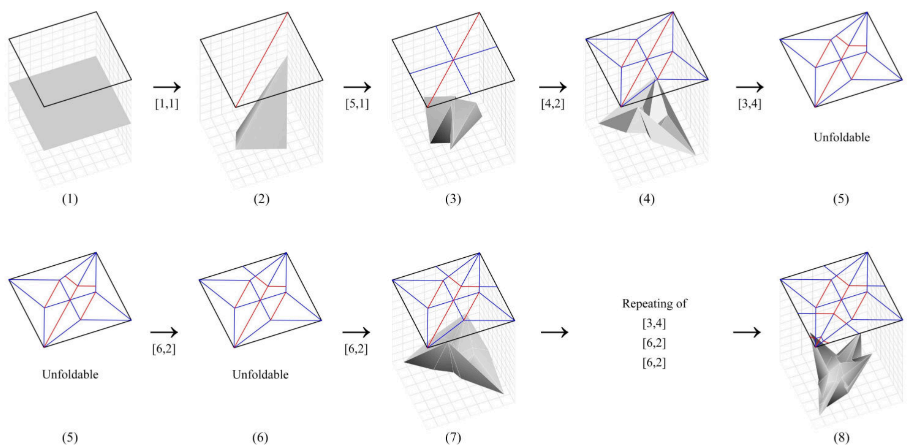

Figure 11. Generation of Crane Origami.

In this example, we started from a unfold paper in (1). After applying rule[1,1], we get the mountain fold origami in (2). Then, we apply rule[5,1] on the mid-point of the mountain line and we get the waterbomb base in (3). Applying rule [4,2] on every valley lines in (3) would generate the crease pattern in (4). From (4) to (7), we generate the tail part of the origami crane. We get (5) by applying rule [3,4] on the mountain line. Then, rule [6,2] is applied to the new vertices generated in (5) and we get the crease pattern in (7). Since the folding of the crane 's head is similar to the tail, we just repeat the operations on the other side of the mountain line. After that, we have completed a classic crane origami design with shape grammar.

5. Contributions

By providing architects with easy-to-use design tools and methods, this research will greatly promote the application of origami in the field of architecture. On the one hand, we can create a large number of new origami forms with the help of computers, which could greatly expand the boundary of origami science. Secondly, by providing designers with an easy-to-use origami design tool, this will attract many designers to participate in origami design. In the following example, we use the shape grammar to design a series of origami units in a generative design way. These units can be further applied to the adaptive facade in architecture. What's more, this study provides the basis for further systematic analysis and understanding of origami patterns. This could create a new branch of computer-aided origami design.

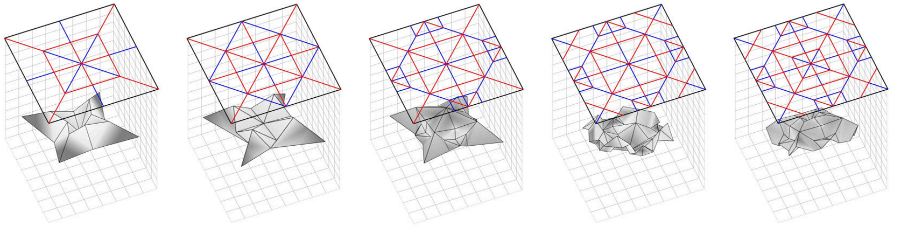

Figure 12. Origami unit designed by shape grammar.

Acknowledgement

Authors wish to thank Dr. Winifred E Newman for her enlightening insights.

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CAADRIA AT AGE 25: MAPPING OUR PAST, PRESENT, AND FUTURE

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Abstract. This paper takes the 25th anniversary conference of CAADRIA as an opportunity to reflect on the association as well as the changing landscape of CAAD research in Asia. Following a discussion of CAADRIA and its organisational structures and procedures, the paper analyses and reflects on past and current developments of our research community. To this end, CAADRIA publication keywords are examined to visually map the development of the association since such keywords started to be recorded consistently 12 years ago. The paper calls for a revived critical discourse on fundamental questions of our field in general, and some disconnects between CAADRIA's mission and its current direction in particular. It concludes with a discussion of potential directions for CAADRIA for the coming 25 years.

Keywords. CAADRIA association; CAAD history; CAAD discourse; diagrams; CAAD development.

1. Introduction

The first CAADRIA conference was held in Hong Kong 25 years ago, spurred by rapidly developing interest in digital design approaches across Asia. As CAADRIA1996 proceedings editor and first CAADRIA president Thomas Kvan emphasises in the brief editorial recorded on the CuminCAD database, digital tools were beginning to be more commonly employed throughout practice and academia: "Computers have established themselves as indispensable tools in the practice of architecture; there are few practices today which do not have access to computers for some aspects of their work. Similarly, we have seen purchases of systems by almost every school of architecture in the region in the past few years. The pervasive application of the tools in practice and the ease of access to some form of computing in architectural schools poses a challenge to which architectural education has responded." (Kvan 1996)

The first conference in Hong Kong drew a mere 32 papers, whereas already one year later, the numbers rose to 48 papers. By 2019, more than 160 papers were accepted - a number which can be expected to grow even further in the coming years with steadily rising numbers of submitted abstracts. Over the course of 25 years, one generation of CAAD researchers, CAADRIA has not only grown in numbers. It has also developed significantly as an organisation, increasing its number of officers alongside expanding its organisational structure. Despite its

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 569-578.

recently increased size, however, CAADRIA has remained a relatively close-knit community, in which administrative processes often remain informal and are taken care of based on the experience and advice of long-standing members of the association. At the same time, the history of the association has not been documented in detail: the community seems to still perceive CAADRIA as a "young" association, such that keeping track of developments is perceived as unnecessary.

Gradually, however, the first generation of CAADRIA's founders are retiring, with only few staying on as active members. CAADRIA has institutionalised the CAADRIA Fellows to make sure continuity is maintained across changing generation of CAAD researchers through advice from senior members of the association. Meanwhile, CAADRIA remains committed to its initial objectives (CAADRIA 2019):

- 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.

Focusing strongly on CAAD related community development across Asia, the CAADRIA objectives centre on educational initiatives and collaboration. At the same time, they emphasise a focus on creativity rather than production. Arguably, recent developments seen in the field are increasingly diverging from these aims: production-oriented digital design support and technical foci have received increasing attention, whereas fewer papers presented in recent CAADRIA conferences address and support the original objectives outlined above. This development calls for renewed reflection: Are the original objectives obsolete or is the change caused by ongoing developments in the Asian academic landscape? While there may not be a simple answer to these questions, the following sections examine and discuss how CAADRIA and its themes have changed over the past decades.

2. The changing academic landscape: Between creativity and production

The objectives CAADRIA set out with 25 years ago reflect a pioneering time, when digital support for architectural design research was still not common throughout the region and members felt that related research needed strengthening and support. In response, the CAADRIA executive committee has established the practice to determine the conference host by alternating well-developed with less developed contexts, the former drawing broader audiences and increasing numbers of participants while the latter serves to support emerging institutions with a budding digital design research community. Asia and its regional economies have changed significantly in the 25 years since CAADRIA was founded, and with it the academic funding landscape. Research presented at CAADRIA tends to be funded by governments rather than private corporations, and thus depends on changing national funding strategies and preferences. While the initial CAADRIA conferences featured a significant number of research papers submitted by authors based in Hong Kong, Taiwan, Singapore and Japan, recent conferences have seen a strong increase of papers submitted by South Korea and especially mainland China-based authors - in 2019, about one third of submitted abstracts came from mainland China. This significant number also reflects the increasing research and development spending of China, which was almost three times that of Japan in 2018, and six times that of South Korea (Radu 2018). Research funding in Asia is predicted to increasingly focus on themes on artificial intelligence, automation, robotics and adjacent software, which will dominate the R&D landscape for the next few years (ibid.).

CAADRIA research papers are typically structured around quantitative studies emphasising scientific methods. A large percentage of papers results in prototype implementations, some of which are developed for wider use. Design-driven studies are more rare, and only few papers pursue qualitative or discursive research approaches. Themes such as CAAD theory, CAAD philosophy or gender studies in digital design are rare. Conducted mostly in academic settings, research presented at CAADRIA remains focused on research as an academic endeavor and relates only loosely to design practice. CAAD research presented at CAADRIA can arguably be described as a parallel to applied architectural design practice rather than either leading or following it. With the increasing dependency on national funding bodies along with the increasing professionalisation of our discipline, it is likely that CAADRIA will continue to move towards pragmatic and utilitarian aims. Meanwhile, the more qualitative approach to CAAD research called for in the last CAADRIA objective listed above: “to promote research and teaching in CAAD that enhances creativity rather than production” seems to receive less attention.

A large percentage of papers presented at CAADRIA - up to about 50% - is authored by PhD students or, less frequently, Master students. CAADRIA has recognised the relevance of this group of researchers early through the establishment of the PGSC (Postgraduate Student Consortium), held annually since its initiation by then-secretary Marc Aurel Schnabel and formal convening by the late Bharat Dave, in 2007. The PGSC is a key event for CAADRIA’s long-term development, as this is a rare opportunity when senior members of the community are invited to discuss developing research projects in detail. Students present their work in progress, allowing for significantly more depth of related discussions than possible within the three minutes typically allocated to questions and answers following regular conference presentations. It is not only the students who benefit from these exchanges: As values and research reasoning are made explicit among a core group of community members, they are subjected to questioning, which indirectly leads to more consistent alignment among the CAADRIA research community.

3. CAADRIA as process

CAADRIA may best be understood as a process, consisting of a changing community transferring values and experiences from year to year and creating both continuity as well as a perpetual negotiation of values and practices. While CAADRIA does have a charter, it is very concise, such that he association mostly relies on traditions of practice that are rarely documented in writing while they are handed down from one executive committee to the next. Decision making within CAADRIA is committed to the core objectives of the association outlined above as well as to academic quality. For successive executive committees, these two not always aligned aims are sometimes challenging to navigate. On the one hand, lesser developed contexts should be supported, while on the other hand, high academic standards have to be upheld. This challenge is navigated conjointly by the CAADRIA executive committees and the paper selection committees that are appointed to oversee the paper selection process. Appointed paper selection committees are entrusted to define the interpretation of academic standards in that particular year and always include at least one experienced member of CAADRIA as well as one CAADRIA member representing the host. CAADRIA separates the paper selection process from the hosting of the conference, to avoid overloading the host on the one hand, and to avoid compromising situations for the host on the other hand. Different strategies have been used in the past to support submissions from lesser developed contexts: Extra support can be provided to such submissions to assist authors in understanding and reaching standards expected by CAADRIA, authors may be encouraged to submit a poster instead of a paper, and at some conferences the host may propose to publish "short paper proceedings". The third option has not always been successful as short paper proceedings have been delegated to the host, who has not always managed to closely coordinate the paper selection and reviewing process with the respective year's paper selection committee. As a result, the short paper proceedings are published together with the printed proceedings, but not included in the CumInCAD database.

While previous studies have examined the recent history of the CAAD research field, no paper has so far addressed the particular development history of CAADRIA. Among the most well-known papers discussing CAAD history is the well-known "CAAD's seven deadly sins" by Tom Maver (1995). This paper is a short and pointed critique of lessons that could be learned from history, but were forgotten time and again - and it still applies in 2020. Maver (ibid, p. 21) also singles out challenges new in 1995 that are still relevant for the development of CAADRIA as well as its sister organisations today. These include xenophilia, an obsession with importing concepts and procedures from other disciplines at the cost of diverting "intellectual effort from the central task of identifying and understanding what lies at the heart of architectural design itself" (ibid.). A core point of Maver's (ibid., p. 22) criticism is a deep-seated "failure to criticise": CAAD research, he argues, has become trapped in a cosy community that encourages self-indulgent speculation and solipsism while failing to sustain a strong critical discourse as part of the discipline. More recently, these themes have been taken up by Martens, Koutamanis and Brown (2007), who use a reflection of past developments to speculate, in a general way, on the future development of the discipline. Offering several possible scenarios they finally emphasise: “CAAD research should not descend into a situation that simply takes current tools and technologies and sees what can be done with them. If debate about aspects relating to the philosophical, the cultural, the educational, or suchlike, is lost, then the field becomes devalued.” (Martens, Koutamanis and Brown 2007, p. 530).

Other studies of recent CAAD history have focused less on a critical assessment of the field and more on describing the relationships of authors and keywords, creating an analytical framework for thematic clustering and ontological learning that remains focused on observing and describing relational networks among current themes as well as authors (Bhatt and Martens 2009). Ziga and Martens (2001) have examined the topics of CAAD research contained in the database CumInCAD with a focus on how to suggest similarly-themed papers to researchers looking for works published on a specific topic. They conclude (Ziga and Martens 2001, p. 559) that machine-based learning directly from the text content was less successful than human-generated lists of topics: “the way we understand the topics of CAAD, and into which this or that paper belongs to, is subjective and based on one’s the current interests and perspectives. What defines a scientific community is, that its members, to a large extent, also share a similar deep understanding of the topic.” (ibid.)

4. CAADRIA themes: 25 years of change

Looking back at the past 25 years, CAADRIA has seen significant changes in the topics addressed at its annual conferences. Papers presented at the first CAADRIA conference in 1996 addressed themes such as shape grammars, education, visualisation, visual art, media, cognition, design systems and collaborative design. At that time, CAADRIA seems to have revolved more around personal interests of CAAD researchers than large-scale funding aspirations. As funding for CAAD-related research is increasingly available in areas that promise utility and application, such as AI and robotic fabrication, this has also had a strong impact on how our community relates to CAAD research. In recent conferences, BIM, digital fabrication, machine learning and parametric design have formed the core themes of CAADRIA conferences. This paper examines the recent past with a view to making educated guesses about the impending future, based on the keywords of CAADRIA papers recorded on the CumInCAD database from 2008 to 2019. The aim is to visualise the development of research themes our community focuses on, identifying core themes as well as development trends and possible future directions. The paper takes inspiration from the well-known diagrams depicting the evolution of architecture in the twentieth century produced by Charles Jencks (2000; 2015). Despite their loose grounding in data, the broad scope and simplicity of these diagrams have continued to spark the imagination of architects and researchers alike (Figure 1).

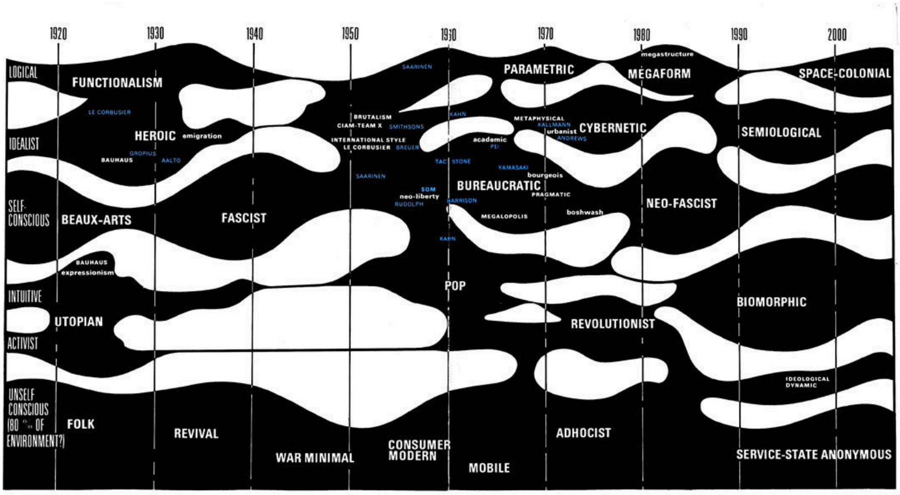

Figure 1. The evolution of architecture in the 20th century by Charles Jencks.

Jencks (2000, p. 76) argues that the architectural themes, seen in their entirety and in their historical development context, show how trends gain in strength and wane again after a decade or so. He argues that the visualisation as a diagram is necessarily a personal one but can be argued, much like Turk and Martens (2001) describe similarity in understanding of key terms among researchers working in the same field and research community. "The main narrative does not belong to any building type, movement, individual or sector. Rather, it belongs to a competitive drama, a dynamic and turbulent flow of ideas, social movements, technical forces and individuals" (Jencks 2000, p. 76). With the visual mapping of CAADRIA research paper keywords, this paper aims to draw attention to general development trends within our research community, and to a gradual drift in focus over the past decades.

5. Mapping CAADRIA keywords between 2008 and 2019

This study examines keywords of CAADRIA papers as indicators of recent developments in CAAD research in Asia. Keywords listed for each paper were retrieved from the CumInCAD database, where all papers published in CAADRIA proceedings are archived digitally. Keywords, as stated by authors, are assumed to reflect core topics of the research presented in the paper. As the formatting of CAADRIA papers has only gradually been standardised, keywords have been collected and archived consistently starting only with CAADRIA2008. For this reason, this study is limited to 12 years, the time frame between 2008 and 2019. Following the retrieval of keywords for all CAADRIA papers between 2008 and 2019, groups of keywords were created to simplify and to emphasise larger thematic clusters for later visualisation. Keywords were sorted according to their number of occurrence in each conference, with a focus on the top 40 keywords. This step requires changes in grammar alongside manual selection and editing in creating thematic groupings, as Turk and Martens (2001) have described. This seems both necessary and acceptable as similar to the diagrams presented previously by Jencks (2015) to describe architectural history, this study aims to provide a general thematic overview of developments rather than a detailed listing of keyword topics. The resulting diagram is presented in Figure 2.

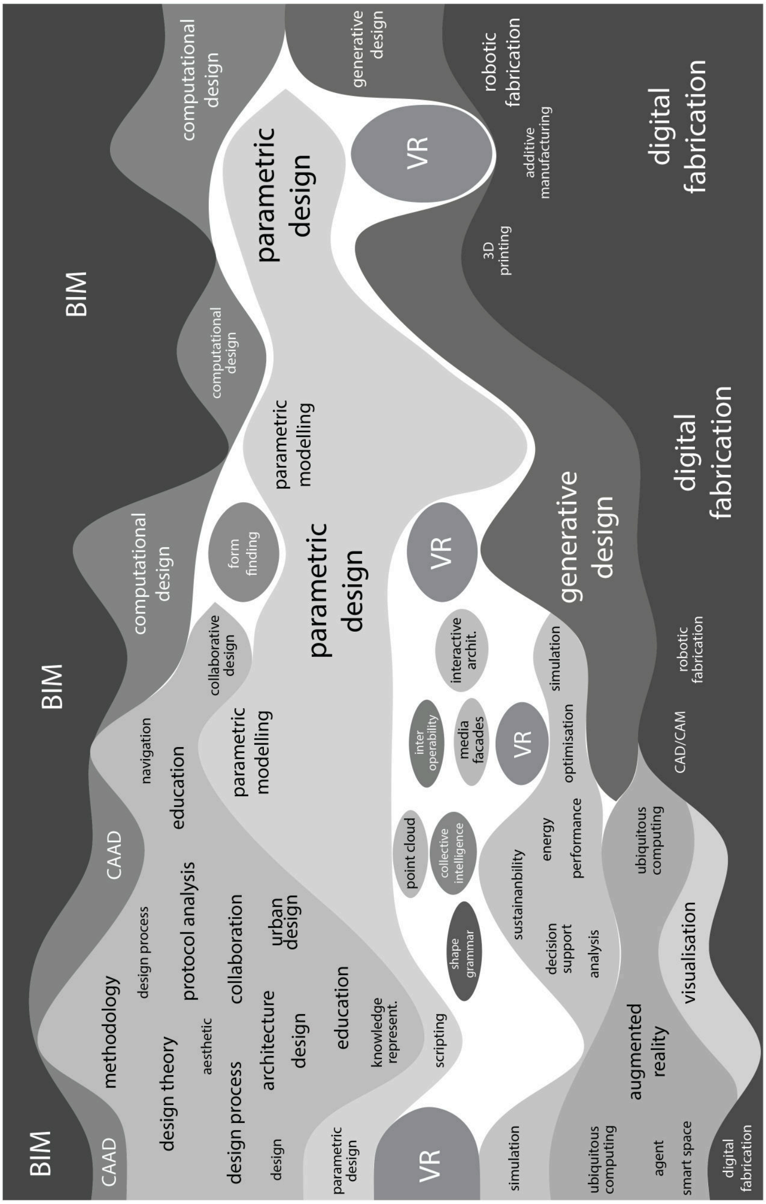

Figure 2. Mapping of CAADRIA research paper keywords between 2008 and 2019.

The visual mapping of research keywords shown in Figure 2 allows various observations concerning our field of research. Different from the diagrams offered by Jencks, the mapping provided here visualises a primarily quantitative analysis of the most prevalent keywords featured in CAADRIA rather than a personal interpretation. Based on the diagram, a gradual change in research focus across our community can be observed between 2008 and 2019. Most notably, CAADRIA 2008 featured more variety in keywords compared to CAADRIA2019. The diagram shows 13 keyword clusters constituting the top 40 keywords for the year 2008, including: BIM, parametric design, fabrication, virtual reality, design theory, design process, CAAD, ubiquitous computing, simulation, design, collaborative virtual environments, agents and smart space. In contrast, the top 40 keywords for 2019 are formed by only 5 keywords, including: BIM, digital fabrication, robotic fabrication, generative design, and computational design. One reason for this apparent homogenisation lies in the recent growth of CAADRIA conferences: the top 40 keywords have become aligned in part due to sheer numbers of participants, making groupings around specific themes more likely. A more immediate reason seems to be that the research interests of CAADRIA authors are increasingly pegged to availability of research funding which is now accessible to CAAD researchers in Asia, specifically in China, for topics emphasising AI, machine learning and digital fabrication.

The progressive professionalisation of our discipline has led to the canonisation of often expensive toolsets and significant institutional investments into specialised machinery. At the same time, funding proposals in our field increasingly involve promises of utility and application, which has focused attention of researchers on related technical questions. Figure 2 illustrates this trend with the increasing frequency of keywords relating to BIM and digital fabrication. It also shows how another thematic complex gradually lost its importance over the same time frame, relating to architecture, design process, design theory and education. The last time education featured among the top 40 keywords of a CAADRIA conference was in 2012 - a development which calls for revived discussion of the CAADRIA core objectives outlined above.

The diagram further shows how in some years, CAADRIA conferences feature a strong presence of particular research communities. Themes relating to virtual reality are a typical case, appearing only intermittently across the mapped time frame. Jencks (2000) describes architectural trends typically waning after about 10 years before gradually merging into new trends. Despite the relatively short time frame of this study, some similarities to such trends may be observed in Figure 2: Parametric design, for example, constituted one of the strongest research keyword groupings until it entirely disappeared from the 40 most frequently named keywords in 2019. This is not necessarily an indication of its disappearance - more likely, parametric design has become such a widely accepted feature of the digital design toolkit that it does not need to be singled out as an area of research any more.

6. Discussion: Where are we going?

A central question when observing the drift in topics described above is how these tendencies relate to larger societal challenges and future R&D directions globally? While the CAAD research field tends to be driven by technical innovation as well as a playful and speculative engagement with technology, can we as a community of researchers afford to largely ignore themes as important as climate change? This was already lamented by Maver (1995), who included lack of addressing sustainability into his list of the “seven deadly sins of CAAD”. CAADRIA 2020 is themed “RE: Anthropocene: Design in the Age of Humans” to call attention to the strong impact technologies are having on human lives as well as the environment in general. It remains to be seen how many authors will consider responding to this theme. While CAADRIA has never forced authors to specifically address a conference theme, calling for more attention to contemporary and future challenges facing humanity seems important. This question seems to be even more relevant when considering the current Covid-19 epidemic that will change our world for years to come. Even though innovation is based on playful exploration and speculation, the question arises whether this type of play could be driven by ethical considerations in addition to strategies to obtain funding? Are we, as CAAD researchers in Asia, free to make these decisions as individuals or do we depend on national funding bodies to give direction to our research interests? It seems that the least we can do is to encourage and maintain diversity in our community, alongside a productive critical reflection of our work and computer aided architectural design research in Asia in general.

7. Summary

CAADRIA has developed significantly in the past 25 years. From changes in its organisational structure and procedures to its increasing size, CAADRIA has grown into a respectable research community and looks set for another successful 25 years of development and growth. Within this development also lie challenges to the field as well as to CAADRIA as an organisation: Can formalised procedures necessary to manage an increasingly large association provide the same community spirit and flexibility that has supported the development of CAADRIA in its first 25 years? CAADRIA’s development and practices have departed from the objectives outlined in its charter, which raises the question whether CAADRIA should revise either its course or its objectives after 25 years? The analysis of keywords of papers submitted to CAADRIA for the past decade illustrates a gradual change from a more diversely focused small research community to an increasing concentration to themes favoured by national funding bodies among a bigger community of researchers. If this trend is to continue, CAADRIA can be expected to develop more towards themes such as AI, machine learning and robotics in the near future, at the continued expense of themes relating to education, the architectural design process and design theory. Future CAADRIA executive committees and paper selection committees may want to consider ways to re-establish a balance between a utilitarian technology focus and critical discourse.

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SPATIAL CONTINUITY DIAGRAM

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Abstract. The article presents the author's original Spatial Continuity Diagram SCD method. The method uses digital techniques to study the urban and architectural features of existing urban structures. The results of these studies are intended to facilitate design decisions regarding the harmonious development of existing urban buildings. The article also discusses a special software for conducting SCD study. The practical application of the research was discussed on the example of a design and implementation of one of the single-family housing estates.

Keywords. Mathematical simulations; urban composition; spatial continuity; heritage.

1. Introduction and purpose of the research

Creating a sense of spatial continuity (understood as a continuation of the principles of building development characteristic for a given area) is one of the most important criteria determining a successful process of urban space development. However, it is important to start by defining a spatial order that is worthy of continuation or not by its value. According to Y. Thompson. "Spatial order is the location of things in order of their physical being. Therefore, a spatial order paragraph is a form of writing that describes items as they are in their physical location. "

However, in the study of spatial relations occurring in large urban structures, one of the basic difficulties is the multiplicity of information accompanying the research process. For this reason, we often try to limit its number to the necessary minimum at the very beginning of the study. It happens, however, that by making a more or less accurate selection of data that we intend to analyze, we may distort the result of the study. It is obvious that such a selection is necessary. However, it should be based on merit rather than on fear of the difficulties associated with the large amount of data that we need to analyze. It can be assumed that in many cases, the large amount of information analyzed will more fully illustrate the characteristics of specific structures of the studied urban-architectural spaces.

However, it is necessary to have an efficient research tool, allowing for an easy analysis of even a very large amount of data. Such a tool can be the author's original method called "Spatial Continuity Diagram" SCD. The use of the words "Spatial Continuity" in the name of the method results from the task that this method is supposed to fulfil. The aim is to facilitate the identification and maintenance of appropriate spatial relationships between newly designed and existing buildings. The use of the word "diagram" results from the fact

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 579-588.

that the analyzed data are presented in the form of tables and diagrams, which can be generally called diagrams graphically illustrating individual stages of the research. The Method SCD is intended to facilitate the preservation of cultural and historical continuity in the development of existing urban and architectural spaces. This can be achieved by appropriately developing guidelines for the design of future developments based on the most relevant urban and architectural features of existing and reconstructed or extended buildings. The problem of lack of proper spatial order in urban development is unfortunately quite frequent (see Fig. 1.). However, there is a problem of ambiguity in the assessment of such spatial activities described, for example, by R. Tavernor and G. Gassner, in their 2010 publication ”Visual consequences of the plan: Managing London’s changing skyline”(Tavner and Gassner, 2010). The problem of tall objects influence is also considered by K. Czyńska in her article from 2018 ”Tall buildings in historical urban context - analysis of selected examples (Czyńska, 2018).

Figure 1. Examples of spatial chaos or controversial design solutions in the immediate vicinity of extremely important urban objects. In the photo on the left : Washington DC with the view of United States Capitol from the city highway 695 at New Jersey Ave SE. On the right the photo of London overlooking the Tower of London from the Tower Bridge. Source: author’s photographs.

The clear ambiguity of the assessment of contemporary urban development transformations does not only concern the areas of special concern, but also less prestigious buildings. This ambiguity in the assessment of this process inspired the author to create the (SCD) method along with the software. First, the initial assumptions were made about the characteristics of the research method support software SCD:

1. To create a software that will support the process of transforming or expanding existing urban structures without leading to their spatial and functional deformation in a maximum objective manner.
2. To design a software as easy to use as possible and encouraging designers to use it in their everyday design activities.
3. To use a commonly available software as the base for the author’s original SCD plugin allowing for conducting appropriate analyses.
4. To design fully automatic test procedures that do not involve the future user too much. The only action on the part of the designer should be to collect and enter appropriate data into the software.

2. The Spatial Continuity Diagram method SCD and entry materials (method and materials)

The SCD method can be symbolically compared to satellite imagery. Only from this global perspective can we sometimes see extremely important relationships that are completely invisible from the ground. The SCD method is designed to examine large urban complexes. For this reason, several thousand or more data are analyzed. Thanks to this, it is possible to obtain a more complete picture of the urban and architectural features of the studied buildings. Thanks to a large area of analysis, research results can often lead to surprising conclusions, difficult to define in random research conducted in smaller areas.

2.1 ACQUISITION OF INPUT DATA FOR SCD STUDY

In its first stage, the SCD method is based on gathering as much information as possible about the studied urban development complex. The research concerns both urban and architectural aspects of the analyzed buildings. The collected information has the structure of sets and sub-sets. The sets are “features” and the subset “categories of features”.

It is very important that the SCD method does not have a fixed set of features and their categories. For each study, they are determined individually so as to reflect as fully as possible the nature of the urban development complex in the urban and architectural dimension. In order to illustrate the data acquisition process, two small urban development complexes were subjected to SCD analysis (see Fig. 2.). These examples serve only for a clear illustration of the idea of dividing into “features” of the investigated buildings and corresponding “categories of features”. In fact, much larger areas of urban development are studied using the SCD method.

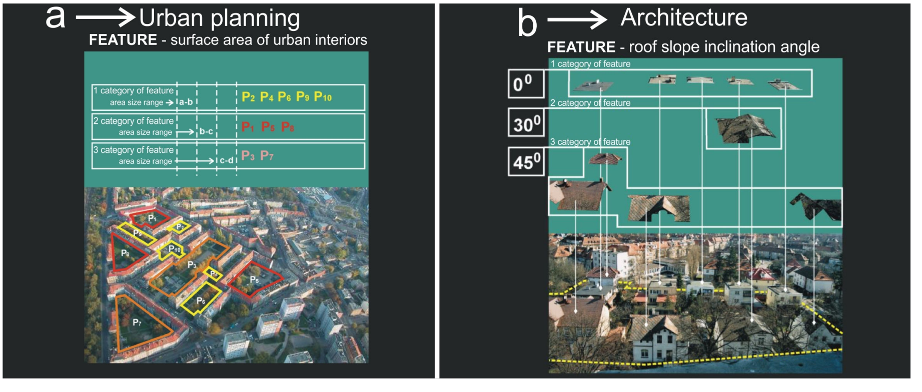

Figure 2. An example of SCD method used to determine particular categories of the tested features, a - urban space study. The examined feature is the “surface of urban interiors”. The categories of features are “areas of individual squares” grouped in appropriate size ranges, b - study of architectural objects included in the studied urban development. The feature is the roof slope inclination angle and the category of features are the individual slopes expressed in degrees. Source: author’s study.

2.2 STUDY OF THE DEGREE OF HOMOGENEITY OF A FEATURE IN THE SCD METHOD

Based on histograms illustrating the percentage of categories of characteristics, the degree of homogeneity of each of these features is calculated. The degrees of homogeneity of the analyzed features in the SCD method are the most important parameters characterizing the studied group in terms of urban planning and architecture. We calculate them using the following mathematical formula(see Fig. 3.).

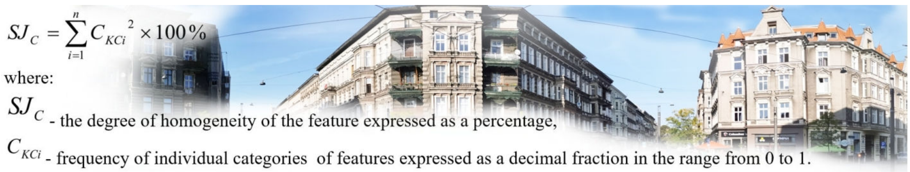

Figure 3. Mathematical formula to calculate the degree the homogeneity of a feature. Source: author's study.

For example, for a histogram of the building "number of floors", where there are only four floor buildings, the degree of homogeneity of the feature is of course 100 % (see Fig.4a.). In the case of developments in which individual buildings have very different number of floors, the tested "number of floors" feature has a much lower value (see Fig. 4b.).

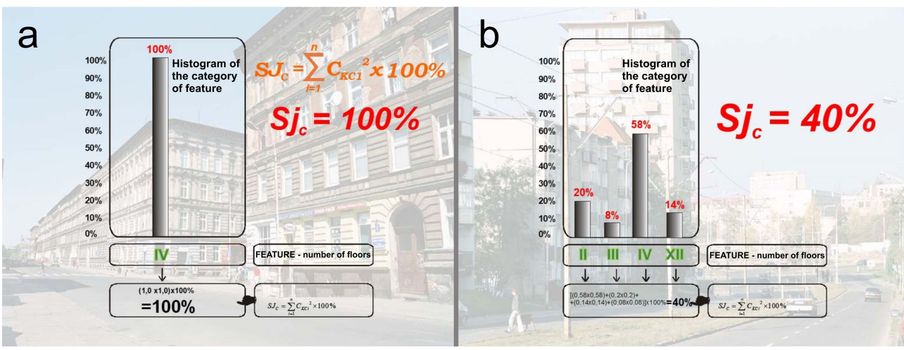

Figure 4. Study of the urban characteristic "number of floors" for two urban complexes differing in the number of buildings with different building heights. Source: author's study.

3. Application of the SCD method with the use of author's original software

Processing thousands of data in everyday design practice without adequate computer support would be very difficult to implement. For the purposes of the research described above, a special original program was developed in Visual Basic language, which works in the form of a plug-in extending the Excel capabilities with the SCD research method. This is an open source software developed for Windows which allows the application of the SCD method in the design practice. The operation of this device is described below.

3.1 DESCRIPTION OF THE OPERATION OF THE SCD SOFTWARE

Launching the program automatically opens the Excel spreadsheet, where in the main menu “Add-ons” you will find a tab called “Analyses”. Using the instructions in the “Analyses” tab, the entire study is carried out, starting with the preparation of the surveys needed to collect data in the field, through all the analyses, and ending with the results.

The first step is to design the study by specifying all the parameters of the planned analyses. For this purpose, an appropriate set of interactive windows is used, in which the number of features, their categories and their names are determined. Once these initial conditions are set, a survey is automatically generated to collect data in the field. All the windows needed for the study appear in the correct order. For demonstration purposes they are shown simultaneously (see Fig. 5.). In addition, each architectural object having the examined feature receives its coordinates for the location of their two-dimensional space. In this way, an “electronic inventory” is generated at a later stage of research. For SCD studies, a 10 m grid of coordinates was used.

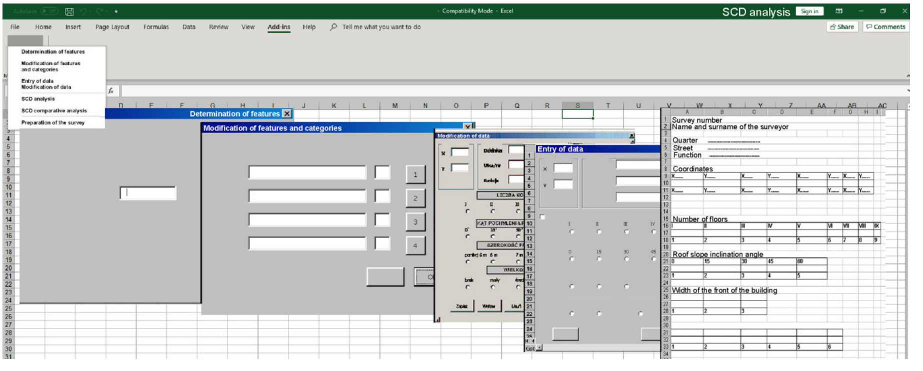

Figure 5. A set of interactive windows allowing to plan the study of urban and architectural features of the analyzed urban development. Source: author’s study.

Computer processing and graphic representation includes two data packages obtained through the analysis of maps and information contained in the inventory surveys. One set of data concerns the character of urban space, the other the architectural features of individual buildings in the studied urban complex.

“Electronic inventory” refers only to the study of architectural features. The “features” and “categories of features” of urban planning shall be compiled only in the form of appropriate histograms. There is no reason to create “electronic inventories” as their location is immediately visible on maps.

3.2 APPLICATION OF THE SCD METHOD IN THE PROCESS OF DESIGNING NEW BUILDINGS

The main objective of the SCD method is to investigate whether the newly designed urban development complex will creatively strive for compositional consistency with existing buildings or it will lead to their disharmonious transformation. Therefore, both the existing development and the design of the future development must be examined. The basic prerequisite for proper testing is that both existing and designed buildings must be subject to identical analyses for the same feature. Although the design of the building does not yet exist, there are no obstacles to obtain the relevant data by reading the adopted design solutions. The course of the study was illustrated in the form of an appropriate scheme (see Fig. 6.).

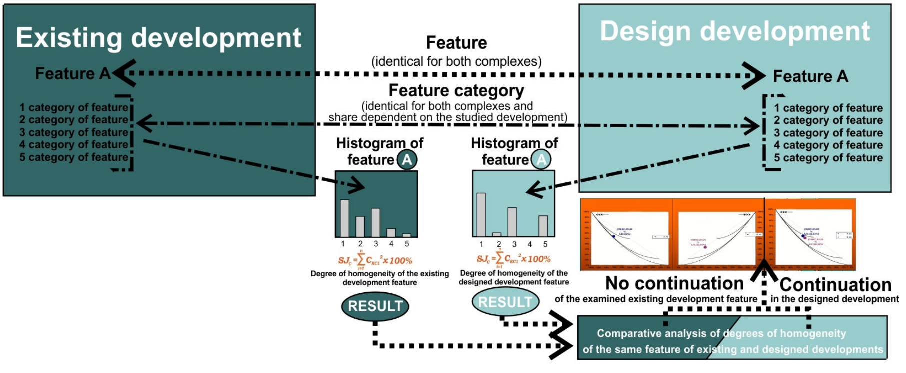

Figure 6. Diagram showing individual stages of SCD examination of one of the existing and designed building features in order to determine whether to continue or not the same feature in the designed building. Source: author's study.

The diagram below shows the way of conducting the study of only one of the features. A complete picture of the urban-architectural relations between the two complexes requires an examination of all the features planned in the study.

After entering the data concerning the existing and planned buildings into the software, we automatically obtain all the necessary results (see Fig. 7.). The analyses presented in the first example (see Fig. 7a.) show that the data distribution and degrees of homogeneity of the existing and designed buildings are so divergent that most probably the planned expansion will be disharmonious in relation to the existing buildings. In such a case, two separate graphs appear in the SCD analysis, placing data distributions on the "feature homogeneity curves" separately for both studied groups. When, as a result of the calculations, one "feature homogeneity curve" common for both surveyed complexes appears, we can conclude that within the examined feature the effect of the planned investment will be the harmonious development of the existing urban space (see Fig. 7b.). "Feature homogeneity curves " are diagrams that illustrate all values of homogeneity that depend on the number of "categories of features".

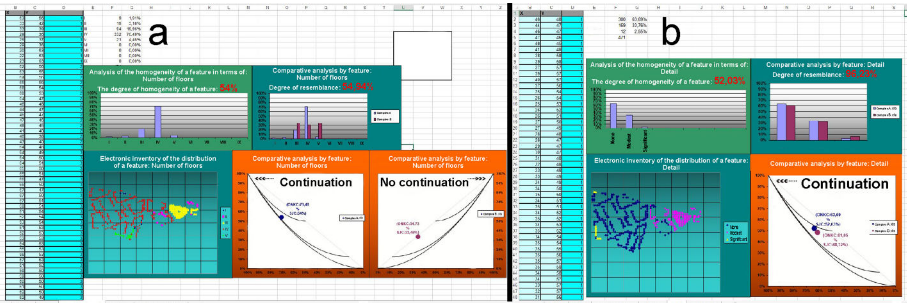

Figure 7. The result of the SCD research concerning one of the features of the existing urban development complexes and the same feature analyzed in the extension project of this complex. a - the analysis of the data of both complexes (existing and planned) indicates a probable disharmony within the examined feature. b - the analysis of the data of both complexes (existing and planned) indicates a probable harmonious design activity. Source: author's study.

4. Gryfino case study

The SCD method can be used both for the expansion of existing urban structures and for the design of housing estates of similar character in other places, following the example of those that already exist and have the desired urban and architectural features.

The subject of the presented case study is the design of a 50 ha single-family housing estate located in the city of Gryfino. The source of data necessary for the SCD analyses and the drawing up of appropriate design guidelines was a single-family housing estate located in Szczecin. This "model" housing estate has a very good reputation as an example of an outstanding urban and architectural concept. It was built at the beginning of the 20th century as a realization of Ebenezer Howard's idea of garden city. The "model" housing estate is located at a distance of 26 km from the designed housing estate.

In this case 20 urban features such as the "distance between intersections", the "value of the street radii along the arc", the "surfaces of the interior squares," the "distances between squares" were analyzed. The data concerning urban features were collected based on maps of existing buildings and urban plans of designed buildings. The architectural analysis concerned, among others, the following building features: "number of floors", "roof slope inclination angle", "architectural detail", etc. The data on architectural features were collected based on questionnaires filled out in the field and design proposals concerning the individual buildings shaping principles.

The comparative analysis determined the distribution of data concerning the category of the examined feature in both complexes and the degrees of their homogeneity. An example of a comparative study of one of the urban features concerning the "distance between street junctions" in "model" and designed development is presented below (see Fig. 8).

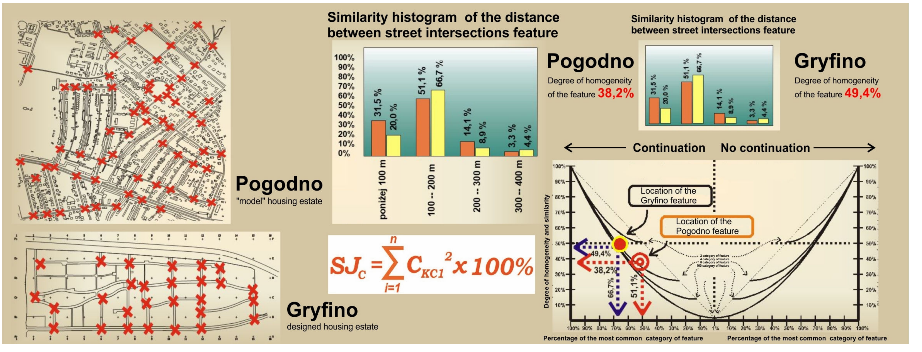

Figure 8. Comparative SCD study of one of the urban features of the "model" housing estate (Pogodno) and designed housing estate (Gryfino). The study covered the feature "distance between street intersections" Source: author's study.

4.1. THE RESULTS OF THE STUDY

In result of the SCD method study of Pogodno estate, an appropriate set of design guidelines was obtained, which was then included in the project of the housing estate in Gryfino. Comparative study of twenty urban and architectural features of the "model" estate (Pogodno) and the designed one (Gryfino) showed a high degree of convergence of "homogeneity of features". This may indicate that despite the different shape of the two complexes, they should have similar urban-architectural features. Based on the analyses carried out with the use of the SCD method, a local spatial development plan was drawn up and approved by the municipality of Gryfino to enable the implementation of the project

At present, the project is being successively implemented by individual investors. Below there is an orthophoto map with the current geodetic division and already completed objects, as well as a bird's eye view photo documenting the status of the housing estate (see Fig. 9.).

At this stage of the investment, it is still difficult to recognize the designed urban layout with individual street interiors, market square (agora) and park. There are still too many undeveloped spaces. However, we trust that when the investment is completed, its inhabitants will feel that they live in a district, which thanks to the design guidelines developed with the SCD method, will have the same spatial and architectural features as its original model existing in Pogodno. Yet, it will not be a copy but an original single-family housing complex with the 'model's' features.

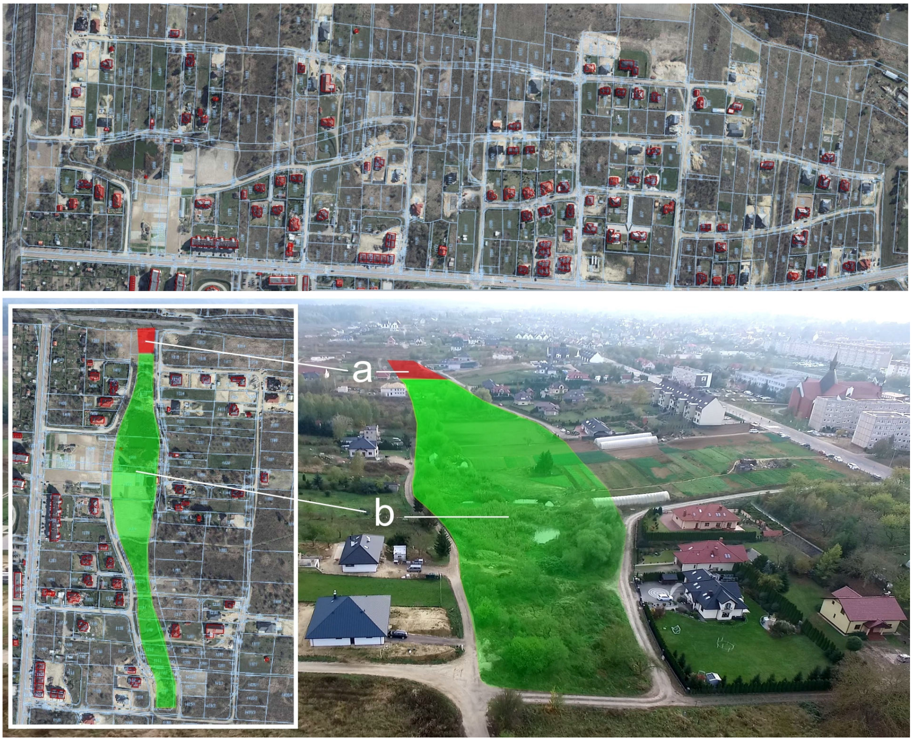

Figure 9. Development status of a housing estate designed with the use of the SCD method. Above the orthophoto map with geodetic divisions and completed single-family houses. Below a bird’s eye view (as of 10.11.2019) with a marking of the designed a - agora and b - park. Source: author’s study.

5. Discussion

The results obtained with the SCD method are used to objectively support design processes aimed at harmonious transformation or expansion of existing urban complexes. This method also makes it possible to design separate housing estates with urban and architectural features based on existing prototypes. The main advantage of the SCD method is that the designer implementing the obtained data into his project can create an original work that is not a copy of the original. The whole research process is particularly focused on the recognition of local values of the studied urban development. For this reason, the finished set of features and their categories are not used in the analyses. They are created each time in close connection with the existing urban and architectural values. Therefore, the SCD method can be used anywhere and in any spatial and cultural context. The SCD method is still being improved and two new research modules are currently being developed. They concern the “concentration factor” and the “range of homogeneity of a feature”. Both modules are to lead to an even more precise definition of the morphology of existing and planned urban structures. The SCD method is part of the international research trend concerning models of interpretation of existing urban spaces with the use of computer techniques. For example Bianca Ilha Pereira describes her research in her “Master Planning With Urban Algorithms” (Pereira, 2019) or Cheng Chen, Chaoyi You, Xianmin Mai, who analyze spatial elements, obtaining general features of the structure of a traditional settlement in order to verify the process of renewal of the morphology of the traditional Qiang settlement (Chen, You and Mai, 2019). They described the issue in “Research on Spatial Morphology of Traditional Settlements Based on Spatial Syntax”. However, the analysis of available literature indicates that the use of computer techniques in the SCD method not just for the analysis of existing urban spaces, but above all for the creation of guidelines for the harmonious development of such spaces in the future may be a new approach to this research and practical issue.

6. Conclusion

The article presents the assumptions and methodology of SCD research. The role of this method in supporting the design process aimed at harmonious transformation of the existing urban buildings has been described. The procedure of conducting analyses with the use of specially created software was also described. It also presents the application of the method in practice on the example of the development of a planning document enabling the construction of an independent single-family housing estate, of which design solutions were based on the guidelines obtained with the use of the SCD method.

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AMBIGUOUS VS. CONCRETE: IDENTIFYING THE EFFECT OF DESIGN REFERENCES WITH VARIOUS LEVEL OF DETAILS ON DESIGNER'S CREATIVITY IN THE EARLY DESIGN PHASE

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Abstract. During the early design phase, spatial designers search for design references to develop design ideas. In this process, the level of detail (LoD) of design references can significantly influence the quality of design outcomes. However, previous studies have only suggested guidelines indicating that abstract references are useful in the early design phase without the degree of LoD. In response, this study aims to identify the impact of LoD of design references on design outcomes during the design concept development. To this end, we proposed three different reference types (abstract, hybrid, and concrete), and conducted experiments to assess the creativity and efficiency of the design outcome per LoD type. We also developed the FPRT (Floor Plan Retrieving Tool) system along with 7,842 existing residential floor plans for the experiments. The results of the study showed that there is a significant difference in design outcomes depending on the LoD types.

Keywords. Design Reference; Design Retrieval; Spatial Design; Level of Details; Early Design Phase.

1. Introduction

In the early design phase, spatial designers search for design references to develop quality designs (Goldschmidt 2011). Often, the unsuccessful use of design references can have a negative impact on the creativity and quality of the design outcomes. According to Goldschmidt (2011), the abstraction of design references is essential to avoid low quality and to enhance the creativity of design in the early design phase. However, researchers have not yet identified how detailed or how abstract the references should be for design creativity and design quality. On the other hand, case-based reasoning (CBR) allows designers to find a design solution by exploring previous references (Maher and de Silva Garza 1997). In this respect, CBR-based floor plan data retrieving systems have been researched to support designers in the task of retrieving appropriate references (Langenhan and Petzold 2010; Weber et al. 2010; Ayzenshtadt et al. 2016; Sabri et al. 2017). Therefore, this study aims to identify the impact of the level of detail (LoD) of references on design outcomes during the spatial design concept development. To do this, we proposed three types of references depending on their level of detail:

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 589-598.

abstract, hybrid, and concrete types. To observe the impact of the different LoD, we created FPRT (Floor Plan Retrieving Tool). The FPRT consists of a total of 7,842 floor plan data. By using these three types of references and the FPRT, we conducted a design task experiment. The results of the study can be used as a fundamental wireframe of LoD with respect to design references.

2. Related Works

2.1. IMPACT OF DESIGN REFERENCES / AMBIGUOUS DIAGRAMMING IN THE EARLY DESIGN PHASE

In the architectural design process, diagrams are an intuitive and essential way of expressing ideas, and it is the simplest representation of design problems and ideas (Do and Gross 2001). Designers sequentially develop a diagram in the design process. It is common in architectural design to use design references that are similar to the current design situation by analogy (Ozkan and Dogan 2013). However, the unsuccessful use of design references reduces the creativity and quality of the design outcomes. According to Goldschmidt (2011), abstraction is essential to avoid low quality and creativity of design when utilizing references. However, the previous literature has not yet identified the impact of LoD of design references during design concept development. It is crucial to clarify the relationship between the LoD of design references and design outcomes.

2.2. ASSESSMENT OF DESIGN CREATIVITY / DESIGN ALTERNATIVE

Good design includes creativity and starts with good design ideas (Goldschmidt and Tatsa 2005). In a study assessing design creativity, Sarkar and Chakrabarti (2011) proposed a method of assessing design creativity by analyzing the novelty and usefulness of the design outcome. The design novelty refers to how new the design is, and the design usefulness pertains to how useful the design is. Similarly, Chakrabarti (2006) argued that novelty, purposefulness, and resource-effectiveness are necessary for creative ideas and solutions. Unlike other studies that only evaluated creativity without specific assessment metrics, their research is meaningful in that they all proposed evaluation metrics for design creativity. In this regard, we would like to assess the creativity of the design result according to the reference used in the design process. Therefore, in this experiment, we use three parameters, design novelty (how it differs from the design references retrieved by the designer to user generated design), design usefulness (design constraint fulfillment), and resource-effectiveness (number of design references used by the designer) to assess the creativity of design outcomes.

2.3. CASE-BASED REASONING AND DESIGN REFERENCE

Case-based reasoning is a method to find a solution by exploring similar problem cases. CBR has been applied to architecture design since the middle of the 1990s (Weber et al. 2010). It has been used for ‘semantic analysis and retrieval of floor plans,’ which refers to the work of retrieving similar floor plans by spatial meaning such as the boundary and function of each room. Langenhan and Petzold (2010) introduced the concept of a ‘semantic fingerprint of a building,’ which extracts building information into topological representation such as the function, number, and accessibility of rooms. For example, a.SCatch (Weber et al. 2010) is a sketch-based floor plan retrieving tool; MetisCBR (Ayzenshtadt et al. 2016) is a retrieving system used by multiple users; and Archistant (Sabri et al. 2017) is a web-based floor plan searching system utilizing GUI. However, these studies have limitations in that they do not utilize the shape information. Also, the size of the dataset used for study is small. Therefore, the FPRT uses a retrieval method based on the room number, location, connectivity, and shape information of the large floor plan datasets (N=7,842).

3. Methodology

This study aims to observe the effect of different LoD of the references on the design outcomes and design process. To do this, first, we collected a total of 7,842 floor plan data from a web-based real-estate database (r114.co.kr). The collected data were analyzed and visualized using Python, OpenCV, and Network X libraries. Lastly, we proposed three types of references: abstract, hybrid, and concrete space (Figure 1). The three types of references have different LoD. Utilizing these three types of references, the FPRT was created to retrieve floor plan data based on the floor plan silhouette, number, location, and connectivity of rooms by using the GUI interface (Figure 2).

3.1. THREE TYPE OF REFERENCES

Figure 1. Three types of references with different LoD (a) Abstract (b) Hybrid (c) Concrete.

3.1.1. Abstract Reference

The abstract type of reference (Figure 1-a) contains the location information of the rooms, where the center point of each room is represented as a node. The rooms of the floor plan have different colors by node per function. Also, a direct room connection is represented by a solid line, and an indirect room connection is represented by a dotted line. A direct room connection represents two spaces that are directly connected through a door. An indirect connection represents adjacent spaces.

3.1.2. Hybrid Reference

Unlike the abstract type, the hybrid type of reference (Figure 1-b) contains both the floor plan and room silhouettes with a simplified representation. The hybrid reference contains information on the relative size between spaces but does not provide detailed information such as furniture or doors. The hybrid type also provides information about direct connections, which are represented as gray rectangles.

3.1.3. Concrete Reference

The concrete type of reference (Figure 1-c) is the raw floor plan data. It contains detailed information, such as walls, doors, and arrangement of furniture.

3.2. FLOOR PLAN RETRIEVING TOOL (FPRT)

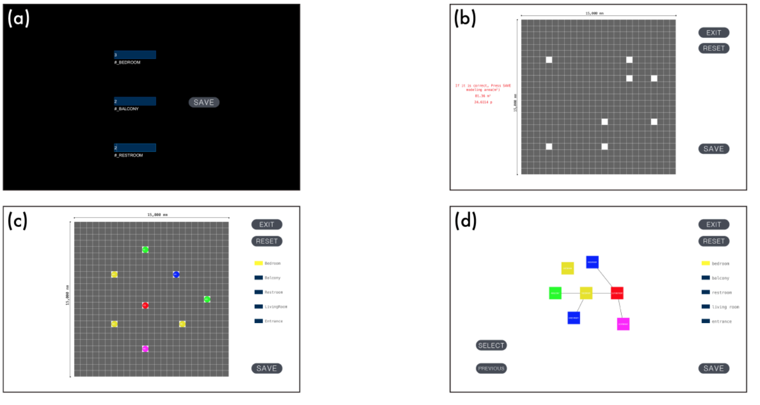

Figure 2. FPRT input UI (a) Number (b) Floor plan silhouettes (c) Location (d) Connectivity.

FPRT is a variation of C-Space (Son et al. 2020) that finds floor plans through user input sketches and a graphical user interface. The interface consists of a part that inputs information, retrieves data, and a result on the screen. The basic principle of the searching method is a cumulative search where if the user does not press the reset button, FPRT looks for data in previous results.

3.2.1. Number of Rooms

FPRT retrieves floor plans that match the number of rooms inputted by the user (Figure 3-a). The user can input the number of balconies, bedrooms, and restrooms (Figure 2-a). Since there are only one living room and one entrance in the collected data, the living room and entrance were excluded from the input process.

3.2.2. Floor Plan Silhouettes

FPRT provides a way to input the floor plan silhouettes. FPRT find floor plans similar to the inputted floor plan silhouette information (Figure 3-b). When inputting the floor plan silhouette information into the system, the user clicks only the corner of the silhouette on the grid board (real size of board: 15m * 15m), such as in Figure 2-b. The floor plan silhouettes-based method retrieves data by using '16 area ratios' and the 'aspect ratio' used in C-Space (Son et al. 2020). To find accurate results, the user can adjust the similarity value, as in C-Space.

3.2.3. Location of Rooms

Another input data type in FPRT is the location of rooms, which is the center of the room. When the user clicks the location of the rooms on the grid board (Figure 2-c), FPRT retrieves all data according to the input data (Figure 3-c). The first item that appears in the list of search results has the most similar location to the inputted data.

3.2.4. Connectivity of Rooms

Lastly, direct connect information is used to retrieve data in the FPRT. The process of inputting the direct connect information into the grid board is shown in Figure 2-d. FPRT finds floor plans that have the same direct connect information as the input data, but the locations of the rooms are not considered (Figure 3-d).

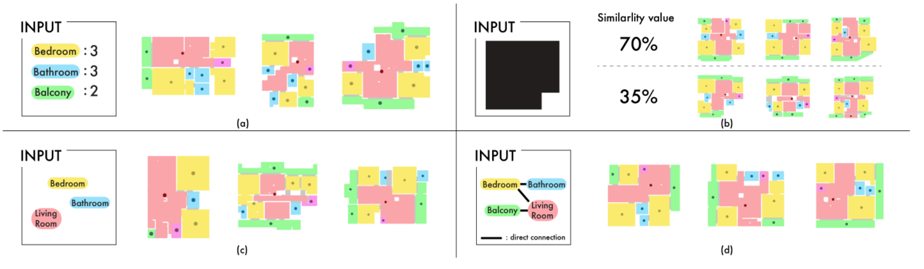

Figure 3. FPRT results (hybrid ver.) (a) Number (b) Floor plan silhouettes (c) Location (d) Connectivity.

4. Implementation and Results

4.1. USER STUDY

To identify how detailed references help designers, we conducted a simple design task experiment. For the experiment, three reference types, the FRRT, and a sketching tool (pen and paper) were used. One participant performed three different design tasks (20 min for each task) with three different types of reference. The participants submitted an idea sketch (Figure 4) and a final simple floor plan sketch for each task (Figure 6). To minimize the ordering effect, the reference type was selected randomly in each task. We conducted surveys, in-depth qualitative interviews, and a quantitative analysis of the design results to analyze the experiment. First, a survey about references was conducted at the end of each task. After all three design tasks and surveys were completed, a survey about the FPRT and in-depth interviews were conducted. The survey results are shown in Figure 8. Lastly, a quantitative assessment of design creativity and efficiency was conducted by using the design diagrams and final results produced by the participants. Five students who majored in interior architecture design participated in the experiment. However, due to procedural inconsistency from one participant, only the results of four participants were analyzed.

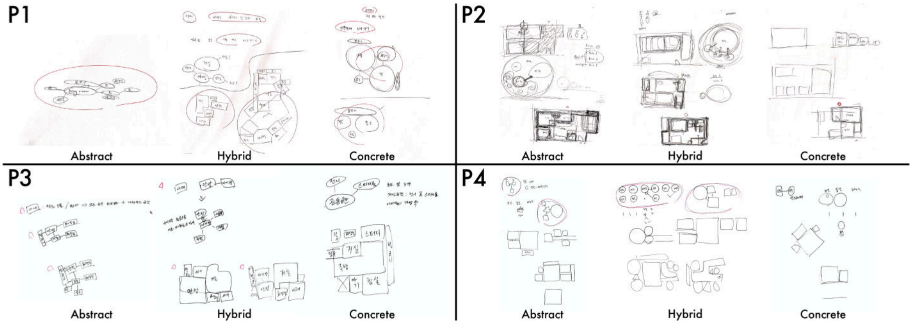

Figure 4. User's diagram.

4.2. RESULTS AND DISCUSSION

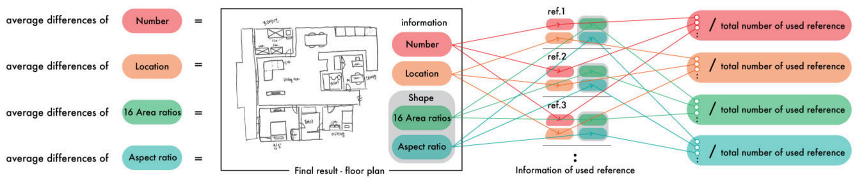

Figure 5. Design novelty analysis process of design results.

We quantitatively analyzed the final results in terms of creativity and efficiency to compare the effects of the three types of reference on the design process. Design novelty, resource-effectiveness, and design usefulness were evaluated to assess the design creativity of the results (Figure 7). First, to assess design novelty, we compared the information of design references used by a participant and the final design result (Figure 5). Second, we measured the number of references used and the number of design constraints satisfied for evaluating resource-effectiveness and design usefulness. However, there were no differences between participants in design usefulness because the design problem was not complicated. Next, to evaluate how efficient the design process was, we used two values: *number of diagrams ÷ number of references used; number of references used ÷ number of references observed.*

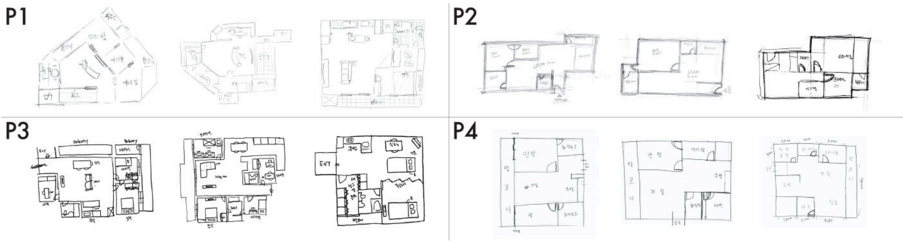

Figure 6. User's final floor plan sketch.

4.2.1. Abstract Type of Reference

The abstract type is a reference that emphasizes the connectivity between spaces using nodes and lines. In the results of the survey (Figure 8), the scores of questions about creativity are not high. P2 and P3 commented, "It took a short amount of time and simple design task to show creativity." However, the participants said that the abstract type of reference was the most helpful in terms of design creativity (Q17; M=4.25, SD=1.26). P2 replied, "The method of representing connect information is useful to generate another idea of connectivity." In addition, P1 and P4 noted, "It is useful to check connectivity between spaces and think about circulation in spaces." In particular, P2, P3, and P4 said, "The key point of space design is considering circulation in spaces." In this respect, the abstract type can help to design circulation and connectivity of spaces. Meanwhile, participants produced more novel design results with respect to the floor plan silhouettes (16 area ratios and aspect ratio) and location when using the abstract type (Figure 7-b; c). However, from P3's answer that "it was difficult to think intuitively and there was not much information" and the aspects of the survey (Figure 8), we could observe the reason for the novelty of results in the overall shape and location.

4.2.2. Hybrid Type of Reference

The hybrid type provides both the floor plan and room silhouettes, not only the information of abstract type. In the survey (Figure 8), the hybrid type was the most helpful to gain design inspiration (Q12; M=5.25, SD=1.50). In particular, P4 replied, "When using the hybrid type, it was easy to change the position of two spaces, because it looked like a zoning diagram." Also, we can check another advantage of the hybrid type in the following response of P3: "Shape was emphasized and shown intuitively, and it was easy to compare in the search result list without having to check each one in detail." The answer of P3 demonstrates that efficient comparison of design references is possible with the hybrid type only by comparing metadata. The interesting aspect is that the concrete type also has information about the shape but showed different aspects of design novelty (Figure 7-a; b; c; d). The two types show a slight difference in the overall shape. However, the hybrid type results in greater novelty of design result than the concrete type in the number and location of the room. The different result between the hybrid and concrete implies that if designers are given more simplified shape information, they will be more likely to consider novel design alternatives. Furthermore, it was possible to create more design diagrams than with the abstract type (Figure 7-e), because the shape information is intuitively provided to designers. As a result, the design process of the hybrid type was also more efficient than with the other types (Figure 7-g; h).

4.2.3. Concrete Type of Reference

The concrete type includes details such as doors, walls, and arrangements of furniture. As a result, all participants agreed that the concrete type provides the most valuable information. Also, the concrete type was the most helpful to develop a design concept (Q16; M=5.25, SD=0.50). Participants explained that it was possible to check and assess the quality of their layout designs with actual dimensions by using the concrete type. Regarding this function of the concrete type, P2 commented, "The concrete type will be more useful in the process of checking the design idea than idea generation because it was possible to obtain feedback on my layout design with actual dimensions by utilizing the concrete type of reference." However, the concrete type received a skeptical response in supporting design creativity. All of the participants said, "It was too detailed to express creativity. Therefore, it was easy to follow the references naturally." This comment showed that the concrete type could cause design fixation. Also, the design novelty evaluation showed that it is difficult to generate a novel design when using the concrete type (Figure 7-a; b; c; d). As seen in Figure 7-g; h, the concrete type resulted in the most inefficient phase among the three types. Therefore, it would be desirable to use the concrete type references as a means of assessing design ideas rather than generating design ideas.

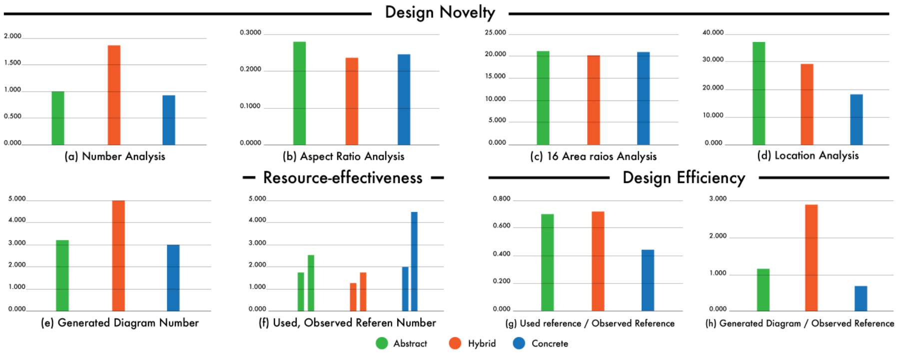

Figure 7. Parameters of design creativity and efficiency .

4.3. DISCUSSION

In this study, we identified the relationship between the LoD of design references and design outcomes in the early phase of spatial design. According to the results, all the participants agreed that information must be provided in a simplified form to develop a creative design concept in the early design phase. In addition, spatial design references should include intuitive shape information. The results show that shape information must be represented as a hybrid type. The concrete type of refence gives an interesting point about design feedback. Participants were able to evaluate their designs using detailed information from the concrete type. However, the concrete type had problems of design fixation and low efficiency and creativity. Lastly, regarding the abstract type, it was found that the abstract type is useful to generate the idea of connectivity and circulation in space. However, the abstract type had a shortcoming regarding the absence of shape information. To sum up, in the early stage of spatial design, the LoD of the reference for enhancing creativity and efficiency should have a hybrid characteristic. Also, for spatial design, it would be helpful if the design reference contained simplified shape information rather than detailed information.

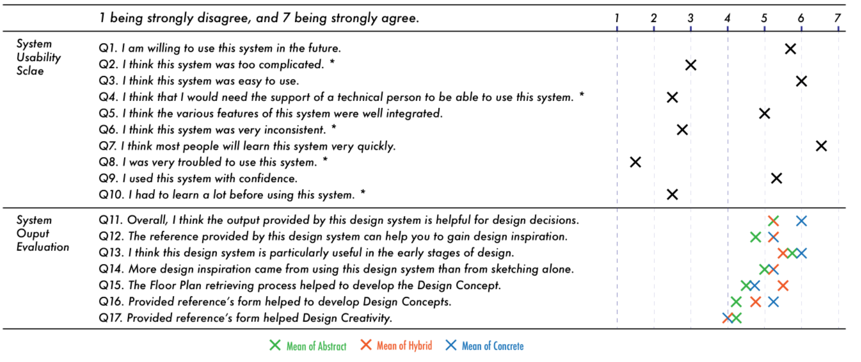

Figure 8. User's response in evaluation survey.

5. Conclusion

This study explores the relationship between LoD of design references and design outcomes in the early design phase. From an experiment using abstract, hybrid, and concrete types of references, we identified the impact of the LoD when presenting design references to designers. The findings regarding LoD type are summarized as follows: (1) the abstract type of reference is useful when designing circulations and space layouts despite that the abstract type contains the least amount of information among the three types; (2) the hybrid type is the most suitable for creativity and efficiency of design outcomes because it provides intuitive shape information with a simplified form while offering room for imagination. Also, the hybrid type shows an efficient comparison process between design references by using metadata about shape; (3) the concrete type of reference causes a fixation problem but is useful when assessing layout designs with actual dimensions. Given the strengths and weaknesses of each type, we suggest that these three types of references should be utilized differently depending on the design process or circumstances. However, the results of the experiment may be limited due to its small sample size, and because it was conducted with students only. Therefore, in future work, we will increase the sample size to look at the difference between experts and students. We are also planning to experiment with similar conditions to the actual design process in the long term.

Acknowledgement

This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2019S1A5A8034285).

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Artificial Intelligence & Machine Learning

APARTMENT FLOOR PLANS GENERATION VIA GENERATIVE ADVERSARIAL NETWORKS

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Abstract. When drawing architectural plans, designers should always define every detail, so the images can contain enough information to support design. This process usually costs much time in the early design stage when the design boundary has not been finally determined. Thus the designers spend a lot of time working forward and backward drawing sketches for different site conditions. Meanwhile, Machine Learning, as a decision-making tool, has been widely used in many fields. Generative Adversarial Network (GAN) is a model frame in machine learning, specially designed to learn and generate image data. Therefore, this research aims to apply GAN in creating architectural plan drawings, helping designers automatically generate the predicted details of apartment floor plans with given boundaries. Through the machine learning of image pairs that show the boundary and the details of plan drawings, the learning program will build a model to learn the connections between two given images, and then the evaluation program will generate architectural drawings according to the inputted boundary images. This automatic design tool can help release the heavy load of architects in the early design stage, quickly providing a preview of design solutions for architectural plans.

Keywords. Machine Learning; Artificial Intelligence; Architectural Design; Interior Design.

1. Introduction

1.1. BACKGROUND

In architectural design, the design process usually follows specific criteria, arranging objects inside space. Despite the cultural and aesthetic considerations, architectural design can be regarded as a box of geometric operations, inputting the design boundary (available space for the design) and outputting the layout of the contents inside the boundary.

As a presentation of architectural design, projected drawings, especially floor plan drawings, have been widely used since the Renaissance (Alberti 1988). With the rapid development of Computer-Aided Design (CAD) technology from the 1960s (Carpo 2017), drawing digitally has been widely practiced by architects.

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Thus, digital image files showing the plan drawings have become the most popular format to communicate between architects and clients.

1.2. PROBLEM STATEMENT

The interior design, the most commonly practiced field in our daily life, however, is subject to the architectural design. For example, the boundary for an apartment might change during the overall design process of the whole floor. Thus a small change in the design boundary will cause a redesign request to the entire interior layout, in which he designers spend a lot of time working forward and backward drawing sketches for different site conditions. Still, most of the floor plans they provide will be discarded because of the adjustment of the boundary.

1.3. PROJECT GOAL

Thus, in the age of Artificial Intelligence, we propose a Machine Learning method to make the computer provide the interior design layout in the early design stage, releasing the heavy load from architects. Generative Adversarial Network (GAN) (Goodfellow, Pouget-Abadie, et al. 2014) supports the learning and generating of real-world images, including architectural floor plan images. The final goal of this research is to build a tool that takes images showing the design boundary as the input and outputs images showing the detailed interior design inside the boundary.

1.4. LITERATURE REVIEW

Previous research about the usage of GAN in architectural design includes the transformation of city maps to satellite images (Zheng 2018); the generation of furniture layout (Huang and Zheng 2018); the recognition of different rooms in architectural plans (Zheng and Huang 2018), and the recognition of different architectural elements (doors, windows, etc.) (Kvochick 2018). This research will fill in the gap of generating detailed apartment floor plans by only providing the design boundary, showing the possibility of applying Machine Learning in more complicated and creative design works.

2. Methodology

2.1. DATA LABELLING AND CLEANING

Two datasets from previous research were used in the learning process. The first dataset contains 1279 images of apartment floor plans in Japan (Liu, Wu et al. 2017), and the second dataset contains 112 images of apartment floor plans in China (Huang and Zheng 2018). The design and drawing styles are different; thus, two GAN models will be trained separately using these two data sets. However, the images in the data set only contain the design layouts without the boundaries, so the first step is to produce the boundary images based on the plan drawings.

First, each image is resized to a bounding area of 500 pixels X 500 pixels, and placed in the middle of a canvas of 512 pixels X 512 pixels, leaving a white margin of 6 pixels in each side. Then, a Photoshop script automatically detects the continuous white pixels from margin to the original image, and find the boundary of the plan. Last, by inversely selecting the area and filling black pixels inside the boundary, the boundary image is produced (figure 1). Thus, the generated boundary image and the resized plan image together become an image pair for the training of GAN.

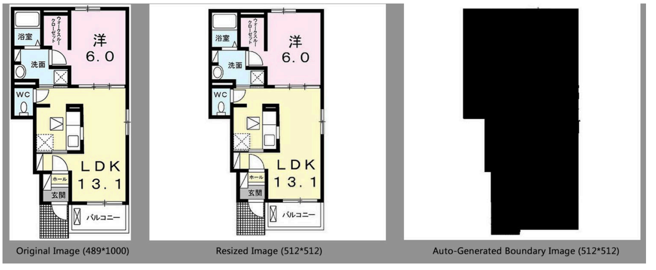

Figure 1. Image resizing and boundary detecting.

After the production of the boundary images, we found there are two types of images that are not suitable for learning in the first dataset (figure 2). One is for having an unrelated rectangular boundary box, and the other one is for having a separate bounding colored area. Thus we removed nine images from the first dataset. There are no such problems in the second dataset.

Figure 2. Invalid image pairs.

2.2. NETWORK STRUCTURE

In this research, the mapping between the input boundary image and the output plan drawing is structurally precise. Image-based neural network GAN (Generative Adversarial Network) with convolution and deconvolution kernels was used as the framework. Based on the conditional GAN invented by(Mirza and Osindero 2014), pix2pixHD (Isola, Zhu, et al. 2017), an open-source project, was finally chosen as the algorithm for this research.

Figure 3 shows the network structure of pix2pixHD, in which two neural networks, Generator (G) and Discriminator (D), are trained simultaneously. The Generator acts to transform an input image to an output image with the same size, using convolutional, residual, and deconvolutional layers. The Discriminator works to distinguish the image generated by the Generator from the ground truth image. The Generator feeds forward the generated result to the Discriminator, while the Discriminator feeds back the loss and gradient to the Generator. Thus the Generator is trained to generate the fake images closer to the ground truth, while the Discriminator is trained to tell the fake image better apart. The two networks are "competing" with each other, so this system is called "adversarial."

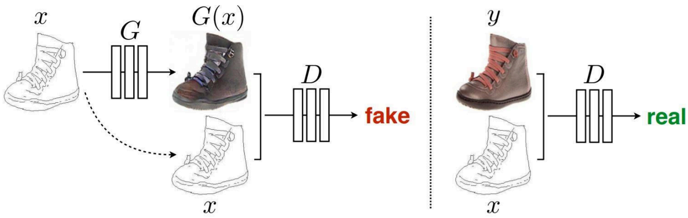

Figure 3. Training a conditional GAN (Isola, Zhu, et al. 2017).

However, to apply pix2pixHD, in addition to provide the program with image pairs described previously, some important hyper-parameters also need to be defined. First, we don't offer instance maps; thus, the function to read and use instance maps should be turned off. Second, we want the program to use RGB colors as input directly, so we set the label_nc as 0. Third, during experiments we found the early training epochs with constant learning rate would not improve the network after 50 epochs, thus we set the learning rate for the first 50 epochs of the training process as a constant value, but the learning rate for the following 50 epochs as decaying values. All other settings are the same as the default settings.

2.3. NETWORK TRAINING

During the training process, the loss values of the Generator and the Discriminator were recorded. Figure 4 and figure 5 show the loss of the two models. Generally speaking, in both models, the Generator loss and the Discriminator loss did not converge, since the two neural networks were, in fact, competing for each other. To be specific, when the loss of the Generator was lower, the loss of the Discriminator would be higher. This phenomenon indicates that the training was successful; the whole system gradually got improved during the balance of the Generator and the Discriminator. What's more, the loss in model 1 was comparatively higher than the loss in model 2, because the variance of dataset 1 is higher than that of dataset 2.

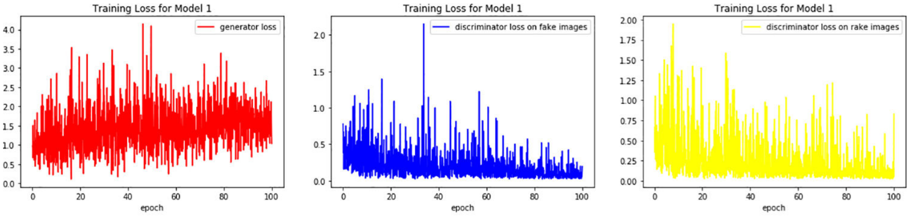

Figure 4. Training Loss of Model 1. Right: generator loss; Middle: discriminator loss on fake images; Left: discriminator loss on rake images.

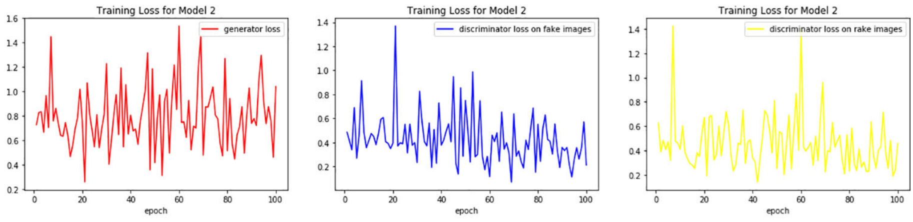

Figure 5. Training Loss of Model 2. Right: generator loss; Middle: discriminator loss on fake images; Left: discriminator loss on rake images.

Since the loss cannot tell us whether the model has been converged or not, in each training epoch, an input image was sent to the neural network, and the output image was recorded. By comparing the generated image with the ground truth image, we can decide whether the performance is satisfied and whether to stop the training.

Figure 6 and figure 7 show the image pairs in each training epoch for model 1 and model 2. At the beginning of the training, the generated images were very blurry. As the training went on, the quality of the generated images was gradually improved. Especially in model 2, the synthesized image in epoch 100 performed nicely, showing a clear pattern of different rooms and furniture. Thus, we decided to stop the training in epoch 100 and stored the final models for the following predictions.

Figure 6. Testing image pair in each training epoch for model 1.

Figure 7. Testing image pair in each training epoch for model 2.

To train the two models, it took a Titan X GPU 33 hours of training for the first data set, and 2.7 hours for the second data set. The time cost is acceptable for most of the cases in the architectural design industry.

3. Results

3.1. TESTING DATA GENERATING USING JAPANESE MODEL

Figure 8 and figure 9 show two Chinese apartments generated by Model 1 (Japanese training dataset). The apartment in figure 8 is an example, while the model does not generate very well. It is hard to tell the positions of the living room, the kitchen, and the bedrooms. The apartment in figure 9 is an example, while the model generates pretty well. Even though the kitchen size in the synthesized image is different from that in the real image, all other parts, including the living room and bedrooms, match perfectly. And the overall layout makes sense to architectural designers.

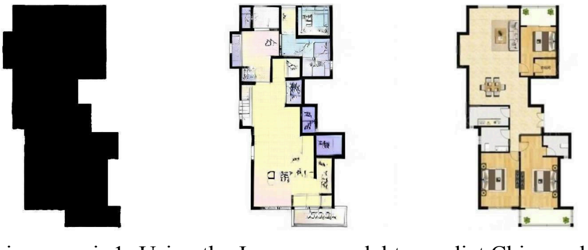

Figure 8. Testing image pair 1. Using the Japanese model to predict Chinese data. Left: input label; Middle: synthesized image; Right: real image.

Figure 9. Testing image pair 2. Using the Japanese model to predict Chinese data. Left: input label; Middle: synthesized image; Right: real image.

Figure 10 and figure 11 show two Japanese apartments generated by Model 1. The apartment in figure 10 is an example, while the model performs poorly. The layout in the synthesized image is blurring. It is hard to tell apart rooms in the image. Thus, this synthesized image does not help to predict the design case. The apartment in figure 11 is an example, while the model generates well. Even though the size of the living room in the synthesized image is different from that of the real image, all other parts, including the living room and bedrooms, almost match, both the synthesized images and the real images show designs with a similar drawing style.

Figure 10. Testing image pair 3. Using the Japanese model to predict Japanese data. Left: input label; Middle: synthesized image; Right: real image.

Figure 11. Testing image pair 4. Using the Japanese model to predict Japanese data. Left: input label; Middle: synthesized image; Right: real image.

Therefore, the model trained with the Japanese dataset is unstable when feeding different design boundaries.

3.2. TESTING DATA GENERATING USING CHINESE MODEL

Figure 12 and figure 13 show the image pairs deserved by using Model 2 (Chinese training dataset) to generate the Japanese apartment. They both perform poorly.

The synthesized image in figure 12 can show the basic structure of the apartment. But the application of the room and the interior decorations are generated wrongly. While the synthesized image in figure 13 even cannot generate the basic structure of the apartment.

Figure 12. Testing image pair 5. Using the Chinese model to predict Japanese data. Left: input label; Middle: synthesized image; Right: real image.

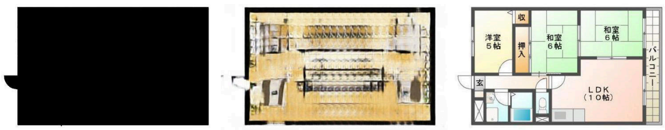

Figure 13. Testing image pair 6. Using the Chinese model to predict Japanese data. Left: input label; Middle: synthesized image; Right: real image.

Figure 14 and figure 15 show the image pairs deserved by using Model 2 to generate the Chinese apartment. The synthesized image in figure 14 performs substantially. It can not only provide a clear structure of the apartment but is also very similar to the original input image. Besides, the synthesized image in figure 15 shows a different but reasonable structure. The pattern is blurry but recognizable by architects. And the drawing style in both image pairs is highly uniform, indicating a perfect match between the training and testing images.

Figure 14. Testing image pair 7. Using the Chinese model to predict Chinese data. Left: input label; Middle: synthesized image; Right: real image.

Figure 15. Testing image pair 8. Using the Chinese model to predict Chinese data. Left: input label; Middle: synthesized image; Right: real image.

Therefore, the model trained with the Chinese dataset performs poorly with the Japanese apartment boundaries but nicely with Chinese apartment boundaries. This phenomenon shows the design strategies for Chinese apartments are more uniform.

3.3. MODEL COMPARISON

Figure 16 shows the Japanese apartment generated by both models. The layout in the synthesized image by the Japanese model is clear to tell the interior design, including the positions of the living room and the bedroom. However, the synthesized image by the Chinese model is not ideal. It is hard to recognize the bedroom pattern. This synthesized image has worse performance than the real image. And the predicted layout does not make sense to the designer. Thus, in terms of generating Japanese apartments, the Japanese model works better than the Chinese model.

Figure 16. Testing image pair 9. Left: input label; Middle Left: synthesized image by Japanese Model; Middle Right: synthesized image by Chinese Model; Right: real image.

Figure 17 shows the image pairs deserved by using both models to generate the Chinese apartment. The synthesized image using the Chinese model performs better than that using the Japanese model. It makes a precise prediction in both the layout design and drawing patterns. However, the synthesized image using the Japanese model generates a clear pattern of the apartment, but it does poorly in providing the internal furnishings and the application of each room.

Figure 17. Testing image pair 10. Left: input label; Middle Left: synthesized image by Chinese Model; Middle Right: synthesized image by Japanese Model; Right: real image.

Therefore, the design style, as well as the drawing style in the two datasets, are different and unique. The models perform well when feeding in similar input images as the training images.

4. Conclusion and Discussion

In conclusion, Generative Adversarial Networks successfully learn and generate apartment floor plans only based on the design boundaries. By training the network with plan drawings from different design styles, the neural network determines various features; thus, it generates plans with varying patterns of design and layouts. The quality and the unity of the patterns in the training images directly influence the resolution of the generated images. To achieve a better result, the training dataset should have uniform drawing styles as well as simple design rules.

In the future, the cooperation between Artificial Intelligence and Architectural Design will become more and more frequent, thus resulting in the birth of a new design concept - Architectural Intelligence, in which the computer not only aids but also decides the design.

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ROCESS PATH DERIVATION METHOD FOR MULTI-TOOL PROCESSING MACHINES USING DEEP-LEARNING-BASED THREE DIMENSIONAL SHAPE RECOGNITION

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Abstract. When multi-axis processing machines are employed for high-mix, low-volume production, they are operated using a dedicated computer-aided design/ computer-aided manufacturing (CAD/CAM) process that derives an operating path concurrently with detailed modeling. This type of work requires dedicated software that occasionally results in complicated front-loading and data management issues. We proposed a three-dimensional (3D) shape recognition method based on deep learning that creates an operational path from 3D part geometry entered by a CAM application to derive a path for processing machinery such as a circular saw, drill, or end mill. The methodology was tested using 11 joint types and five processing patterns. The results show that the proposed method has several practical applications, as it addresses wooden object creation and may also have other applications.

Keywords. Three-dimensional Shape Recognition; Deep Learning; Digital Fabrication; Multi-axis Processing Machine.

1. Introduction

One of the features of multi-axis processing machines such as a five-axis-machine or an articulated robot for parts processing is to navigate three-dimensional (3D) space accurately along a process path. Even though several different tilt cuts are inputted, the processing machines will process them correctly without customized jigs for each tilt. Thus, this feature has many possibilities in high-mix low-volume production that produce small quantities of various types of parts. The processing machines that equip woodworking tools can also be leveraged in wooden part fabrication to realize a new wooden project fabrication system. However, when the processing machines are employed for high-mix low-volume production, we find problems in process path derivation.

Figure 1 shows an example of a workflow with five-axis machines employed at a pre-fabrication site. In this workflow type, the processing machines are operated by a dedicated computer-aided design/computer-aided manufacturing (CAD/CAM) process, which is typified by HSB CAD operating a five-axis

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 611-620.

machine manufactured by Hundegger. The dedicated CAD/CAM has a function that creates joints parametrically and processing paths that are derived for the joint creation using parameters that specify each joint type and dimension. This workflow is based on dedicated software and sometimes results in complicated frontloading and data management issues, especially in cases where the design and fabrication teams are different and not in the same work environment.

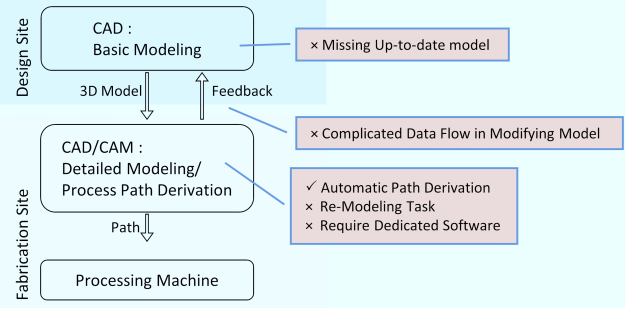

Figure 1. Dedicated CAD/CAM-based workflow.

Figure 2 shows another workflow that separates detailed modeling CAD and path derivation CAM processes. This workflow is employed in almost all Fused-Deposition-Modeling (FDM) 3D printers and allows us to use all software types in the design stage including detailed modeling. Data management could simply be built in the design stage, because 3D models are only operated by the design team. However, in this workflow, the separated CAM process creates an operation path based on the 3D part geometry. The process path derivation would create a new bottleneck despite this workflow having potential for overcoming the problems based on the dedicated CAD/CAM-based workflow. Therefore, a new process path derivation method that works efficiently in this workflow would be required when the processing machines are employed to fabricate complex wooden parts in a high-mix low-volume production environment.

In this paper, we present 3D shape recognition for an auto-processing path creation, for processing machinery such as a circular saw, drill, and end mill.

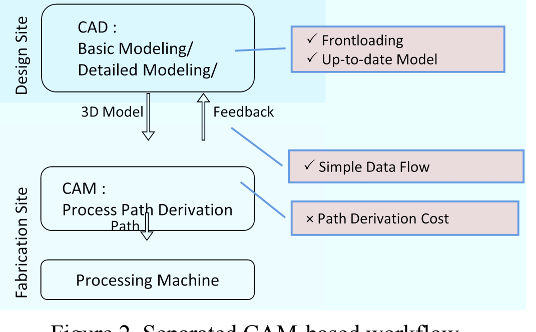

Figure 2. Separated CAM-based workflow.

2. Method

A processing path for a circular saw could be derived from 3D geometry entered as follows:

1. Create a unit path by specifying edges or polygons.
2. Adjust the depth or length of the unit path according to a cut pattern and a work pose.
3. Sort the unit paths.
4. Create diverting paths that connect each unit path.

Nakamura (2018) reported an auto-creation methodology for Step 1 that represents the circular saw trajectory as a half-plane and detects cuttable polygons by calculating collisions between the trajectory and the 3D geometry. Three circular saw cut types were reported; however, this methodology only addressed two types: cut-off and partial cut (omitting the grooving cut). Some human intervention tasks are still required in Steps 2 to 4. On the other hand, the dedicated CAD/CAM process derives a processing path with the joint type and parameters specified while a detailed joint is created. Applying pre-defined adjustment parameters, orders, and diversion paths, also automates Steps 2 to 4. These imply that a process path could be efficiently derived even in the separated CAM workflow if a joint type and some parameters, more specifically cut patterns of each polygon, could be estimated from only the entered 3D geometry. Given these considerations, we attempt to employ a deep-learning-based 3D shape recognition that classifies a joint type and segments a processing pattern to streamline the process path derivation in the separated CAM workflow. The proposed method overview is summarized into three steps as shown in Figure 3. We developed the proposed method in Python including some libraries; Keras (keras.io), Trimesh (trimsh.org), and Open3D (www.open3d.org). PointNet, a well-known model to handle 3D point clouds in deep learning as reported by Qi (2017), is used to recognize a joint type and processing pattern.

1. Extract joints: Boolean operations between the 3D geometry of the target component and its bounding box were used to extract the processed joints.
2. Convert into point clouds: The extracted joints are converted into point clouds. The converted point clouds include vertices and their normal vectors.
3. Classify and Segment the joints: Recognition is performed using the classification model that organizes the point clouds according to the joint types and the segmentation model that determines the polygon processing patterns.

After Steps 1 to 3, processing paths could be adjusted and sorted by applying a pre-defined procedure for the predicted joint types. Diversion paths could also be created according to the pre-defined procedure.

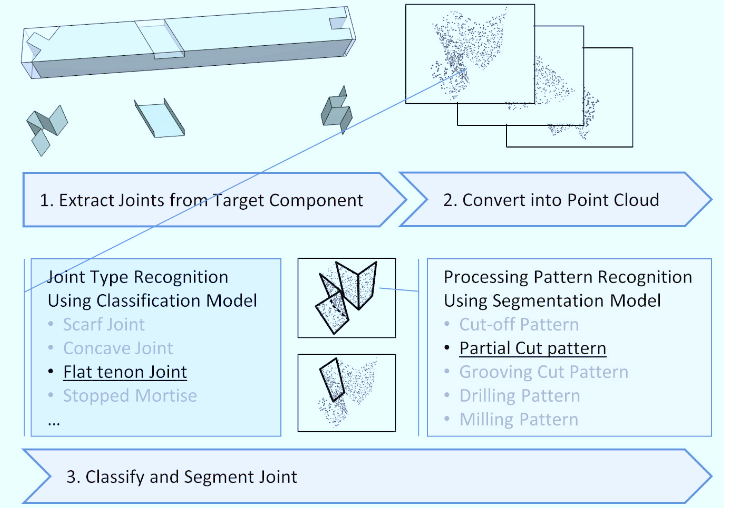

Figure 3. Overview of Proposed Method.

2.1. RELATED WORKS

Chai (2019) reported the potential use of robots for processing equipped bandsaws through the creation of a pavilion that has space-curved beams, which is a characteristic of advanced fabrication. The robot operated using a dedicated system; hence, this example is classified into the dedicated CAD/CAM workflow. As mentioned previously, this type of workflow is difficult to employ in generic wooden prefabrication sites. Conversely, 3D printers use the separated CAM workflow, and work with a processing path calculated from recorded 3D geometry. This has brought us high-mix production at low volumes typified by an on-demand 3D printing service. However, when processing machines are to be employed in the CAM workflow, path derivation is a problematic task. This report focuses on how a processing path could be efficiently derived by 3D geometry recognition using deep learning. This idea is based on an advantage in the CAD/CAM workflow; path derivation is simplified because the modeled shape is known.

Several studies on data recognition have reported image data recognition using deep learning. Supervised learning that estimates a function from pairs of training data and the correct answer, as typified by the Mixed National Institute of Standards and Technology database (MNIST), has been employed to recognize captured objects in images. Nia (2017) reported an architectural application that predicts the degree of building damage caused by earthquakes based on ground-level image data. Nishimura (2019) reported a method for constructing a photo management system that estimates positions and shapes on construction machinery images. Deep learning can input 3D geometry, and PointNet is a well-known deep neural network that can classify and segment a 3D point cloud. Xiu (2018) showed that derived point clouds can be labeled the same way for attributes such as buildings, parks, and roads by prediction using PointNet.

3. Classification model and segment model

As mentioned previously, we developed two models: classification and segmentation. The classification model is based on the PointNet implementation that classifies the entered point cloud into some categories such as a mug, table, or car. In this study, the classification model classifies a joint recorded as a point cloud into 11 joint types. The segmentation model is based on the PointNet implementation named "part segmentation" that segments an object into its parts, for example, a table would be segmented into a top panel and legs. The segmentation model segments each point involved in an entered point cloud into five process patterns. As a side note, there is another implementation named "semantic segmentation" that detects objects from the point cloud of a room interior. This implementation had greater versatility in detecting and classifying a joint from the point cloud of a component; however, we did not employ it because a colored point cloud is required as its input.

Figure 4 shows 11 joint types: a scarf, concave corner, flat tenon, stopped mortise, through mortise, semi-open mortise, open mortise, combination mortise for a metal joint, convex corner, convex corner with a horizontal slit, and convex corner with a vertical slit. The legend at the bottom of Figure 4 shows five process patterns: a cut off, partial cut, grooving cut (these patterns are for a circular saw), drilling, and milling pattern. Polygons indicated by the work-surface color in the legend are not converted into point clouds. These polygons were displayed only for visualizing the actual joint shapes.

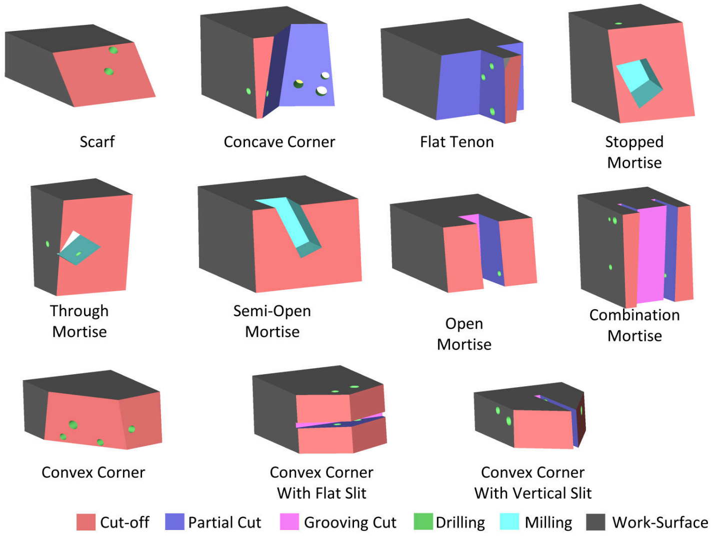

Figure 4. Joint Types and Processing Patterns.

3.1. TRAINING CLASSIFICATION MODEL

To employ supervised training, we implemented a generator that creates morphed variations of each joint type. The generator creates normalized 3D shapes with the longest dimension as one. Drill holes are created randomly but with rules determining creatable polygons and the number of holes. Figure 5 shows variations of the flat tenon joint. In the flat tenon type case, holes are only created on the tenon side polygons with a maximum of four holes.

Point clouds for training the models are converted from created 3D shapes before data are entered into the network. Two extensions were employed for this conversion. First, the point clouds include only 3D positions in default PointNet implementations and we added a normal vector to each point in the point cloud for recognizing the difference between convex and concave corners. Second, the data augmentations using jittering for addressing a 3D-scanned point cloud were removed. The perpendicular rotating augmentation was also removed, and a data augmentation applying 3D affine transformation (except skew) was alternatively added. The data-augmented process is a common technique for improving deep learning performance by making some modifications (3D affine transformation in this case).

The classification model was trained using 198,000 datasets (18,000 datasets for each joint type) with a data augment. The datasets were inputted as 1024-point cloud points for training. Table 1 summarizes the results that classified 1,000 test datasets after training. It attained 97.9% accuracy (categorical cross-entropy loss: 0.0651) for the test datasets.

Table 1. Confusion Matrix of Classification Model.

GT \ Res	S	CcC	FT	SM	TM	SOM	OM	CM	CvC	CvCH	CvCV
S	**98.3**	0.2	0.3	0.1	0.0	0.3	0.0	0.0	0.8	0.0	0.0
CcC	0.0	**99.5**	0.0	0.0	0.1	0.0	0.3	0.0	0.1	0.0	0.0
FT	0.0	0.0	**99.9**	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
SM	0.2	0.0	0.0	**85.9**	3.9	9.1	0.7	0.1	0.1	0.0	0.0
TM	0.1	0.5	0.0	1.5	**95.7**	1.2	0.2	0.0	0.2	0.1	0.5
SOM	0.4	0.0	0.1	7.2	0.9	**89.2**	1.9	0.0	0.1	0.2	0.0
OM	0.0	0.1	0.0	0.1	0.2	2.6	**96.8**	0.2	0.0	0.0	0.0
CM	0.0	0.0	0.0	0.0	0.0	0.0	0.1	**99.6**	0.0	0.0	0.3
CvC	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.0	**98.9**	0.0	0.7
CvCH	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	**98.7**	1.0
CvCV	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.2	0.4	0.5	**98.6**

S: Scarf, CcC: ConCave Corner, FT: Flat Tenon, SM: Stopped Mortise, TM: Through Mortise, SOM: Semi-Open Mortise, OM: Open Mortise, CM: Combination Mortise, CvC: ConVex Corners, CvCH: ConVex Corners with Horizontal slit,CvCV: ConVex Corners with Vertical slit

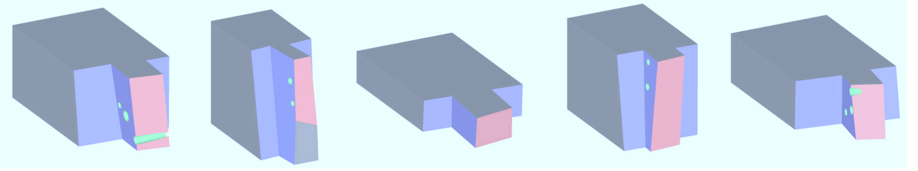

Figure 5. Variations of the Flat Tenon Joint.

3.2. TRAINING SEGMENTATION MODEL

This model segments each point into five process patterns. A developed generator creates each joint type variation in the same way as for the classification model. The difference from the classification model is that created 3D shapes consist of colored polygons indicating process patterns. Before the point clouds are entered into the network for training, each point is labeled respectively with a proper process pattern as the correct response by referring to the polygon color in which the point resides. Thus, the segmentation model estimates the processing pattern for each point when a point cloud is entered. The same extensions are also employed in this model.

The segmentation model was trained using 198,000 datasets (18,000 datasets for each joint type) with the data augmentation. The datasets were entered as 1024-point cloud points. Table 2 and Figure 6 summarize the result of segmenting 1,000 test datasets after training. It performed at over 98.9% accuracy (categorical cross-entropy loss: 0.0363). Additionally, that accuracy could be improved by counting pointwise results as polygons.

Table 2. Confusion Matrix of Segmentation Model.

GT \ Res	Cut-off	Partial Cut	Grooving Cut	Drilling	Milling
Cut-off	**99.4**	0.0	0.1	0.5	0.0
Partial Cut	0.2	**91.0**	0.1	8.0	0.6
Grooving Cut	0.1	0.0	**98.8**	0.8	0.3
Drilling	0.4	0.2	0.9	**97.1**	1.4
Milling	0.0	0.1	1.1	4.7	**94.1**

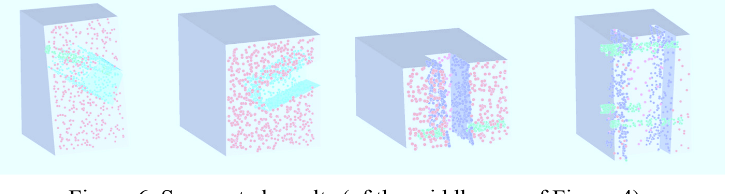

Figure 6. Segmented results (of the middle row of Figure 4).

4. Study Cases

Both the classification and segmentation models performed with high accuracy on the test data. Figure 8 shows the recognition results in the study cases.

Case A is a typical component of the wooden frame shown in Figure 3, which has a flat tenon, open mortise, and semi-open mortise from the left. Each joint was properly classified and segmented. This open mortise joint, in a precise sense, is not correctly classified as the open mortise type because cut-off pattern polygons are not included. However, the segmentation model correctly recognized the process patterns. This ambiguity will be discussed in the next section.

The parts listed in Case B are wooden object components that were designed in our other projects regarding the development of a five-axis machine for algorithmic-designed parts. The reciprocal, dodecahedral object component has convex corner type joints at both ends. The joints also have two drill holes to fix to other components. The components of the reciprocal tower object contain scarf type joints with two drill holes at each end. However, their gradients and positions differ by component type; thus, they are categorized into 11 geometries. When joint type classification and process pattern segmentation steps remain as human intervention tasks, the cost increases as the number of geometries increases. This cost is significantly greater in high-mix low-volume production and would block new design realization. The proposed method contributes to driving down this cost by automatic classification and segmentation. By adapting pre-defined procedures, the paths would be more efficiently derived. This step is planned as future work.

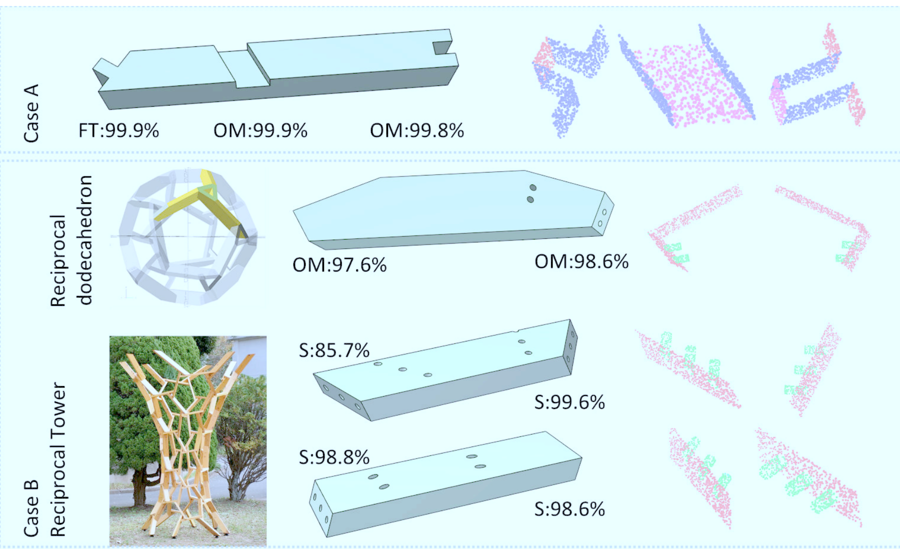

Figure 7. Study Cases.

5. Discussion

In the Case A study case, the open mortise joint without cut-off pattern polygons was properly segmented into process patterns despite this joint type not being included in the model training data. It suggests the segmentation model is versatile enough to recognize novel processing patterns and more complicated joint types.

Figure 8 shows an extra study case for considering that versatility. This component has a standard tenon, haunched open mortise, and cross mortise, starting from the left. As a result, the standard tenon was accurately recognized from their processing patterns. However, there were mis-segmented points in the cross and haunched mortises. For one of the cross mortise side polygons, it was estimated that only 40.5% of points (30 points) were segmented into the partial cut pattern (the correct pattern) and the rest were the drilling pattern. In the shallow bottom of the haunched mortise, it was estimated that 73.4 % of points were the grooving cut pattern (the correct pattern) and the remaining points were the cut-off pattern. The former seems to be caused by the input of a new shape type not included in the learning data. The latter was influenced by the training data bias, that the open mortise joint always has cut-off polygons around the mortise. In this study, we employed the generator for creating the training and test data. However, the accuracy evaluated with the created virtual data, and the versatility for actual components that would be entered in a fabrication site seem to have a difficult relationship. The same was observed during the hole creation rule. Specifically, the loose rule that increases randomness (e.g., not limited hole-creatable polygons) and reduced the test data accuracy, and the tight rule that decreases randomness (e.g., limiting hole position parametrically) and increased accuracy. A data generation method that creates training data fitting the actual components is required to improve the accuracy . Moreover, there are new approaches for 3D shape recognition such as PointNet++ (Qi, 2017). Improving the data generation and using these new approaches through actual creations are planned as future work.

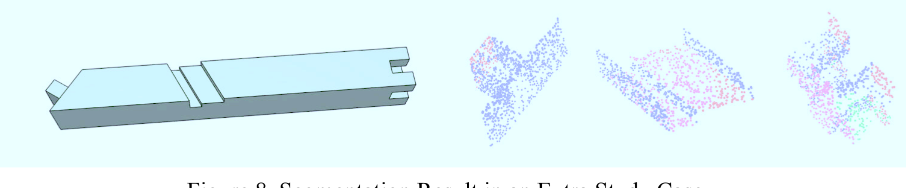

Figure 8. Segmentation Result in an Extra Study Case.

6. Conclusion

The processing machines employed in manufacturing sites for wooden project fabrication are operated in the dedicated CAD/CAM workflow. The processing path is derived efficiently using parameters such as joint type and dimensions concurrently with joint modeling. However, there are challenges, as this workflow requires dedicated software, and sometimes results in complicated frontloading and data management issues.

In this paper, we reported on 3D shape recognition for an automated processing path creation for processing machinery to overcome these challenges. PointNet-based models were used to recognize the 3D part geometry, which was the input into CAM. The recognition consisted of a classification model that classified shapes, and a segmentation model that determined the processing pattern of each polygon. The methodology was tested using 11 joint types and five processing patterns. The classification and segmentation models both performed at over 95% accuracy for the test datasets. The study cases showed that the proposed method has practical applications as it properly estimated joint types and processing patterns in the typical wooden frame component, and the wooden reciprocal object components were designed algorithmically. The versatility of the proposed method was also considered in the discussion section. The importance of the data generation method fitting actual fabrication was highlighted in this consideration.

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THE SPIRE OF AI

Voxel-based 3D Neural Style Transfer

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Abstract. In the architecture field, humans have mastered various skills for creating unique spatial experiences with unknown interplays between known contents and styles. Meanwhile, machine learning, as a popular tool for mapping different input factors and generating unpredictable outputs, links the similarity of the machine intelligence with the typical form-finding process. Style Transfer, therefore, is widely used in 2D visuals for mixing styles while inspiring the architecture field with new form-finding possibilities. Researchers have applied the algorithm in generating 2D renderings of buildings, limiting the results in 2D pixels rather than real full volume forms. Therefore, this paper aims to develop a voxel-based form generation methodology to extend the 3D architectural application of Style Transfer. Briefly, through cutting the original 3D model into multiple plans and apply them to the 2D style image, the stylized 2D results generated by Style Transfer are then abstracted and filtered as groups of pixel points in space. By adjusting the feature parameters with user customization and replacing pixel points with basic voxelization units, designers can easily recreate the original 3D geometries into different design styles, which proposes an intelligent way of finding new and inspiring 3D forms.

Keywords. Form Finding; Machine Learning; Artificial Intelligence; Style Transfer.

1. Introduction

1.1. DEEP LEARNING AND CONVOLUTIONAL NEURAL NETWORKS

Machine Learning, a decision-making tool, takes inputted factors as training neurons and calculates the computational relations among the input and the output data (McCulloch and Pitts 1943). Thus, Deep Learning, as a popular Machine Learning method, contains a class of trainable neural networks with multilayers, that low-level features in the first layers are combined into high-level features for precise classifications in the last layers (LeCun, Bengio, and Hinton 2015). Convolutional Neural Networks (CNN), one of the most representative algorithms

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of Deep Learning invented by (LeCun, Yoshua, and Geoffrey 1998) is widely applied to visual imagery recognition analysis. The core working structure of CNN can be summarized as a differentiating scoring simulator with five layers: Input, Convolutional, Pooling, ReLU, and Loss Layer (Krizhevsky, Sutskever, and Hinton 2012). According to the CNN VGG-19 model (figure 1), feature signals are continuously-superimposed and passed on to high-dimensional classified layers.

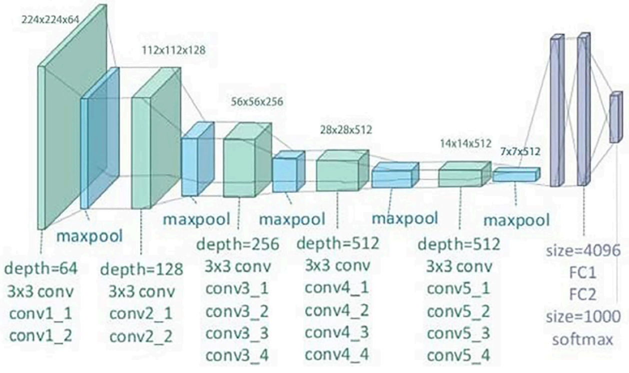

Figure 1. The Network Structure of VGG-19 CNN Network (Zheng, Yang, and Merkulov 2018).

In the architecture field, recent CNN applications mostly focus on extracting 2D features for classification and design predictions. For example, Kim, Song, and Lee (2019a) train CNN for inputting furniture image and outputting parameters such as seat capacity and materials. Based on image reorganization, Kim, Song, and Lee (2019b) also apply CNN to classify the elements of the images exported in the BIM models. Ng et al. (2019) introduce the classification function as well for distinguishing the building plans from sections.

1.2. WORKING PRINCIPLE OF STYLE TRANSFER

Based on the workflow of CNN, Neural Style Transfer (NST) refers to a representation system, according to Justin Johnson's code that manipulates digital images to combine the visual style of another image. It was first introduced in "A Neural Algorithm of Artistic Style" by Leon A. Gatys with the core innovation of a pre-trained deep learning network (Gatys, Ecker, and Bethge 2015).

During the pre-training process, the machine focuses on learning different features of the content and style in each layer of the VGG-19 model. In figure 2, as the number of the training layer increase, the learned information is then superimposed from a simple structure to intricate details (Simonyan and Zisserman 2014).

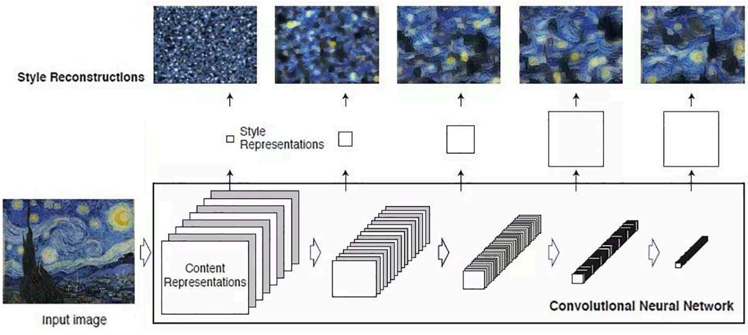

Figure 2. Five Layers of Different Style Information in VGG-19 (Gatys, Ecker, and Bethge 2015).

During the operation process, users only need to input a content image and a style image with the pre-trained framework. The editing process behind contains a series of optimizations through gradient descent of content and style loss. According to the formulas, content weight (α) and style weight (β) are the main influencing parameters for generating images (G). In figure 3, when the content weight keeps constant, the addition of style weight will result in a higher similarity between the style and the generated image. Thus, the total amount of style weight and content weight from in all layers is 100%, different proportion division of β and α in each layer will also result in different output solutions. (1) expresses the Content Loss Formula, (2) represents the Style Loss Formula, and (3) expresses the Generation Formula.

$$J_{\text{content}}(C, G) = \frac{1}{4 \cdot n_H \cdot n_W \cdot n_C} \sum_{\text{AllEntries}} \left(a^{(\mathrm{C})} - a^{(\mathrm{G})}\right)^2 \tag{1}$$

$$J^{[\mathrm{l}]}_{\text{style}}(S, C) = \frac{1}{4 \cdot n_C^2 \cdot (n_H \cdot n_W)^2} \sum_{\mathrm{i}=1}^{n_C} \sum_{\mathrm{j}=1}^{n_C} \left(G_{\mathrm{ij}}^{(\mathrm{S})} - G_{\mathrm{ij}}^{(\mathrm{G})}\right)^2 \tag{2}$$

$$J(G) = J_{\text{content}}(C, G) + J_{\text{style}}(S, G) \tag{3}$$

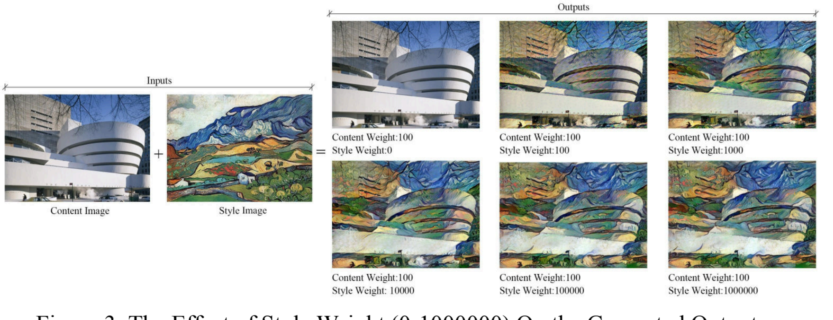

Figure 3. The Effect of Style Weight (0-1000000) On the Generated Outputs.

1.3. LITERATURE REVIEW

Neural Style Transfer is initially applied in the art field, for example, the stroke mapping. Though most applications mainly focus on 2D feature extraction, there are a few breakthroughs recently in architecture fields for introducing 3D modeling concepts. Ma, Huang, and Sheffer (2014) compute a single feature of the source model to the target model for new outputs. However, the algorithm is limited with models in similar forms in the same perspective views. Another approach is to map the chosen style images on 3D models. For example, Campo et al. (2019) use a transfer algorithm for mapping images to the model surface to change the patterns, which still works with plane space without changing the geometries. Kato, Ushiku, and Karada (2018) develop a multi-angle rendering system to divide an object with a series of 2D images. The stylized images are then mapped back into the 3D model. The network fits styles on 3D objects but also has limitations with fixed perspective and solid models with few geometric possibilities.

1.4. PROJECT GOAL

Therefore, there are possibilities for developing Style Transfer as a 3D form-finding tool rather than just the renderer for pixelized images. This paper develops a new NST method for generating 3D voxelized volumes with detailed interior forms. Both the applied content and the style are the guidance during the generation that provides more spatial inspirations.

2. Methodology

The proposed method can be summarized into two mutual steps: the transformation and recreation between the 3D voxelized volume and 2D pixelized images. Generally, during the translation process from the 3D model to 2D data, the 3D volume is first sliced into 2D pixel layers and then mapped to the style with controllable parameters for the stylized output images. While during the recreation process from 2D stylized images to a new 3D structure, the amount of the pixels of each image can also be filtered. The pixels are then replaced by voxel blocks and reform a fully voxelized volume modeling with interior details.

2.1. TRANSLATION FROM 3D MODEL TO 2D STYLIZED IMAGES

During the preparation stage, users should firstly get their demanded 3D content model and 2D style image. For the 3D volume, as the morphological changes inside the building are the primary concern, the interior area is defined as the content for later training. Accordingly, the original 3D model has to be a closed surface or mesh that has a definite content boundary for effective machine reorganization.

With the appropriate 3D model, translating 3D data into 2D plan images is the most convenient way to feed the data to the machine. The model is then cut into multiple plans to match the Style Transfer data structure. Thus, the more the number of the plans cut with the same spacing, the more the reconstructed model will be inclined to the original form. Meanwhile, the color division settings should also keep simple for the training reorganization. Therefore, users can fill the interior boundary surface as black, while the exterior surface as white and export all the colored plans as single images with specific resolution (figure 4). There are also certain requirements for the 2D style image. For generating better-stylized outputs in visual, the more substantial RGB difference between the adjacent pixels of the style image results in a higher distinction of the machine learning data.

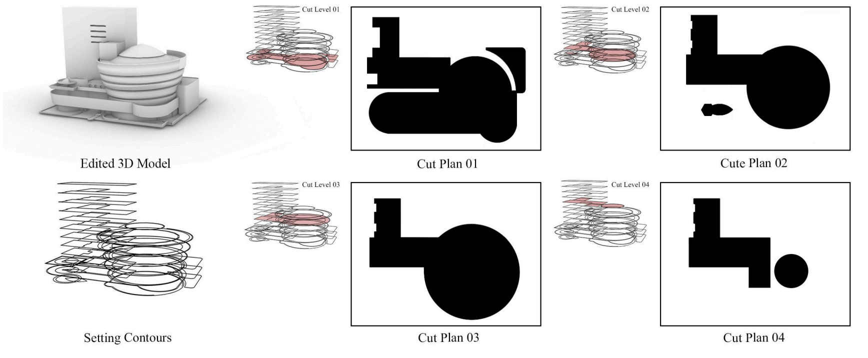

Figure 4. Abstraction Process of the Cut Content Plans in the 3D Model.

With the edited 2D content images and the 2D style image, users can then input them into the VGG-19 network for adjusting the key parameters. There are four main style-training parameters: 1) the total amount of the content weight (α); 2) the total amount of the style weight (β); 3) the proportions of the content weight in each convolutional layer; 4) the proportions of the style weight in each convolutional layer. The first two parameters work to control the general fitting tendency, and the last two proportions control the learning details.

2.2. RECREATION FROM 2D STYLIZED PIXELS TO 3D STYLIZED VOLUMES

In the final step, the set parameters are correspondingly assigned to the style image and each content plan, then the Style Transfer training starts. Thus, after obtaining the style-trained plans, the next goal is to recreate a new 3D geometry based on the stylized images and the users' customized settings. The idea of replacing the plan pixels with box voxelization is proposed as a new form-finding method.

Before having further edition, there are two main settings for output standardization. First, the interior area of the stylized results should be abstracted according to the content boundaries. Thus, pixels' RGB values of the image can be unified into corresponding gray values, which can be represented as a readable grayscale file (figure 5). These pixel points are also placed back to the original 3D locations for rebuilding the original volume. Moreover, three feature factors of the spatial points are defined for controlling the final outputs: 1) the grayscale filtration value of the pixel points; 2) the number of the closest pixel points; 3) the distance domain of the closest pixel points.

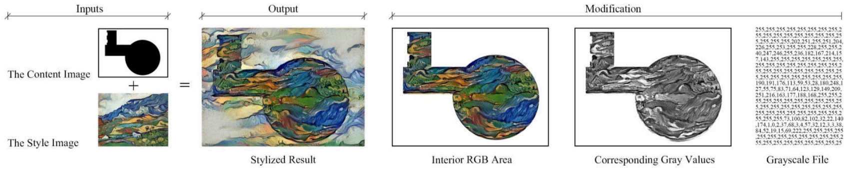

Figure 5. The Modification of Stylized Image from Interior RGB to Grayscale Value File.

After getting all the spatial pixels, as figure 6 shows, users can adjust the filtration degree by setting a certain value within the grayscale domain. Those pixels' values that are smaller than the setting remain, others that are larger are abandoned, and finally, all the abstracted points are obtained.

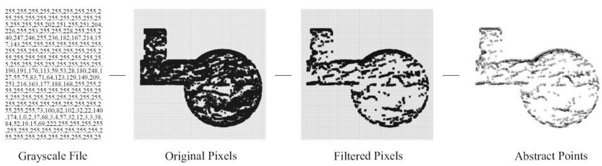

Figure 6. Grayscale Value Filtration and Points Abstraction.

To convert the 3D lattices into a formed geometry, the fundamental element of voxel modeling is then placed to the filtered points above for generating the voxelization structure (figure 7). The adjustment of the grayscale values is then visualized as the hollowing density, controlling the distribution of the solid and the void area. The original style image also becomes the interior structural basis rather than plane patterns on the surface.

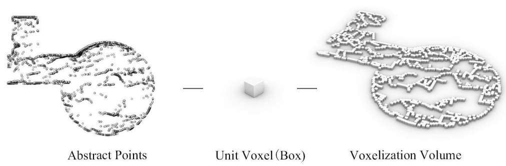

Figure 7. Box Voxelization Value with Hollowed Structure.

However, because of the changeable gray-scale features of different trained images, the distances between the inputted boxes may not be reasonable, and the voxelization structure may appear as separated and rough. Therefore, for improving the results as continuous and smooth, rules that control the closest points numbers and the boxes centroid distance are added. The blank area between the two nearest points is also designed to be filled with solid voxels based on the connectivity spontaneously, and the fragmented blocks are better connected as a whole volume.

For enriching the expression of the geometry, the smooth algorithm is applied for the final form modifications apart from the Style Transfer network. With the increase in the number of smoothing iterations, the angularity tends to be much sleeker. Users can also choose visual types, such as Gaussian, Laplacian, and Medium, according to different visualization needs (figure 8).

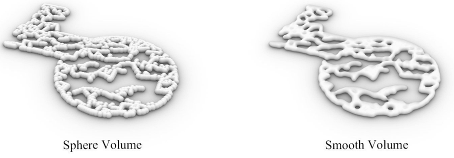

Figure 8. Different Voxel Smoothing Effect.

3. Results - The Rebuilding of The Pairs Spire

To add more reconstruction meanings to the real-world form-finding process, the spire of Notre Dame De Paris is chosen for rebuilding in the next step to test the performance of the methodology, which also explores the possibilities the AI manipulation within the historic culture context.

3.1. TRANSLATION FROM 3D SPIRE TO 2D GOTHIC PATTERNS

First, in the data preparation stage, it is necessary to edit the model of the spire as the content model with specific file requirements. Considering the general geometric composition and certain decorations of the spire, the reference model is simplified and reedited into a closed mesh.

Second, the re-edited model is then cut into a series of plans for matching the spire contents with the 2D training structure of Style Transfer. However, in practice, as different buildings have their corresponding considerations in design, the cut levels and plan numbers need to base on each building's length-width-height ratio. Thus, according to the actual measurement of the spire and the scale collection in the Rhino model, the spire is decided to be divided in the Z-axis direction with the distance of one unit. As a result, 406 closed contours are generated. Then, by defining the spire's interior as the content and distinguish the internal area as a black block, 406 content images are exported in the top viewport with a resolution of 50x50 pixels (figure 9).

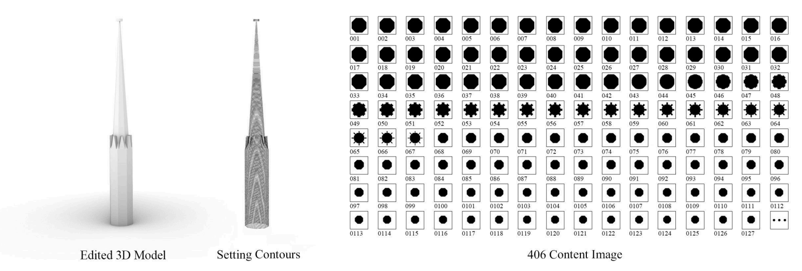

Figure 9. Surface Model, Abstracted Contours and the Content Image of the Paris Spire.

For the style image, the Gothic ornamentation of the rose window from the Notre-Dame de Paris is selected for connecting with the architecture. The figures collected online also need a further edition of the RGB difference. In figure 10, the color of the line and the background are all removed, and the overall contrast is raised for better visual results in later training.

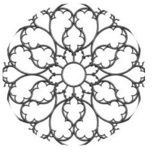

Figure 10. The Style Image, Details of the Rose Window.

With the content plans and the modified style image, content weight, style weight, and their respective proportions in the five layers of VGG-19 are considered in the next step. However, since there is certain unpredictability of the stylized outputs, another experiment process is added to test the possible influence of these feature parameters. To be specific, three plans extracted from the bottom (layer 000), middle (layer 170), and the top part (layer 340) of the spire are chosen for the testing. The content and the image proportion are set as the default value with 20% in each of the five training layers, and consequently, the total value of the content weight and the style weight become the two main impact factors. Moreover, the variable adjustment focuses more on the style weight (β).

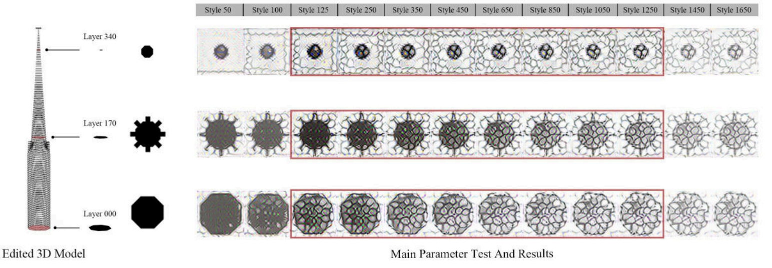

Figure 11. Generated Stylized Plans with Gradually Changed Style Weights.

Based on the parameters conversion, the value of the content weight is fixed by 300. In figure 11, when β varies between (0,125), the initial results would be over-blurred with a large scale of black blocks as the content weight takes up a more significant proportion. While with the increase of β from (125,650), black blocks are gradually neutralized and show the intermediate forms between the content and the style. However, when β reaches 650, the content image starts to have less impact on the outputs. The content interior area is fully-stylized, with the curvature changes slightly when approaching 1250. After β exceeding 1250, the resulting forms are then fixed without much difference. In conclusion, the final optimized ratio between the content weight (α) and the style weight (β) is decided to be (300:125 to 300:1250). Thus, to increase the visual diversity for the later training effects, the style weight is designed to be gradient changed instead of a simple linear increase.

3.2. RECREATION FROM 2D GOTHIC PIXELS TO THE SPIRE OF AI

Following the volume recreation methodology, previous outputs are then converted into a standardized grayscale file. Final effects of a continuous, flowing, and intricate spire are presumed through 3 geometric set-tings: the grayscale cutting rate, closest point number, and the closet point distance.

The three sets of data are all set to be in a balanced situation in the testing. First, after relocating the pixelized points to the original level in the spire volume, different grayscale value (0-255) is tested to create the preliminary view of the hollowed effects. Since the white parts (255) account for a larger proportion in the generated plans, the filtration rate is decided as 75, that the pixels with (0-75) would be retained as the main structure points to continue the next stage of building (figure 12). The closest number domain and closest distance domain (0-10) are all fixed at 5 for reaching the balanced effects between segmented and continuous with rich detailed. The smoothing algorithm is then used with multiple values to replace the voxelization box with spherical surfaces, and the number of the smoothing iteration domain (0-15) is also set at 3. In figure 13, the pixelized volume is transformed into smooth geometries with multiple design options.

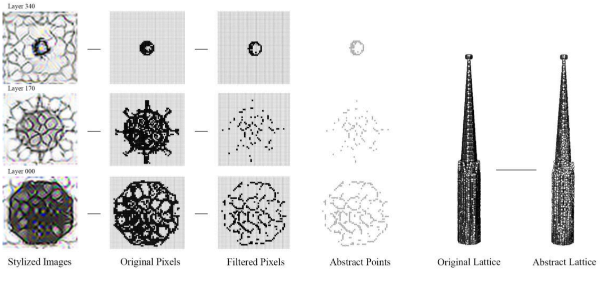

Figure 12. Pixels Filter Process from 2D to 3D lattice.

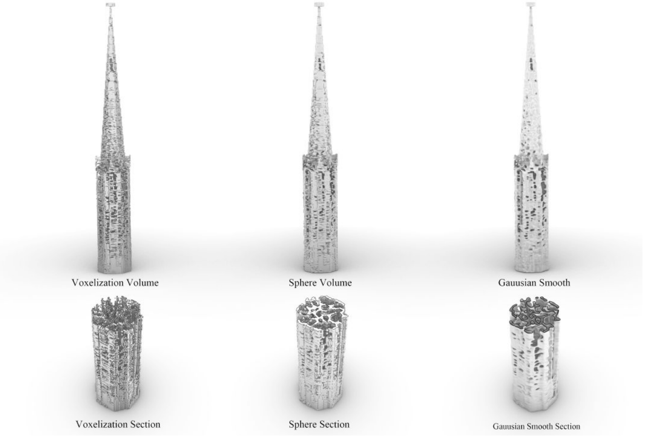

Figure 13. Final Conversion from Voxelization Volume to Gaussian Smooth.

4. Conclusion

Machine Learning Style Transfer is an ideal tool for architectural form-finding. By inputting various content volume, customized data, and feature parameters, this form-finding method can generate diverse 3D forms with styles given by the designers and achieve multiple design effects through the designer's own rectifications in the designed system. It also has a great potential in inspiring the CNN algorithm as the possible development of 3D voxelization Style Transfer.

As an experimental design, this research includes a re-design on the spire of Notre Dame De Paris. In the design improvement aspects, this method digitally and mathematically redefines design strategies as the method that provides the generated form at the early design stage and works to give the designers fresh possibilities of combining different styles with any architecture unit.

Lastly, this voxel-based 3D Style Transfer method provides an inspiring workflow that transfers 2D style images into 3D modelings while keeping the design boundary constant. From the perspective of design practice, evaluating and improving the generated results according to criteria such as structural and aesthetic analysis is the next step for this research.

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T-SNE: A DIMENSIONALITY REDUCTION TOOL FOR DESIGN DATA VISUALISATION

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Abstract. One can argue that data is the 'new oil'. Yet more important than the sheer quantity of data is the question, in the context of architecture and design, how data is represented in design, as this is becoming a more relevant question to the architecture profession. We argue that data, in particular n-dimensional, is often hidden even in BIM models. Hence we propose a new way of understanding the space by (1) generate and integrate space analytics data using space syntax method as well as space usage data and (2) visualise the data using t-Distributed Stochastic Neighbour Embedding (t-SNE), an unsupervised learning and dimensionality reduction tool to help intuitively display high dimensions of data. This approach may help to discover the 'hidden layers' of the building information that may be otherwise omitted. This investigation, its proposed hypothesis, methodology, implications, significance and evaluation are presented in the paper.

Keywords. Data-Driven Design; t-SNE; Machine Learning; Space Syntax.

1. Background, Objectives, Research Question and Outcomes

When Brynjolfson et al (2016) discussed the general-purpose technologies for the second machine age, data (data in the following are digitalised data which once exist in a digital format can be easily shared and distributed for an infinitive number of purposes) ranked together with machine learning, robotics, Internet of Things as core essence for the 21st-century economy. Publications such as *Big Data - A Revolution that will transform how we live, work and think* (Mayer-Schoenberger & Cukier, 2014) back up this argument that data can be understood as the 'new oil'. Undoubtedly this had and will have an effect on business in various sectors all aim to transform themselves into "data organisations" (van Rijmenam 2019) and consequently has and will affect the Architecture, Engineering, Construction

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 631-640.

(AEC) sector. Yet while these data exist and are often already used to inform design decisions, one may ask the question of how we can leverage these data even further to inform decision making? Data manipulation tools are readily available but architectural practices are merely playing a catch-up game with finance and information technology fields, all who use machine learning to understand and leverage data to increase their productivity. The AEC sector, and especially design-focussed aspects have been slow to adopt new technology, and benefit from advances being made in Artificial Intelligence (AI), Machine Learning (ML) and Computational Design. In this paper we aim to address the following objectives:

(a) A brief literature review of t-SNE and space syntax followed by a case study of status quo data approach in architectural design practice. (b) Present a framework involving t-SNE and space syntax and (c) test and discuss t-SNE's application in three different architectural projects.

Based on these observations and objectives one could ask the following two related research questions:

(a) how can we more intuitively observe the increasingly complex information of the building, while (b) compress various n-dimensional information layer into two dimensions in order to assist the decision making process?

The outcomes of the projects is to showcase the application of t-SNE, all in the hope to accomplish the goal of leverage data even further to inform decision making. Finally, we conclude our project and discuss its further implications.

2. Introduce t-SNE and Space Syntax

The literature review discussing Information Visualisation Using Machine Learning Technique, under which t-SNE falls, consists two parts: algorithms and unsupervised machine learning's current architectural applications.

Algorithm 1: Simple version of t-Distributed Stochastic Neighbor Embedding.

Data: data set $X = \{x_1, x_2, ..., x_n\}$,
cost function parameters: perplexity $Perp$,
optimization parameters: number of iterations T, learning rate η, momentum $\alpha(t)$.
Result: low-dimensional data representation $\mathcal{Y}^{(T)} = \{y_1, y_2, ..., y_n\}$.
begin
  compute pairwise affinities $p_{j|i}$ with perplexity $Perp$ (using Equation 1)
  set $p_{ij} = \frac{p_{j|i} + p_{i|j}}{2n}$
  sample initial solution $\mathcal{Y}^{(0)} = \{y_1, y_2, ..., y_n\}$ from $\mathcal{N}(0, 10^{-4}I)$
  for t=*1* **to** T **do**
    compute low-dimensional affinities q_{ij} (using Equation 4)
    compute gradient $\frac{\delta C}{\delta \mathcal{Y}}$ (using Equation 5)
    set $\mathcal{Y}^{(t)} = \mathcal{Y}^{(t-1)} + \eta \frac{\delta C}{\delta \mathcal{Y}} + \alpha(t)\left(\mathcal{Y}^{(t-1)} - \mathcal{Y}^{(t-2)}\right)$
  end
end

Figure 1. Screenshot of Algorithm shows the simplified conceptual workflow of t-SNE (C) Maaten (image adjusted by authors for better representation), 2008.

Algorithms. T-SNE is short for t-Distributed Stochastic Neighbor Embedding, a widely used dimension reduction algorithm in the machine learning field, a dimensionality reduction algorithm for high-dimensional datasets, created by L.J.P. van der Maaten in 2008. Comparing with other dimensionality reduction techniques such as Principal Component Analysis (PCA), K-Means and Sammon Mapping, t-SNE seems to be able to preserve the local structures better while clearly distinguish clusters set of data. In numerous occasions, t-SNE has been successfully implemented to organise large quantity of data. For example, Bell et al. (2015) used a convolutional network to extract features of furniture images into a 256 dimension embedding dataset and used t-SNE to project the embeddings into a 2D map. The 2D embedding map shows that furniture images have high visual similarity with images nearby.

Diagne et al. (2018) used a similar technique to curate thousands of artifact images in Google Art and Culture Experiment. Tautkute et al (2019) combined both image and text embedding of interior images and their contextual information and visualised using t-SNE. Findings showed that several images of different room classes fall into clear clusters. T-SNE is widely used in the field of machine learning for the purpose of visualising the hidden layers of neural network, for its ability of reducing data dimensionality while preserving neighbouring relationships while showing clear clusters.

Unsupervised machine learning's current architectural applications. In CAAD area, Song et al. (2018) used natural language processing technique along with t-SNE to claster nouns in Korean Building Act. The results showed that words related to building elements are clustered to specific areas. However, the author also pointed out the limitation due to the agglutinative nature of korean language, and part of the result is erroneous. Except the instance above, it seems that the implementation of the t-SNE algorithm in the CAAD discipline is still rare. On the other hand, similar unsupervised dimensionality reduction techniques, such as PCA and self-organising maps (SOM) are widely used. Aschwanden (2016) used SOM to project urban neighbourhoods' high dimensional attributes to 2 dimensional space to visualise neighbourhood communities' similarity. Langley et al. (2007) used SOM to map the "urban territories" and identified vacant sites. A similar SOM topological mapping is performed to replicate the forms from point cloud (Algeciras-Rodriguez, 2016) and generate new sculptures forms with several input references. (Algeciras-Rodriguez, 2018).

Space syntax. Space syntax is a set of analytical measures which applies to both building and urban configurations first raised by Hillier and Leaman (1973). Initially, space syntax is constructed using three basic spatial definitions: convex space, axial space and isovist space. These three concepts help to convert geometrical features of the space into analytical features. (Klarqvist, 1976). Today space syntax is widely used in building and urban design, mainly applied at two scales, (i) urban scale to observe the road network grid, land parcel arrangement and possible traffic movements (Major, 2018) (ii) building scale to extract geometrical property of the spatial configuration for analysis (Dursun, 2007, Pramanik et al. 2015). Space syntax may refer to a set a more sophisticated analysis being developed over the last forty years, including Visibility Graph Analysis (Turner et al., 2001), Justified Graph, Axial Maps, Convex Map (Hillier and Hanson, 1984), and Segment Analysis (Turner, 2004).

From the practice side of architecture, we have observed many tools and extensions being created to help architects make design inquiries using space syntax. We have also observed several software extensions that are implemented in Rhino Grasshopper and Revit Dynamo, SYNTACTIC (Nourian et al., 2013), UNA Toolbox (Sevtsuk and Kalvo, 2016), GH Reach Analysis Toolkit (Feng et al. 2019), Isovist View analysis (Wintour, 2016).

3. Observe the status quo data-approach

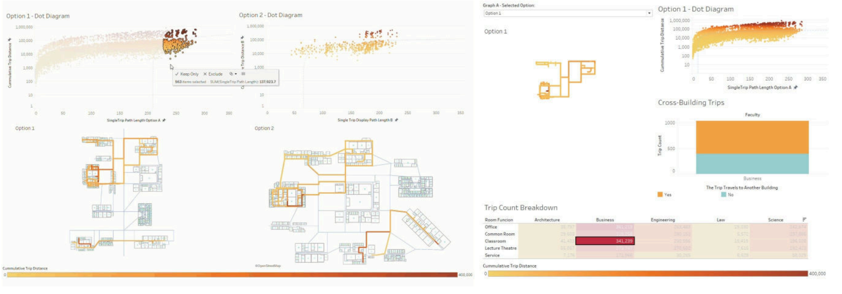


Figure 2. Case Study: Data Visualisation Helps Design Decision.

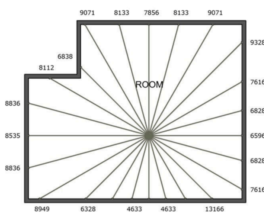
In architectural design practice. Information visualisation is widely used in numerous disciplines and demonstrated its potential value to architectural education and practice (Andrew, 2005; Bermudez et al., 2006). Abdulmawla et al. (2018) integrated statistical data visualisation into the parametric modelling workflow using R language in grasshopper and helped to support parametric design decision making. Aparicio (2018) showcased a construction project management framework at Gehry Technology that involves data mining, analysis and visualisation that helped to accelerate the project delivery time. The sheer amount of data is not the answer to all design queries. Zamora (2011) noted that not all BIM data are geometrical information, and not all project information are BIM data. As object-oriented models, building information models often prioritise the display of 2D and 3D geometry over other details. Furthermore, there should be a way to manage data more intuitively, which included *"having multiple views that present the data simultaneously and consistently help users to search for correlations of divers types of attributes."* (Zamora, 2011). When information stored in project growth exponentially, simplifying sorting and trying to fit a singular framework may not be the most convenient for the users.

How data visualisation tells the story - a case study. The project is based in HDR's D3 research group. This group comprises of a combination of expertise including data scientists, industrial engineers and computational designers. The D3 group provides value in assisting clients to understand their internal data sets through cleaning, analysing and visualising their data for insight which may otherwise have been inaccessible to traditional practice. For example, higher education clients often have large data sets pertinent to space utilisation and population growth relevant to their assets. The motivation of the project is to discuss the campus masterplan layout efficiency with the cumulative trip distance being a key metric. Two possible campus layouts are created with room data injected using an HDR in-house tool. A synthetic external database of 'class and stuff' timetable describes the trip originality, trip destination and frequency over a year. A space-syntax inspired path mapping has been used to generate the geometrical path in the 3D model, and lengths have been calculated and saved with the room information. With data visualisation, the designer can intuitively compare the two master plan layout's overall efficiency, and can inquire different design options with spontaneous feedback, such as: what is the business school's office staff's cumulative yearly trip distance in layout option one? (highlighted in Fig. 2 right)

4. Methodology

T-SNE. In T-SNE, each entry of data is treated as a n-dimensional vector represented as a 'point' in high dimensional space. t-SNE uses an iterative process to locate points' lower dimension representation while maintaining their neighbouring relationships from their higher dimension counterparts. The similarity is evaluated using a stochastic method involving t-distribution. It starts by converting high dimensional Euclidean distances between each data points into conditional probability, and establish a pairwise similarity between the paired points. The cost function is defined as that by using the iterative gradient descent technique, the pairwise similarity between higher dimension and lower dimension will eventually become close.

Room data collection using space syntax - isovist. Peng et al. (2018) used 3D isovist as a way extract geometrical features from the model into numerical values, to train neural networks to classify spaces from different architect. This paper uses a similar isovist data extraction method but in 2D. From each room's central location, 24 rays at equal angles shootout at height of 500mm from the floor, and stops when each of them reaches the first solid object in the model (below left, middle). The length of the resultant lines are recorded and exported for each room.



Point	ROOM 1	ROOM2
1	7856	...
2	8133	
3	9071	
4	9328	
5	7616	
...	...	

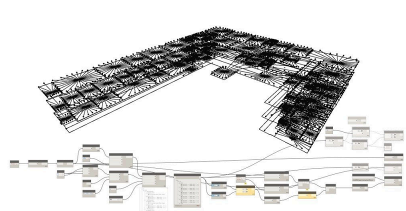


Figure 3. Collect Room Geometrical Data using Space Syntax Inspired Dynamo Script.

The data workflow. T-SNE has many implementations on different platforms. For the projects we are executing, we chose Orange as the data processing and visualisation platform for its interactive data workflow. We first extracted the data into CSV format from Dynamo (Project 1), Revit (Project 1), Grasshopper (Project 2) and Tableau (Project 2) for further processing. In orange, we then merged the data from various sources by identifying a unique feature, then process to cleaning and sampling to reduce the computational demand while retaining the meaningful data structure. Finally, we produce t-SNE plot by fine-tuning the parameters of perplexity and PCA components. Below is an example of the visualised workflow.

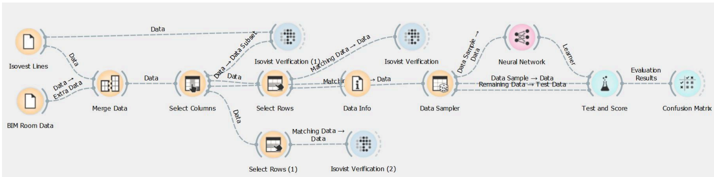


Figure 4. Graphical Representation of Orange Workflow (Project 1).

5. Projects and outcomes

5.1. PROJECT 1 (GEOMETRICAL DATA CLUSTERING)

The first project aims to test if t-SNE may meaningfully cluster room data points with distinctive geometrical features without knowing other room attributes, inspired by Peng et al. (2018). The project is based on an architectural BIM model from an education project designed at HDR's office. The model geometrical feature is extracted using Isovist in Dynamo as is described in the methodology. Other types of room data related to rooms are directly exported from Revit using schedule function, and remain metadata as categorical labels, which are not taken into consideration when performing t-SNE computation. The data are matched by identifying unique room numbers.


Figure 5. left: first run, mid: second run, right: third run.

The first run included all data points available, showing that *'Base Build'* (points in red) department is widespread across the map. After examining the design drawings, the *'Base Build'* room department is discovered to be used to distinguish the task allocation with the other architect, instead of the description of the room's functional category (left image). The *'Base Build'* are thus excluded as it does not represent real contextual meaning in this project. The second run shows the improved clustering of department category.

The third run only chose a few types of rooms that seem to be serving similar functionalities judged by the name. The data points are coloured by room name labels. From the figure below we can observe that most types of rooms are clearly clustered: Experiment Lab (yellow), Chill Out Zone (orange), 150P Conference Room (blue). We may also deduct that *'30P Learning Studio'* (red) may have similar geometrical features as *'30P/30P Learning Studio'* (green), as they are weaved together in the plot. It is noted that even though *'Chill Out Zone'* has similar area as *'30P Learning Studio'*, it has shown a clear cluster (orange).

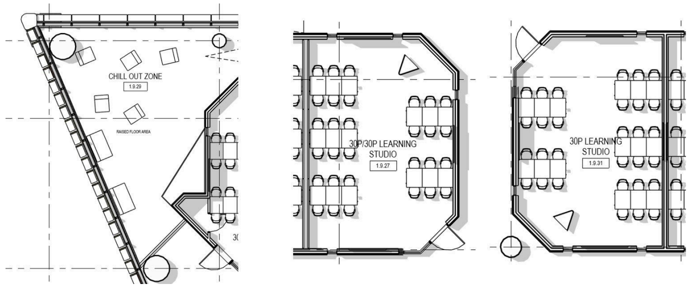


Figure 6. Typical room layouts for: 'Chill Out Zone' (left), '30P Learning Studio' (mid) and '30P/30P Learning Studio' (Right).

From the figure above, we verified our hypothesis that *'30P Learning Studio'* are almost similar to *'30P/30P Learning Studio'*, while *'Chill Out Zone'* have distinctively different geometrical feature. This point is further confirmed by the design architect, that the name difference was to reflect on the operational differences, while the geometrical features remain the same. In Project 1, we have observed that t-SNE effectively sorted the data points into distinctive clusters in a 2D plot. Some data points weaves together may infer due to geometrical similarities.

5.2. PROJECT 2 (ATTRIBUTE DATA CLUSTERING)

The project two further tested the clustering functionality with heterogeneous features and tested its ability of clustering. Project two used the dataset in a synthetic campus layout visualisation project as is mentioned in the section 3 *case study*. The visualisation project used Tableau to visualise two different scenarios that compares time-tabled trip distance and cumulative travel distance, along with other room meta-data such as room function and room faculty belong-ship. The data points are defined as multidimensional tensors with trips with distinctive *'From to ID'*, with features associated with origin rooms and trip itself. The Project 2 uses data exported from the Tableau data visualisation case study mentioned in the previous section. Data features used are: *'Faculty; From Room; SingleTrip Path Length; Cummulative Trip Distance; Room Function; Count; From; Out Building; Path Length; Trip From A; To Trip A Cross Building; Trip To A; Coordinate: X; Coordinate: Y; and Coordinate: Z'*. A random sample of 10% is extracted from the original 87,384 instances.

The map shows clear clustering cross different buildings, faculties and shows local clusters of different room functions. It is also observed that the numerical features are also taken into consideration. The points shows that origin location x, y, z, trip distances and cumulative trip distances are shifting points towards the side of clusters according to their numerical values. By comparing the original map showcased in earlier data visualisation project, we understand that the points are shifted from its original geometrical location to be equally reflecting the distribution of each feature. Project 2 indicates that t-SNE is able to cluster numerical data with homogeneous nature along with categorical data with heterogeneous nature, with each feature being taken into account.

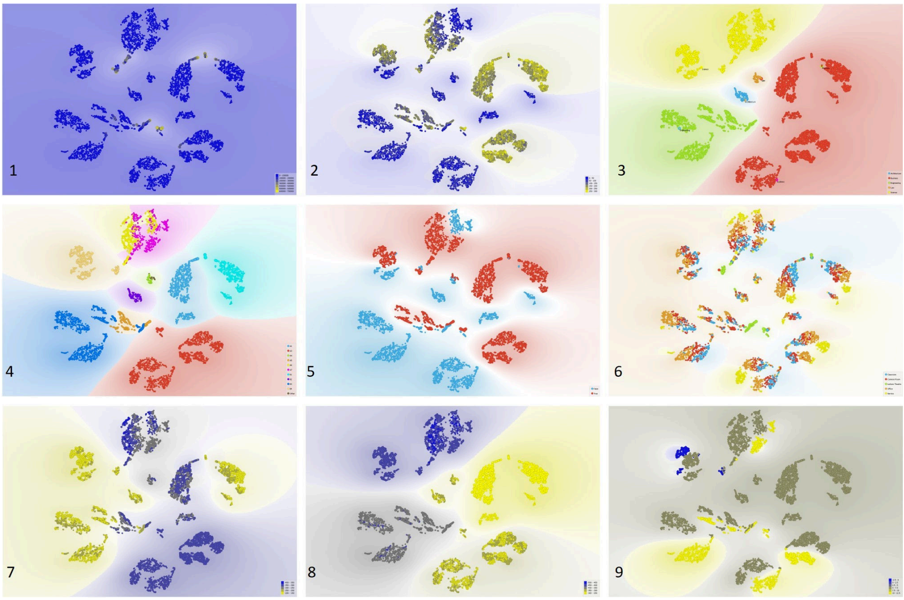


Figure 7. Project two t-SNE plots coloured by different features, namely: 1. Cumulative distance 2. Single trip distance 3. Faculty 4. Building 5. If the trips cross building 6. Room function 7. Origin coordinate X 8. Origin coordinate Y 9. Origin coordinate Z.

6. Conclusion, Significance, Limitations and Future Work

At the beginning of this paper, we asked the question of how we can leverage these data even further to inform decision making. By experimenting with the t-SNE projects above, we have explored new ways to represent design data that could be more intuitive and truthful. Through the work of the two projects, we were able to demonstrate:

(1) t-SNE represent high dimensional data in lower dimensions, in a more intuitive way as graphical plot. What could be done by laboriously viewing several plans, tables or 3D views in BIM can potentially be integrated in one flat graph. (2) t-SNE equally consider all input attributes, from the experiment two we observed that all features are taken into consideration as expected; (3) being able to preserve high dimensional neighbouring relationship means t-SNE may reveal hidden information observed from lower dimensions. As is indicated in project 1, the cluster with two mixed labels indicated that the input data are similar. The algorithm drew its own conclusions on a *'hidden'* piece of information in the model, that two types of rooms are the same in design. Moreover, as an unsupervised learning technique, t-SNE is less intense in data preparation. Being implemented on several platforms and multiple programming languages means t-SNE is easily accessible by anyone.

What are the limitations? Even though t-SNE is powerful in clustering data points, like any information graph, the conclusion is dependent on personal interpretation. Without prior knowledge of the data source, t-SNE cannot guarantee that the conclusion has practical value to the project. Project 1 and 2 suggests that T-SNE can be more useful in combination with other data mining, processing techniques. In a similar way of the above limitations, t-SNE may also be limited by a poor source of data, messy dataset and lack data interoperability (t-SNE cannot read .rvt or .ifc file). The algorithm itself has certain limitations. T-SNE performs a stochastic process, which may generate slightly different results each time. Comparing with PCA, the iterative process of t-SNE has made t-SNE computationally expensive. From a practical perspective, this means t-SNE is limited in the amount of data and timeframe this can be performed.

Thus we position our future works in: (i) study the differences between t-SNE and other unsupervised learning models using the same dataset in the architectural context. (ii) further investigate how t-SNE may inform the design decision-making process by applying t-SNE in a broader range of visualisation tasks in architectural design. (iii) find suitable data processing techniques and workflow in architecture to ensure meaningful plot can be achieved with the least amount of computational resources is needed to perform a single task. (iv) Apply t-SNE in combination with other Machine Learning techniques to further leverage the abundance of data in the AEC world. We can predict future designer use case for t-SNE could be: (i) finding data points (rooms, objects, buildings) of similar nature without checking details of each points (ii) presenting design data in an all-in-one graph (iii) cross-validate dataset that may have missing information by discovering features or relationships that are not directly established. Thus we should conclude that, through the exercise of applying t-SNE in the architectural data visualisation process, we have gained an understanding of how such machine learning technique may help architects to leverage the value of data in the age of the digital in the future.

Acknowledgement

This work was carried out as embedded research at HDR Inc. in Sydney, Australia. The lead author wishes to acknowledge the sponsorship of HDR Architecture Scholarship and intellectual contributions from the following people/group: Garth Highland, Graeme Spencer, Matthew Goldsberry, Scott Foral, Stefano Cottini, and the HDR D3 Group.

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THE AUGMENTED MUSEUM

A Machinic Experience with Deep Learning

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Abstract. Today we witness a shift in the role with which museum used to play – from one that was simply a spatial container filled with physical artworks on display, to one that is now layered with the digital/online version of the artworks themselves. Deep learning algorithms have become an important means to process such large datasets of digital artworks in providing an alternative curatorial practice (biased/unbiased), and consequentially, augmenting the navigation of the museum's physical spaces. In collaboration with a selection of museums, a series of web/mobile applications have been made to investigate the potential of such machinic inference, as well as interference of the physical experience.

Keywords. Machine Learning; Deep Learning; Experience Design; Artificial Intelligence.

1. Introduction

The digitization of museum art collections is amongst the most invested pursuit in recent years. Physical art objects are not only digitally archived, but virtually situated within their respective scanned museum spaces and interactively curated and experienced by users online. This situation poses a contemporary challenge to the role that architecture used to play, from one that was traditionally a container of physical objects and humans, to one that is now surrounded by a proliferation of machine curated virtual objects/spaces and human avatars. In the case of the museum typology, the selection and arrangement of artworks, as well as, their curated itineraries become highly contested, where deep learning algorithm becomes the main workhorse used by tech giants to process large datasets of artworks in providing a machinic point of view (biased/unbiased) to the curation of objects; and in turn the navigation and perception of their architectural spaces. Rather than accepting the loss of architecture's physical relevance, we argue that architecture is in fact the very physical substrate for generating novel curatorial experiences and spatial itineraries. In collaboration with a selection of museums, a series of web/mobile applications have been made to investigate the relational interplay among specific users, art works and museum spaces, in generating alternative forms of museum experiences.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 641-650.

Museum studies involving the empirical analysis of visitor experiences that relates to the spatial design of museums are surprisingly limited (Volker & Tröndle, 2012), despite the fact that the earliest behavioural studies using spatial tracking of museum visitors dates back about a century ago (Robinson, 1928). Research on constructing a predictive model of museum visitor experience only become more apparent with the influential publication of John Falk (2009). More recent research along this line of inquiry is the 'eMotion' project that incorporates tracking technologies to spatially map visitor movement in order to understand their museum experiences (Volker & Tröndle, 2015). However, none of these aforementioned works takes on a projective approach that lends itself to the redesign of museum experiences. Likewise, the generative use of machine learning on offline/online presence to reimagine a new form of machine augmented visitor experience remain unexplored.

The experience of museum space presented in this paper is understood as a complex layering of both physical and virtual spaces - one that is continually augmented by the sensing and learning mechanism of today's machine learning models. With the increasingly ubiquitous access to pre-trained deep learning models, whether in the form of online APIs or open-sourced frameworks, prototypes could be quickly developed without the need for large amount of training data. In this paper, four different projects have been developed and spatially contextualized according to their respective museums and art collections, while significantly leveraging on those aforementioned deep learning infrastructures, to quickly speculate on the ways in which architectural space could informed and be informed by both its human participants and non-human artefacts.

For example, the experience of a museum today is increasingly a function of its instagrammability for the millennials. "Instagrammability" is a project that trains a convolutional neural network to predict the scores based on the visual features of artworks in relation to its on-site spatial configurations. Another project "Face2Face" uses deep learning to carry out sentiment analysis of the museum visitors, based on the idea that the artworks themselves could be scored against a list of human emotions. Thus, the curation of the artworks is no longer simply dependent on the visual features (e.g. colour or composition) or historical features of art genres, but the immediate emotional effects it triggers on humans. The project "Immersive" allows visitors to generate their own museum trails by choosing a complex combination of parameters, such as, word frequency, colour histograms and artistic techniques. The "Artswap" project allows users to have their own portrait, not only overlay, but blend seamlessly onto Google's 360s photographs using deep generative models; and in turn generating an alternative and customized virtual gallery for every user. Finally, the last project is an application that provides a voting system for crowdsourcing of comments and scores the value of each exhibition artefact accordingly. It then uses the scores as the basis to generate new spatial configuration according to their popularity.

This paper aims to address three main research questions: (1) How would architectural designs incorporate museum curatorial practice that are based on a machinic evaluation of artworks? (2) How would architectural designs reconsider the augmented aesthetics values generated by crowdsourced visual and social data? (3) How would architectural designs be inclusive of multiplicities, in both its physical and virtual representations. The collective contribution of these design research projects is in the formulation of what might constitute a museum experience that is now enmeshed in a complex network of machinic curation.

2. Projects

2.1. INSTAGRAMMABILITY

Concept. (See Figure 1.) Instagram has not only changed the way millennials capture and share photography, but it has redefined where people decide to spend their time, and how they interact with the world around them. Nowhere has the effect of Instagram been more strongly felt than at Museums, where instagrammable exhibits have driven record visitorship (Pardes, 2017), and caused many, previously non-camera friendly, institutions to revise rules around permitting photography. For millenials, instagrammability is now an essential part of a successful museum experience. This project explores what it means to take an instagrammable photo in the context of Lausanne museums, and strive to enable museum curators and visitors alike to understand the instagrammability of their own museums and photos. An interface to input and score a photo for instagrammability has been developed and allows any user to take or upload a photograph from his/her desktop or mobile web browser, and receive a numerical score from 0 to 100 predicting the instagrammable quality of the photograph. Predictions are made based on a predictive model generated from training a convolutional neural network with 7,704 Lausanne museum-related images, each of which are scored on the ratio of Instagram Likes over Followers.

Data. Web scraping is used to download all the Instagram images that are publicly available online and tagged with the top 7 most popularly instagrammed museums in Lausanne, namely Le Musée Olympique, Collection de l’Art Brut, Musée de design et d’art appliqués contemporains (mudac), Musée de l’Elysée, Espace Arlaud, Fondation de l’Hermitage and Musée Cantonal des Beaux-Arts. A total of ten thousand images of various sizes, along with metadata on the Likes and Followers, are collected. The images are further cropped and resized to a standard 224 x 224 pixels before being used as training data for the deep learing model.

Pre-trained model. The key task is to map images to instagrammability scores. This can be viewed as a regression problem, since the goal is to predict a value from a continuous set. Transfer learning is used by fine-tuning a pre-trained model (ResNet50), thus leveraging on the pre-initialized weights of the model previously trained on 14 million ImageNet images. ResNet50 differs from traditional sequential models in its use of heavy batch normalization and “identity shortcut connections” in which one or more layers are skipped. However, only the last of the model’s 50 layers is being trained, with batch size of 32 and a sigmoid activation function, for this image regression problem. The validation mean squared loss was 0.2094.

Evaluation. What are the main features that improve the Instagramability of those museum photographs? Or, are there specific combination of museum display configurations that might augment one's interest in an artwork as a result of its instagrammable score? By looking at the top 25 liked photographs for example, it is discovered that images with strong elements of perspective or depth have more success. In addition, photographs with easily recognizable subjects or that are less personal are also more often liked. Not least, bright or harmonious colours that enhance the beauty of the region of Lausanne have a positive impact.

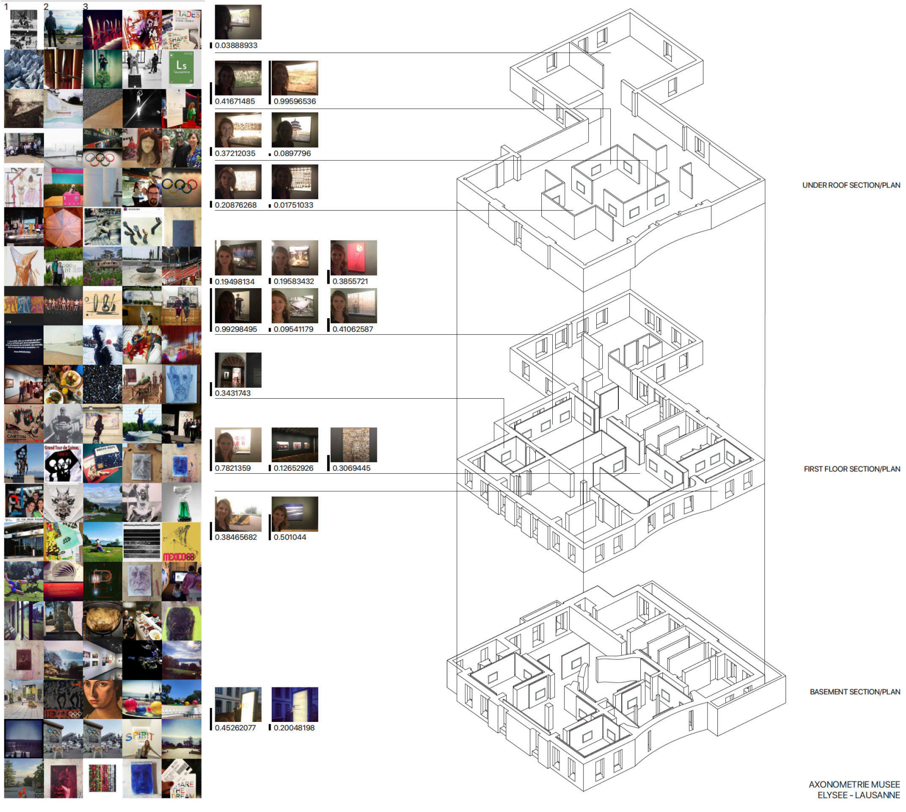

Figure 1. (Left) Most instagrammable museum photographs ordered from top to bottom. (Right) Axonometric view of Musée de l'Elysée with the position of selfies taken and scored using the proposed prototype.

2.2. COMBINABILITY

Concept. (See Figure 2.) Exhibitions are often curated according to a theme that directly dictate the positions of the artworks and consequently the itinerary of the visitors. In other words, a single narrative for all visitors. Could a diversity of dynamically customized itineraries be possible without repositioning the physical artworks? How might these personalized sub-narratives be constructed by leveraging machine learning's predictive capabilities in image-to-concepts translation, as well as image-to-colours search? The project demonstrates the possibility of combining different themes to generate (and modify) personalized itinerary.

Data. The Fondation de l'Hermitage museum has been chosen as the site and web scrapping is used to data mine all the paintings from its permanent collection, namely the digital images and other meta-data. In addition, the physical positions of all the currently exhibited paintings are also recorded on site.

Pre-trained model. The first task is to train a deep learning model capable of generating key descriptive words/concepts relating to the image and its constituent elements. Several deep learning models (as a service) currently exist online that provide such a feature, including Google Cloud Vision and Clarifai. Clarifai is eventually used in the prototype to take an image and output a list of possible words with their respective probabilities. Once these words are obtained for each painting it is possible to build a wordcloud, for one painting or for all of the painting by merging the words together, thus facilitating itinerary generation with word inputs. The second task is to use unsupervised clustering to annotate an image by its dominant colours to facilitate itinerary generation with colour selection inputs. The K-Means algorithm (applied on colour space) is used to extract and then map each painting to 3 dominant colours. Thus, when the user search for a colour, only painting labelled with colours that are not too "far" in Euclidean RGB distance are kept for the itinerary generation.

Evaluation. The app allows mixing of themes by first representing each of them as a set and by the set operations of intersection/union/difference/delete, different combinations can be generated. The process of theme selection, path generation, path modification serves the basis for augmenting the sequential experience of the paintings in space and time.

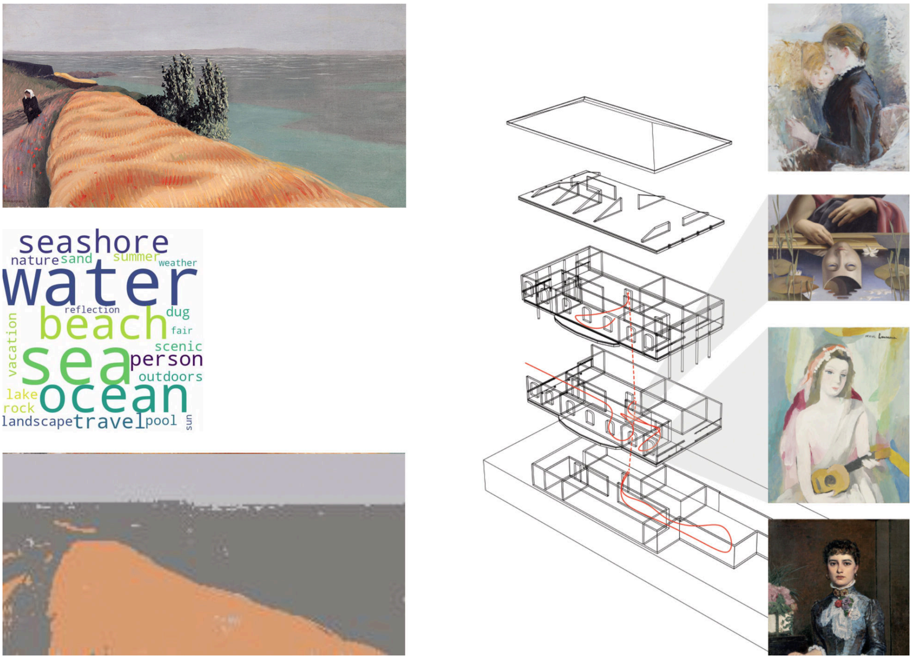

Figure 2. (Left) Image-to-Concepts translation and Image-to-Colours extraction. (Right) Part of the app interface showing an axonometric view of the museum spaces and the paintings to be visited. User could also modify/add/delete any of those paintings within the generated itinerary.

2.3. REVERSIBILITY

Concept. (See Figure 3 & 4.)The aim is to analyze and record the emotions triggered when viewing different artworks. It is as if the paintings could see the visitors. With such understanding, it is possible to generate specific paths according to users' own preferred sequence of emotions. Likewise, curators could use the same information to craft possible sequence of emotions to be evoked when visitors view the paintings.

Data. Musée de l'Elysée's exhibition called Le théâtre des apparences by artist Liu Bolin has been used as the source dataset for the proposed prototype. Apart from web scrapping all the artworks' digital images from the museum website, 10 human subjects have been asked to provide the initial dataset of facial expressions. Each subject is asked to sit in front of the computer and to watch a sequence of artworks for 2 to 3 minutes. The sequence of painting should resemble a possible museum path, it is generated randomly for each person to avoid the possibility that an artwork could potentially affect the emotion of the subsequent ones. Each artwork is showed for 6 seconds during which the web camera of the computer records 4 pictures (each one every 1.5 seconds) to detect the emotion trend of an artwork. With the library OpenCV, the experiment starts when the user presses the corresponding button on the homepage of the web app prototype. Every time a new artwork is showed, an ajax request is made. The back-end then records 4 pictures of the painting and sends a GET request to Microsoft Azure to get the corresponding emotions recorded.

Pre-trained model. The deep learning facial recognition software (Microsoft, 2018) called *Azure Face API* is thus used to analyze all the recorded images collected via the aforementioned web camera. With this information, all the artworks could be rated according to their respective aggregated scores. In fact, it is now possible to also compare (side-by-side) human subjects and paintings in terms of their emotional resemblance. Using PCA (principal component analysis) to do dimensionality reduction both entities could be represented on a 2D plot, where the distance between any two data points being a metric of their emotional likelihood. As inputs to the PCA plot, all the emotional vectors from the art pieces and the mean of all persons' reactions are used.

Evaluation. By emphasizing the implicit emotional response of visitors towards the artworks in view, it is possible to consider artworks beyond its material presence, but bestow an emotional dimension on them. This new information would then serve as a basis for generating itineraries that in turn alter the museum experience of the visitors.

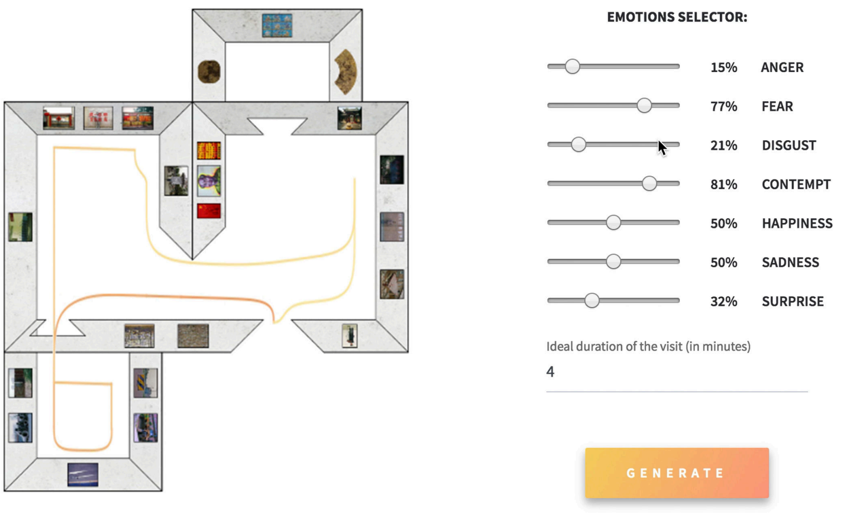

Figure 3. An instance of a generated path based on the set of emotion inputs.

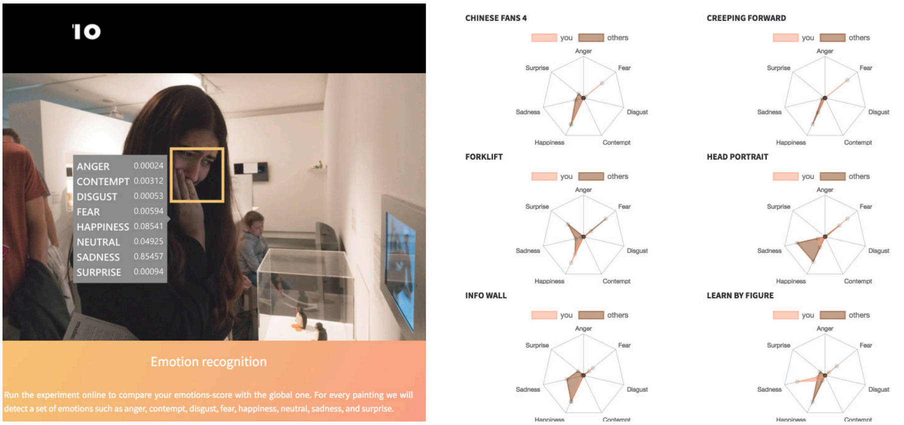

Figure 4. (Left) The facial recognition algorithm used. (Right) Each artwork stores and aggregates the emotional responses of all viewers (yours and others).

2.4. SWAPPABILITY

Concept. (See Figure 5.) How might DeepFake, a term used to describe face swapping algorithms based on deep learning models, be appropriated for an augmented museum experience? To what extent is DeepFake even cultural acceptable (Porter, 2019) when contextualized for museum? The project aims to speculate on its potential to augment the curatorial logic of the museums with that of the visitors.

Data. The 360 camera Ricoh Theta is used to take omni-directional pictures of all the exhibition rooms at the Fondation de l'Hermitage museum. This virtual environment is generated where users could visualize their own online version of Fondation de l'Hermitage where the portraits in the original paintings could be morphed into that of their own faces.

Pre-trained model. Face++ is a set of online APIs authored by Chinese startup company megvii. The company specializes in state-of-the-art AI technologies related to face recognition. One of the API functionalities is face merging between images. In addition to the merging capability, its in-built face detection algorithm also worked effectively on those museum portrait paintings.

Evaluation. The use of DeepFake on cultural artefacts and spaces might seem irreverent to some. Yet, it manages to expand the range of possible engagement between artworks and visitors. The proposed mobile app's live face detection and live QR code reading further facilitate a unique real-time overlapping of both physical and virtual spaces during the face swapping interactions.

Figure 5. (Left) Catalogue of generated face swaps with decreasing degree of synthetic realism. (Right) 360 views of actual gallery space with face-swapped paintings.

3. Conclusion

The series of four projects is to demonstrate the ways in which deep learning technologies might be used in augmenting the museum experience. In particularly, each of the projects represents the respective notion of instagrammability, combinability, reversibility and swappability. Instagrammability suggest that the virtual 2D composition of a space is often times more critical than its actual physical 3D spatial configuration. Combinability suggests that through mixing and matching of selection filters, several new museum itineraries can be generated. Reversibility hints on the potential of humanizing artworks in constructing new virtual and physical interaction at the museum. Swappability speculates that the virtual manipulation of artworks could even push cultural acceptance of machine learning technologies to its limits, with the museum architectural space remaining intact physically and virtually. Although these simple (or at times banal-looking) design experiments discussed have only touched upon four out of the potentially infinite number of strategies in using deep learning-based technologies to augment museum experiences, one could now at least attempt to address the three research questions stated in the introduction of the paper. Accordingly, the (1) machinic evaluation, (2) aesthetics augmentation and (3) multiple representations of artworks are indeed inevitable informational layers of today's museum experience. Whether they enhance or complicate the physical spaces in which the artworks are placed depends on the designer's ability to draw relationships among them that could then enable a highly personalized visitor experience. However, these machinic layers might best be understood as simply experiential filters, analogous to those Instagram filters. Without the spatial (physical or virtual) reference to a museum architecture, these filters would remain generic and uncontextualized. In other words, architecture continues to validate its role by asserting its symbolic reality to anchor these machinic augmentations spatially.

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A RAPID BUILDING DENSITY SURVEY METHOD BASED ON IMPROVED UNET

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Abstract. How to rapidly obtain building density information in a large range is a key problem for architecture and planning. This is because architectural design or urban planning is not isolated, and the environment of the building is influenced by the distribution of other buildings in a larger area. For areas where building density data are not readily available, the current methods to estimate building density are more or less inadequate. For example, the manual survey method is relatively slow and expensive, the traditional satellite image processing method is not very accurate or needs to purchase high-precision multispectral remote sensing image from satellite companies. Based on the deep neural network, this paper proposes a method to quickly extract large-scale building density information by using open satellite images platforms such as Baidu map, Google Earth, etc., and optimizes the application in the field of building and planning. Compared with the traditional method, it has the advantages of less time and money, higher precision, and can provide data support for architectural design and regional planning rapidly and conveniently.

Keywords. Building density; rapidly and conveniently; neural network.

1. Introduction

With the fast development of urbanization in developing countries, the boundaries of cities are changing with each passing day. The rapid expansion of urban fringe also brings many problems, such as energy crisis, heat island effect, traffic jam and so on (Ho et al. 2014).

To deal with these challenges, building density is an important parameter in architectural designing and urban planning. Building density indicates the ratio of the coverage of the buildings' footprints to the size of the area of interest (Kajimoto, Susaki 2013). In terms of energy, urban planners are very interested in the solar energy development potential of the city, which can be used as a reference for urban planners. In Li's work (Li 2019), roof area was used to assess the solar potential of the city, and the roof area can be directly calculated from the urban building density. In Yang's work(Yang 2019), the relationship between block form and building energy consumption is studied by using the city's figure-ground relationship, as *Figure 1* shown. On the issue of heat island, many

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 651-660.

scholars (Bindajam 2019; Luo et al. 2014; Giridharan et al. 2017) have found the relationship between building density and heat island effect. When designing buildings, if we know the large-scale distribution of building density around, we can evaluate the intensity of heat island effect of buildings, so as to optimize the design of heat effect of buildings. In terms of traffic, the building density distribution map of urban area is an important reference for urban planners to evaluate and optimize the traffic line (Bu et al. 2006), and it is also one of the bases for architects to select the main entrance and exit orientation of buildings.

Figure 1. Figure-ground relationship used in Yang's work(Yang 2019).

Easy access to a wide range of building density information requires a well-designed and up-to-date urban management system, which is not available in all rapidly urbanizing areas. In order to obtain the building density information that cannot be directly inquired, other than manual research which is time-consuming and expensive, it is more common to extract building density from remote sensing images. When the area of interest is very small, building information extraction can be interpreted manually, however, a lot of human resources will be consumed if it is a large area. So, when the area of interest is large, it is necessary to extract building density automatically for the quickness and cheapness.

Generally speaking, there are two kinds of approaches for automatically extracting building density. One is traditional expert system, which According to the characteristics of remote sensing images and regions of interest, a series of graphics processing is applied to extract spectral information and geometric information of edges and corners of images. Wang (Wang et al. 2013) developed a novel approach for building detection using corner detection, segmentation and adaptive windowed Hough Transform is presented. The other is to use machine learning, which has recently emerged. Zhang (Zhang et al. 2017) presents a method for the quantitative estimation of building density using a support vector regression model to establish the relationship between building density and the features extracted from the image, including spectral, morphological, and textural features. The data used in Zhang's study were remote sensing images provided by the geoeye-1 and worldview-2 satellites, which required not only remote sensing images of the visible band but also near-infrared band. In Xu's (Xu et al. 2016) research, an adaptive volume scattering model for the model-based decomposition is proposed in this study to help detect the building area. Together with the support vector machine algorithm, marker-controlled watershed algorithm and regression analysis, the ratio of building density can be calculated more precisely and comprehensively. In Xu's method, not only the optical image provided by Google earth, but also the span image of PolSAR is requiredThe common problem faced by existing researchers is that the algorithm of automatic building extraction has poor adaptability to different regions and low extraction accuracy.

In traditional expert systems or machine learning methods, if we want to improve the extraction accuracy, we need to combine more information, such as LiDAR, DSM or multi-spectral information (Xu et al. 2018), and also need to combine satellite parameters to correct remote sensing images. However, it is usually more difficult to obtain these more diverse remote sensing images, which need to be purchased from satellite companies or use aerial photography equipment to map altitude data.

In this paper, we propose an automatic building density extraction method based on depth neural network. This method does not need to use multispectral satellite images or high-definition aerial photos. It is very convenient to obtain satellite images of the target area from Google Earth or Baidu map and other platforms. On the premise of fast and convenient, the relative area error of our method is less than 3%.

2. Method

In order to solve this problem, this paper uses the method of deep learning to extract building density from ordinary satellite images (which can be easily downloaded from Google Earth) using deep learning image recognition model. Overall, the method in this paper is divided into four steps: the first step is to prepare data sets, the second step is to train models with prepared data sets, the third step is to evaluate the performance of models, and the fourth step is to extract building density information with trained models. (*Figure 2*)

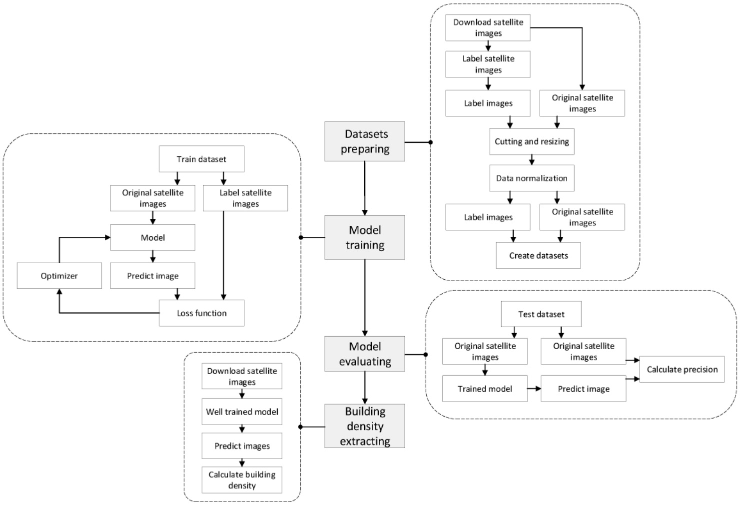

Figure 2. Method flow chart.

2.1. DATASETS PREPARING

The data preparing stage is mainly divided into downloading satellite map, manual labeling, data preprocessing and data set packaging.

The model of building density extracted from open source images needs to be trained by open source image. In this paper, we train the model with satellite images of Google earth. Enough sample data is necessary to train parameters of the model if a working well model is wanted. We choose Suzhou, a Chinese city, as the data collection area. The terrain is plain, and the main building types are industrial buildings and residential buildings. We downloaded 315 high-definition satellite images from Google Earth, each with a size of 4096^2 pixels and a resolution of 0.3 meters, and label these pictures manually as *Figure 3* showed. The 4096^2 pixels satellite image is too large for the deep neural network and needs further cutting. But can't divide the pictures too small to prevent a lot of buildings from being broken into pieces. After experiments, we found that it is appropriate to divide 4096^2 images into 64 images of 512^2pixels. Through further experiments, it is found that resize 512^2pictures to 256^2does not lose accuracy and can greatly improve the training speed of the model. Before packaging pictures into data sets, image data need to be normalized to the range of 0-1 to make training editing easier. We pack the picture set into a whole binary format file. The advantage of this is that it can reduce the burden of the trainer CPU, because the CPU performance is the bottleneck in the training process.

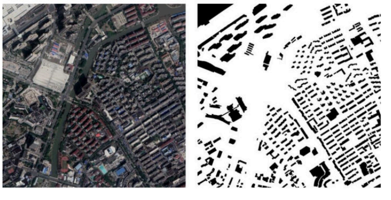

Figure 3. Satellite image (left) and label (right).

2.2. MODEL AND LOSS FUNCTION

In the model of deep learning, model structure and loss function are the two most important elements. The model structure represents the process of model calculation, and the loss function represents the goal of the model.

The model structure of this paper is based on Unet. Unet was first proposed by Olaf Ronneberger(Ronneberger et al. 2015). It was first applied to medical image processing in order to recognize tumors automatically. The model structure we used in this paper is shown as *Figure 4*. Satellite images are input into Unet from the inputs end. After a series of convolution (Goodfellow et al. 2016) operations, the building probability distribution map, i.e. a bitmap, will be output at the outputs end, each pixel is a number of 0 to 1 which represents the probability that the pixel is a part of building.

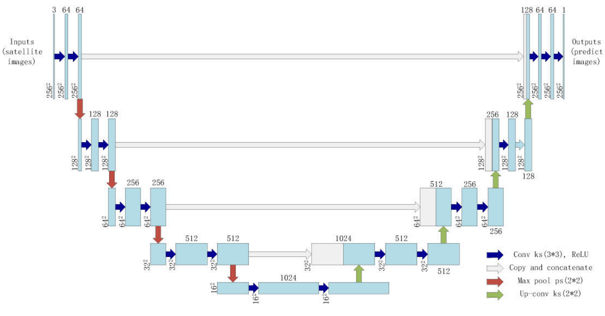

Figure 4. Structure of U-net.

By inputting the satellite images of the test dataset into the trained Unet model, we can get a probability map with value of 0 to 1. By setting less than 0.5 as non-building and greater or equal than 0.5 as building, we get a postprocessed building map. Then compare with the corresponding training set label. Here are some commonly used model performance evaluation indicators in the field of graph recognition.

In this study, the model is improved by using the improved loss function. The basic Unet is applied to medical image segmentation, the medical application scene is obviously different from the architectural scene. In image classification of Y/N problem (in our model, is building or non-building), the loss function of basic U-net is binary cross-entropy. In our application of building density extraction, compared with medical application, there are some different requirements. We are not only concerned about whether it is a building, but also about the accuracy of total area extraction of buildings. So, we combine binary cross-entropy (BCE) and error of area (EOA, defined as Formula 2 shown) in loss function, use α to control the weight of the combination, as shown in Formula 1. In our study, it is found that α = 0.2 is appropriate. The advantage of this loss function is that it improves the accuracy of building area while considering the accuracy of overall building identification.

$$L = \cdot BCE + (1 -) \cdot EOA \tag{1}$$

$$EOA = \frac{|\sum predict - \sum label|}{area_{\text{image}}} \tag{2}$$

2.3. MODEL TRAINING

The model was trained with the data set we prepared, and for comparison the basic Unet model was also trained with the data set we prepared.

In the training process, it was found that the model is difficult to converge with our combined loss function, as *Figure 5* shown.

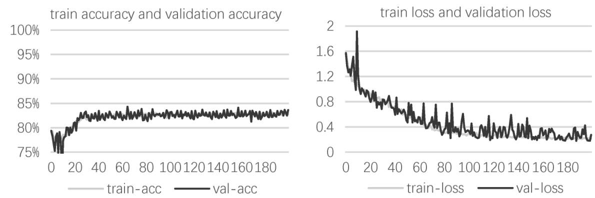

Figure 5. Direct training with combined loss function.

To solve this problem, a redesigned training process was proposed. The two-step training method was applicated in our research. *Step.1* we used BCE loss function to train to the optimal result, and then used our improved loss function to continue training. *Figure6* shows the loss and accuracy in training process with BCE, after 200 epochs training, the result has been optimal.

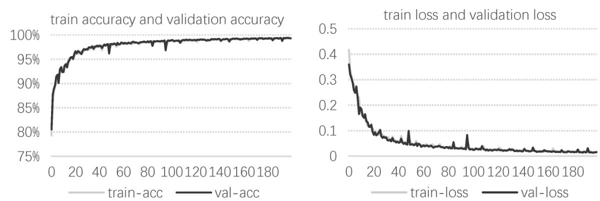

Figure 6. Accuracy and loss of train and validation in step.1.

Step.2 after we finished training with BCE, we used our improved loss function to train 50 epochs.

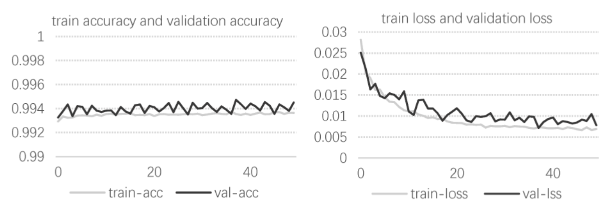

Figure 7. Accuracy and loss of train and validation in step.2.

3. Validation and Result

The test dataset is satellite images and labels of Jiading District, Shanghai, which is a typical plain city. The building types include industrial building, residential building, office building and commercial building, as *Figure 8* shown. The total area of the test set area is 50.28 square kilometers, and the total building area marked on the label is 10.91 million square meters.

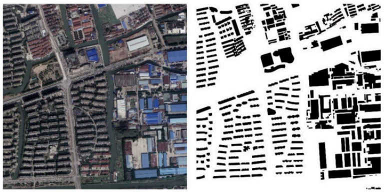

Figure 8. One of satellite images and labels in test dataset.

In this paper, F_1score and relative area error were used to evaluate the performance of the model. F_1score is a common evaluation index in the field of image classification, defined as *Formula 3* shown. Relative area error is defined as the difference between the real building area and the predicted building area divided by the real building area.

$$F_1\text{score} = 2 \cdot \frac{\text{precision} \cdot recall}{\text{precision} + recall} \tag{3}$$

The following *Figure 9* shows the model evaluation results of the basic Unet and improved model. It can be seen that our method can recognize the buildings in the cities in the plain area without using the multispectral satellite map, only using the publicly downloaded satellite map, and achieve a good result of F1score over 86%. Especially for the recognition of building area, we improved the model based on the basic Unet, which reduced the relative area error drop from 5.84% to 2.96%, while the F1score slightly increased as 86.42% to 86.73%. As for the building density, the test area labeled that the building density is 20.82%, the building density predicted by the basic Unet is 19.60%, and the building density predicted by improved model is 20.20%.

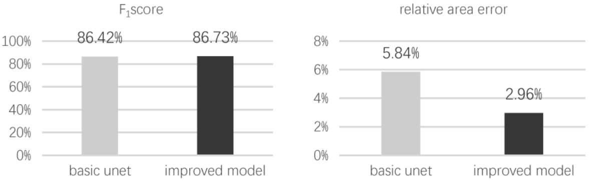

Figure 9. F1score and relative area error.

Some predict building images predicted by improved model compared to the satellite/ label images are shown in *Figure 10*. It can be seen that our method can maintain the high-precision recognition of building area, and the recognition of building shape is also good.

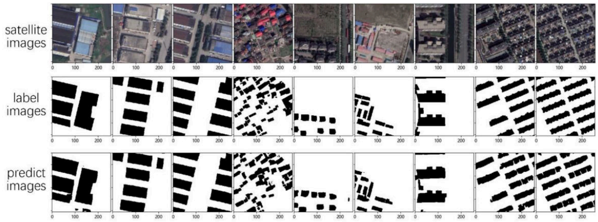

Figure 10. Satellite images/ labels and predict images.

4. Further validation

In the test dataset above, our model performed well in the application of modern cities in plain areas. Further, we validated the performance of our model in very different terrain and building shape areas. For further verification, we chose a region in Chongqing, China. The terrain of this area is mountainous, and the building types are industrial buildings and residential buildings. The form and layout of the buildings are quite different from the plain modern city we used for training.

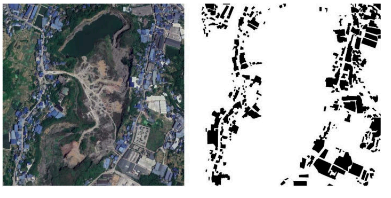

Figure 11. One of satellite images and labels in Chongqing dataset.

As results shown, the prediction of building density is 11.12% and 11.58%, respectively, compared with 12.47% of the labeled ground truth. The relative area error of basic Unet is 10.77%, and that of improved model is 7.10%.

5. Application

The model was applied to the building density prediction of Yangpu District, Shanghai, as shown in *Figure 12*.

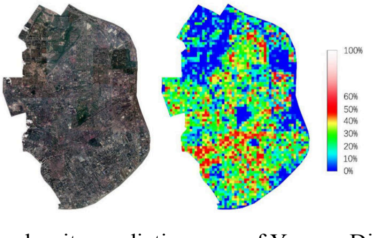

Figure 12. Building density prediction map of Yangpu District, Shanghai.

The total area of this area is about 60 square kilometers. After the satellite image were downloaded from Google Earth, it took less than a minute for our model to predict the building density map. As can be seen from the building density map, the building density of Yangpu District is mostly distributed between 20% and 60%.

6. Summary

A method to quickly extract large-scale building area / density based on publicly downloaded satellite images was proposed in this work. Compared with the existing methods, our method could extract large-scale building area / density more quickly and conveniently, and the error rate of area recognition in our 96 square kilometer area test set was less than 3%.

In this study, the following results were achieved.

1. A dataset based on publicly downloading satellite images was set up, and based on this data feature, the classic model of deep neural network Unet was used to get the basic model of this method.
2. For our goal of building density extraction, the basic model was improved. To solve the problem that the improved model was difficult to train, the two-step training method was used in training process.
3. The validation results of our model were shown, both the F_1score of the basic model and the improved model were over 86%, the relative area error of the basic model was 5.84%, and the improved model was further reduced to 2.96%.
4. Our model was further validated in areas with very different terrain and architectural forms. The F_1score was 81%, and the relative area error was 7.10%.
5. The experiment of building area prediction for an area of 60 square kilometers was carried out, and the running time was less than 1 minute.

7. Future work

In completed studies, some achievements have been made, but there are still two shortcomings. The first is the single type of training data set. Although it can achieve high accuracy in the same type of areas, it can only reach an acceptable level in other areas with completely different types. The second is in the application of some architectural design and planning, we hope to get the area/ density of a certain type of building in a large area, such as industrial buildings, residential buildings, even specific to low-rise residential buildings or high-rise residential buildings, but our current method can't distinguish different types of buildings.

In the future, these two problems will be our research direction. On the one hand, the training data set with more types will be established, so that the model can achieve high accuracy in a variety of terrain and building forms. On the other hand, we will build data sets to distinguish different types of buildings, and train models to distinguish different types of buildings.

In addition, the automated estimation of building density also provides data support for the machine-learning-assisted building design currently under exploration. In the subsequent research, the data interface of building density will be introduced in the machine-learning-assisted building design process, so as to optimize the obtained results.

Financial Disclosure: The research was supported by a project of Natural Science Foundation of China titled “An internet-plus-based approach of crowd simulation for public buildings” (no. 51778417), a project of Bei Chuang Teaching Supporting Fundation of University Innovation Fundation of Science and Technology Development Center of Education Ministry of China titled “Multi-headwear virtual collaborative construction platform” (no. 2018C01045), a key reform project for undergraduate education in Shanghai in 2019 titled “Exploration on a self-motivated talent cultivation method based on virtual curriculums”.

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3D ARCHITECTURAL FORM STYLE TRANSFER THROUGH MACHINE LEARNING

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Abstract. In recent years, a tremendous amount of progress is being made in the field of machine learning, but it is still very hard to directly apply 3D Machine Learning on the architectural design due to the practical constraints on model resolution and training time. Based on the past several years' development of GAN (Generative Adversarial Network), also the method of spatial sequence rules, the authors mainly introduces 3D architectural form style transfer on 2 levels of scale (overall and detailed) through multiple methods of machine learning algorithms which are trained with 2 types of 2D training data set (serial stack and multi-view) at a relatively decent resolution. By exploring how styles interact and influence the original content in neural networks on the 2D level, it is possible for designers to manually control the expected output of 2D images, result in creating the new style 3D architectural model with a clear designing approach.

Keywords. 3D; Form Finding; Style Transfer; Machine Learning; Architectural Design.

1. Introduction

With regard to the form-finding of architectural design, It would be quite enlightening to study the simulation or integration of different architectural styles through machine learning, which could produces the form of architecture from the "mind" (or the algorithm) of artificial intelligence that go beyond human thought patterns, and open up more possibilities for aesthetic exploration and innovative design. Several related studies have been made, such as Huang et al. (2018) applied pix2pixHD to recognize and generate architectural drawings, also mark rooms with different colors to identify and reorganize different functional divisions within the plan drawings. Campo et al. (2019) applied neural-style transfer to architectural drawings, exploring the style-transformation possibilities of artificial intelligence and automation with respect to architecture.

However, these studies are confined to the 2D level and do not involve the information of the 3D space, making it difficult to explore the spatial form-finding of style mixing. More recently, there have been several attempts to explore 3D architectural forms based on machine learning. Sousa et al. (2019) introduced a methodology for generation, manipulation, and form-finding of structural typologies using variational autoencoders. Zheng (2020) proposed an interesting

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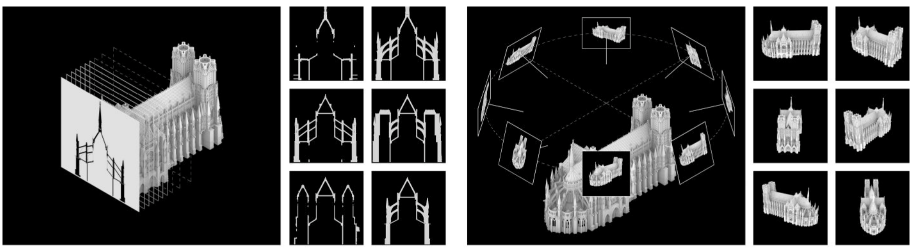
method regarded to 3DGS (3D Graphic Statics) that quantifying the design preference of forms using machine learning. Zhang (2019) applied StyleGAN to train 2D architectural plan or section drawings, exploring the intermediate state between different input styles then generating serialized transformation images accordingly to build a 3D model.

Nevertheless, it is still very hard to directly apply 3D Machine Learning to architectural design, as those previous approaches are more or less suffered from the extreme limitation of the overall resolution of generated results. Therefore, based on these previous study of recognition and classification of architectural styles and 3D architectural form-finding through machine learning, this article mainly introduces 3D architectural form style transfer on 2 levels of scale (overall and detailed) through multiple methods of machine learning algorithms which are trained with 2 types of 2D training data set (serial stack and multi-view) at a relatively decent resolution (in terms of the Lenth*Width*Height, ranges from 1024*1024*1024 pixels in overall scale and 2048*2048*1024 pixels in detailed scale).

2. Method



(a) Serial Stack (b) Multiple View

Figure 1. These are two different methods for deconstruction of the "Notre-Dame de Reims" 3D model : (a) From images stack to 3D. (b) From multi-view images to 3D. In each category, the left side is the schematic of the cutting principle, and the right side is the resulting sample.

In order to convert the 3D data of the architectural model into 2D pixel images, as is been shown in Figure 1, two methods for deconstruction and reconstruction of the 3D model are given: serial stack and multi-view. From images stack to 3D form, style transfer basically processes on the z-axis (plan), x-axis and y-axis(section) through the decomposition of a linear way. The method of serial stack transfer the style conditions on each 2D layer of plan or section and integrates them to construct 3D. From. multi-view images to the 3D form, it is a method of capturing 2D pixel information of corresponding angles by surrounding the 3D model. Through the method of 3D reconstruction by giving a series of calibrated 2D images presented by Kolev et al. (2012), the authors simply extracted multi-view rendered images from the content 3D model, then reconstructed the new model from style-transferred results with the same density and position. This approach will avoid the direct calculation of massive complex 3D spatial data, and the process of style transfer could stay at the 2D level, which significantly reduces the training time and equipment requirements.

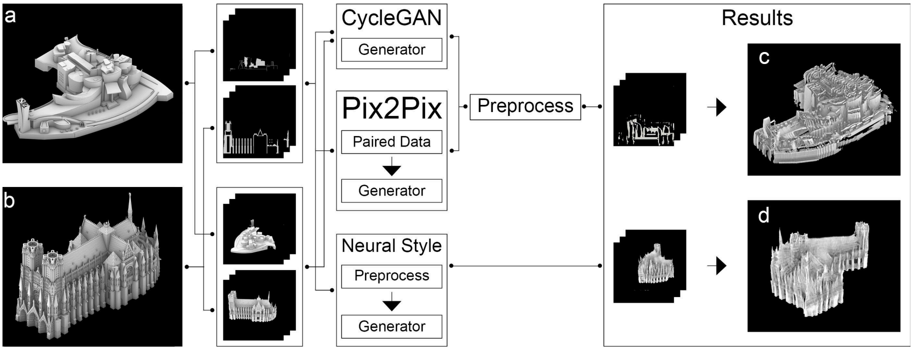


Figure 2. These are Preprocess-based workflow with different algorithms and data types : (a) Input Model A. (b) Input Model B. (c) Results from Serial Stacks. (d) Results from Multi-view.

Although methods have been given to decompose and reassemble the 3D model, the machine is hard to understand the spatial sequence rules in architectural images and the relationships within adjacent front and rear contained by spatial continuity in the original buildings. As shown in Figure 2, in order to record the rule of pixel transition between these 2D images then establishing the corresponding information correlation, during the style transfer process the authors preprocessed the data by calculating the transforming tendency of pixels before and after each of the single image based on the previous study from Ruder et al. (2016) which proposed the video style transfer, as a result of maintaining the consistency between each layer (in videos this refers to the frames). If the timeline before and after each frame in the video is the third axis that crosses the 2D screen, then the progressive sequence of these sliced stack or multi-view images is a similar third axis for a 3D building that is decomposed into serial 2D sequence images. The continuity of the third axis of 3D architectural space somehow bears a fascinating resemblance to the continuity of the video timeline.

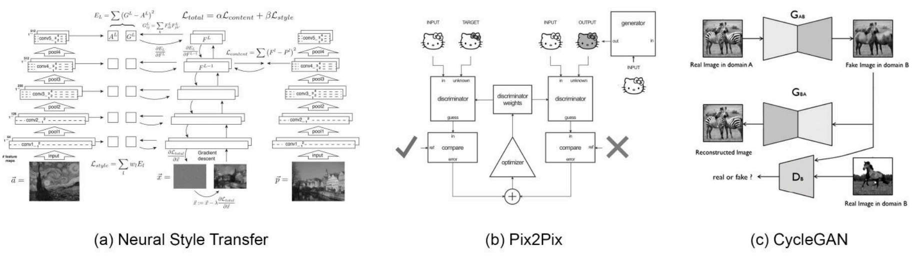


Figure 3. These are the main process of the machine learning algorithm this article will use : (a) Neural Style Transfer. (b) Pix2Pix. (c) CycleGAN.

Figure 3 shows the main structure of algorithms this paper will use. When the demand of design is to make the style transfer on the detailed level, the generated results need to retain the original structural shapes and spatial characteristics but integrate or synthesize the features from a new style into its local construction and organization. Gatys et al. (2016) presented a 2D style transfer of artistic paintings through neural networks named “Neural Style Transfer”. This algorithm will remain the original style’s general spatial organizational framework while its composition is imbued with a new style’s architectural language. As for style transfer on the overall level, which means the original style of the original model will no longer be recognized but transformed into a new or hardly identified style, this goal requires the training of our own model from a specific design approach. For now, there are two state-of-the-art style transfer GANs on 2D level: pix2pix and CycleGAN. the authors utilize both pix2pix and CycleGAN to train the decomposed 2D architectural images with paired or not paired target-style data, linking the corresponding connection between the content model (original style) and style model (target style), as a result of generating a brand new 3D form from these previous two styles.

3. Results from Serial Stacks

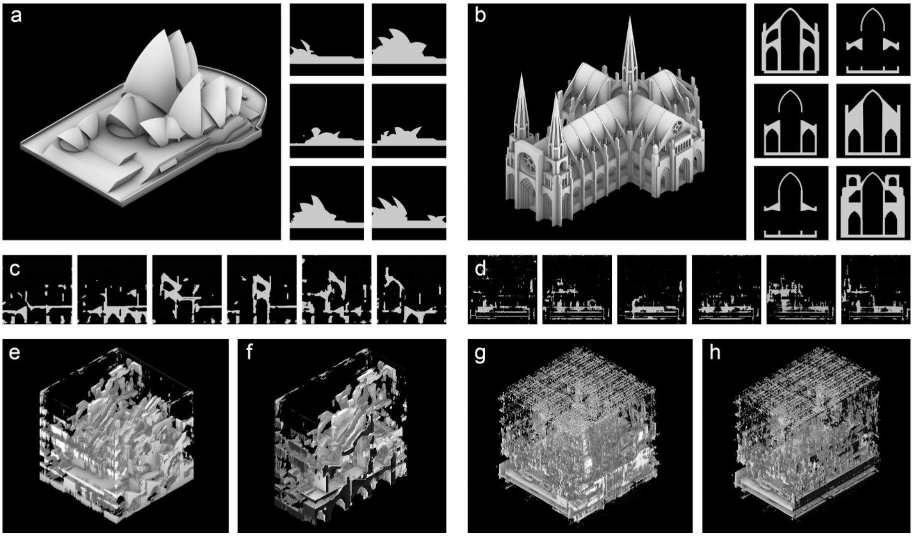


Figure 4. These are style transfer results through CycleGAN with and without continuity PRE (preprocess) : (a) Original input Model. (b) Target input Model. (c) 2D Results with PRE. (d) 2D Results no PRE. (e) 3D Result with PRE. (f) Section Model with PRE. (g) 3D Result no PRE. (h) Section Model no PRE.

3.1. OVERALL LEVEL

The transfer of styles at the overall level aims to explore the potential possibilities of innovation for architectural spatial design under the collision of various forms of styles, especially how to break through the inherent spatial structure characteristics of various styles that go beyond human thought patterns. According to the modification of input data, algorithm logic, and preprocessing methods, the oriented style transfer can be realized with specific design ideas and the generated results can be controlled within a certain expectation range.

3.1.1. Continuity Preprocess

As mentioned in the method section, the preprocess of pixel continuity on the training data will help ensure the smooth combination of spatial sequences in the progress of 3D model decomposition and composition, otherwise, the generated results will have a large number of fragments, which are chaotic and disordered. Figure 4 shows the style transfer results through CycleGAN with and without continuity preprocess. While in the absence of this preprocessing method, the generator of the whole algorithm produces highly random results because there is no correlation information between the data, resulting in the chaos of the final 3d model.

3.1.2. Paired and Unpaired

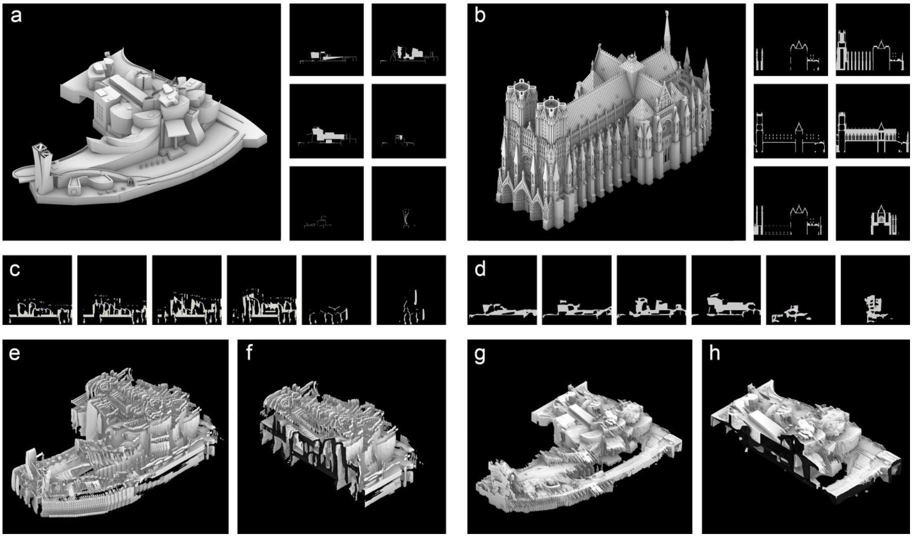


Figure 5. These are style transfer results from CycleGAN (unpaired) and Pix2Pix (paired) : (a) Original input Model. (b) Target input Model. (c) Image Results from CycleGAN. (d) Image Results from Pix2Pix. (e) 3D Result from CycleGAN. (f) Section Model from CycleGAN. (g) 3D Result from Pix2Pix. (h) Section Model from Pix2Pix.

While converting the input 3D model data into a 2D image sequence, the way of organizing the acquisition of data by style transfer will affect both the preparation of the data set and the specific GAN algorithm the authors use. In terms of the overall scale, this organizational structure is mainly reflected in the paired and unpaired, which correspondingly refer to the Pix2Pix and CycleGAN. Figure 5 shows the results from CycleGAN and Pix2Pix which have exactly the same input 3D model. The difference between them in the data set is that Pix2Pix matches the cutting images of the two groups of models at the same position one by one, while CycleGAN has no such correspondence. And it is CycleGAN's relatively free and flexible data structure that makes its style transfer results richer and more diverse than Pix2Pix.

At the same time, it is obvious to notice that the result of this round is significantly different from that of Figure 4 in scale. Depending on the different scale of the input style data, the resulting refactoring will be able to produce disruptive changes based on the corresponding scale relationship between the original style and target style. In the whole training process, the network absorbs the spatial organization rules in the target style's own scale, meaning that the generated result will erase the original style scaling information and reorganizes completely according to the spatial scale of the target style.

3.1.3. Multiple Axis

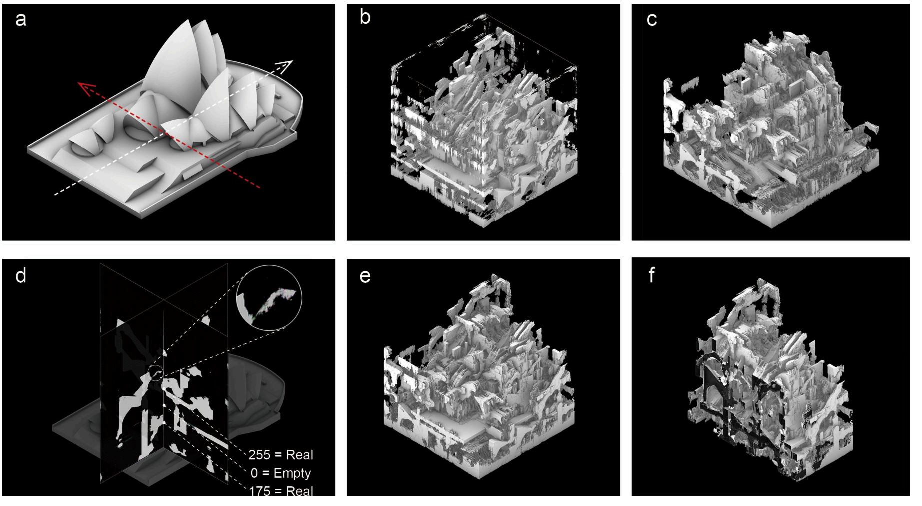


Figure 6. These are the method and results of multiple axis through CycleGAN : (a) Two style transfer Direction: Red – First, White – Second. (b) The First Direction Result. (c) The Second Direction Result. (d) Method of Value Calculation. (e) Result of Multiple Axis. (f) Section Model of Multiple Axis.

It is not feasible to simply piece together the generated results of three axes, which will produce a bloated and jumbled geometry. Benefited from the previous work that each image on linear sequence has their own serialization tag which indicating their respective positions in space, The pixel information owned by each 3d coordinate point is sampled and averaged from the matrix data at its specific position in the corresponding ordinal image. As a result, these 2D serial image sequences will be compiled into the RGB data value of each coordinate point in the spatial point cloud. Through Boolean filtering of RGB data, that is, if the value is greater than the set condition (in this article it is 128), it is real otherwise is empty, so as to determine whether each point in 3d space is the spatial entity of the final model.

Figure 6 shows the method and results of multiple axis through CycleGAN. The results in the first direction are from Figure 4. The authors tried to train an additional 3D model from the other side and obtained the combined model through the method of pixel value calculation mentioned above.

3.2. DETAILED LEVEL

Compared with the overall level, the transfer of style in a detailed level focuses more on the organizational relationship and language of local architectural components, therefore its effect on spatial morphology was more conservative. The target style will attach its pattern, organizational logic and geometric characteristics to the skeleton of content style and then spread its growth, which meanwhile will not destroy the original architectural spatial structure.

3.2.1. Continuity Preprocess

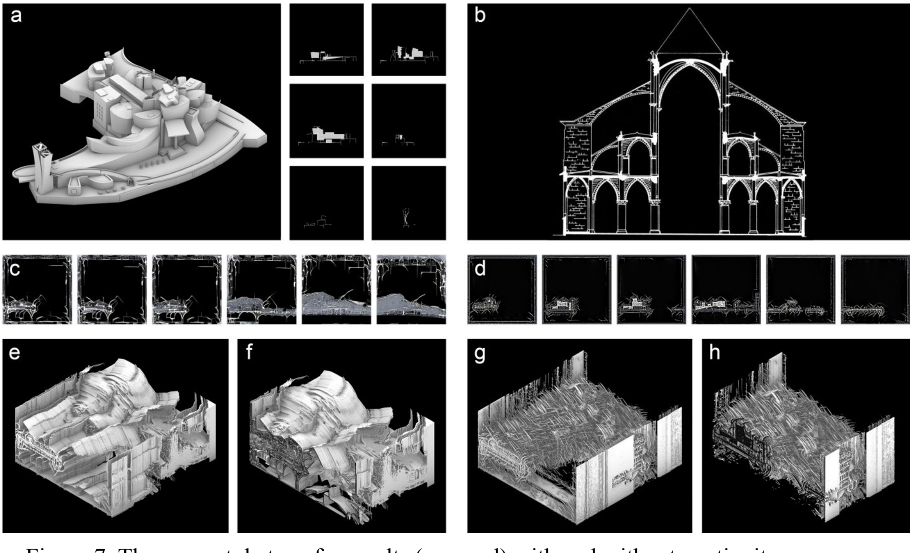


Figure 7. These are style transfer results (cropped) with and without continuity preprocess through Neural Style Transfer : (a) Original input Model. (b) Target input Model. (c) Image Results with Preprocess. (d) Image Results without Preprocess. (e) 3D Result with Preprocess. (f) Section Model with Preprocess. (g) 3D Result without Preprocess. (h) Section Model without Preprocess.

It will be much harder for “neural style transfer” (the algorithm used for detailed level) to achieve the convergence of 3D form because the randomness of this method is so high that the results will be completely different if there is a slight change in input data, which will aggravate the difficulty of spatial continuity maintenance. As a result, different from the overall level, the preprocess of continuity will be embedded in the training process of the neural network, rather than given to the final generator of the algorithm after the training.

Figure 7 shows the results with and without continuity preprocess (The noise-filled edges of the model have been trimmed because they obscure the full view of the model). Without preprocess, gothic drawing transfers its style to make the generated model look like random weed. Given the contextual information, the result contains the explicit gothic element, such as an arched corridor.

4. Results form Multiple Views

The data set of multiple views directly maps the shape characteristics of the model in various parts of the space, so the results obtained from it will gain more transferability in the overall appearance although the possibility of exerting influence on the internal space is sacrificed.

4.1. PAIRED AND UNPAIRED

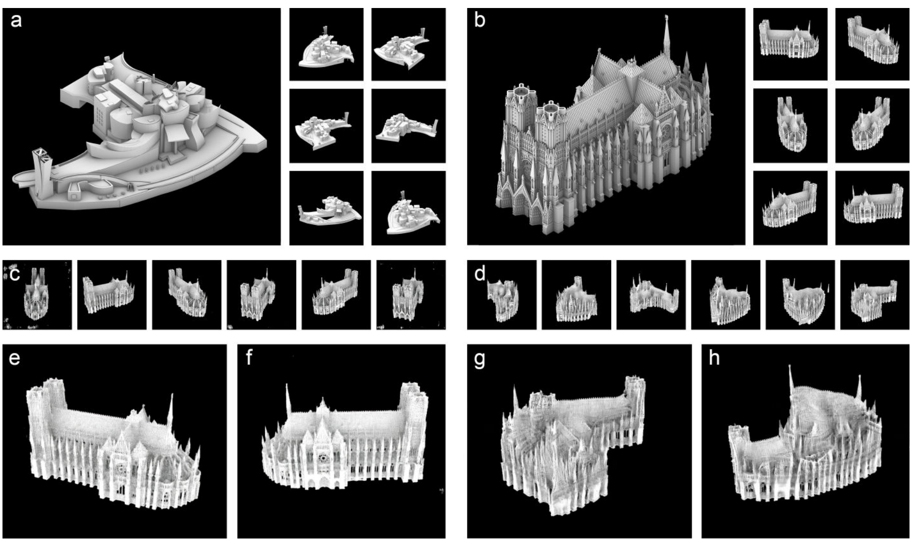


Figure 8. These are style transfer results from CycleGAN (unpaired) and Pix2Pix (paired) : (a) Original input Model. (b) Target input Model. (c) Image Results from CycleGAN. (d) Image Results from Pix2Pix. (e) 3D Result from CycleGAN. (f) 3D Result from CycleGAN. (g) 3D Result from Pix2Pix. (h) 3D Result from Pix2Pix.

As is been shown in Figure 8, The application of Pix2Pix to the data set of multiple views seems to indirectly prove the strict correspondence of this algorithm, and the generated results are almost the same as the target model, losing the characteristic of style transfer. CycleGAN, by contrast, does a good job of transferring the morphological qualities of gothic, such as its columns, spires, and roofs, to the overall contours of “Guggenheim Museum Bilbao”.

4.2. COLOR TAG

Although the black and white sequence images obtained through the cutting model can be used for the preparation of training data simply and efficiently, the three-channel image learning ability possessed by the GAN system does not fully play its role. we can generate corresponding results in different colors for the components of different architectural elements in the 3D architectural model. This method of color tag will give the GAN system the ability to identify different architectural elements, so as to realize the oriented style transfer of specific parts or partitions.

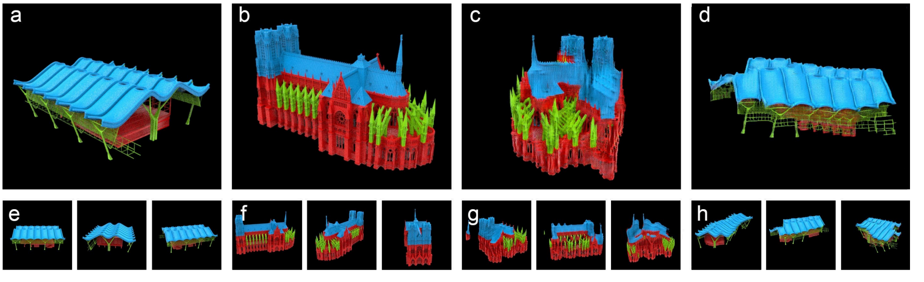


Figure 9. These are results of style transfer through CycleGAN with color tagged data set : (a) Style A Model. (b) Style B Model. (c) 3D Result from Style A to B. (d) 3D Result from Style B to A. (e) Data Set Sample of Style A. (f) Data Set Sample of Style B. (g) Image Results from Style A to B. (h) Image Results from Style B to A.

Figure 9 shows the results through CycleGAN with color tagged and double direction of style transfer. CycleGAN has the ability of bidirectional style transfer, so in this round of training, architectural elements of the corresponding colors of Style A and B have realized directional Style conversion to each other, such as the transformation of roof Style (Blue), and the mutual influence between flying buttress and steel frame structure (Green).

5. Conclusion

In terms of the basic logic, the style transfer on a detailed level is completely different from the overall. Compared to these GAN system we used for overall level style transfer, Its training time is almost negligible due to the avoidance of training through complex adversarial networks. Whereas, relatively, since there are no purpose-specific original style and target style data sets designed in advance, its training results are more difficult to predict. But this is also an interesting part of machine learning. It can always break out of the limitation of human thinking through unexpected results, while these accidents are controlled within a reasonable range so that we can explore more possibilities of architectural forms and structures with the help of it. Other types of similar generative algorithms, such as shape grammar, are a little bit monotonous because their carefully designed and scrutiny of logic will always accurate to realize what we expect, in the form of tend to be predictable. The most interesting part of the style transfer is that, although the generated result has been permeated and dominated by target style, more or less it still retains the outline of the original style, which is more like the fight and game between original style and target style, to find their respective balance points in chaos and order, leading to the final synthesis and coexistence. In the collision and fusion of different styles, these aesthetics created by machine, instead of artificial, will break the traditional image inherent in architectural style and elements, expanding the broader boundary of design thinking.

Furthermore, for the time being, style transfer at the 3D level still remains a complex and lengthy process. Starting from 2D to build 3D is always a compromise because almost all the results have obvious deficiencies, for example, from multi-view, the result almost lost all interior details, and from the serial stack, the generated results are still more or less with traces of uniaxial slicing. Accordingly, the future work can focus on how to further optimize the structure of the network and workflow while maintaining the advantage of 2D machine learning network HD resolution, so as to obtain a more accurate and detailed 3D spatial information for innovative design. Or perhaps in the future, with the development of 3D GAN and computer technology, such as quantum computing, we could have the opportunity to directly achieve fast and efficient style transformation on the 3D level with a promising value of details.

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INTEGRATING BUILDING FOOTPRINT PREDICTION AND BUILDING MASSING

An experiment in Pittsburgh

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Abstract. We present a novel method for generating building geometry using deep learning techniques based on contextual geometry in urban context and explore its potential to support building massing. For contextual geometry, we opted to investigate the building footprint, a main interface between urban and architectural forms. For training, we collected GIS data of building footprints and geometries of parcels from Pittsburgh and created a large dataset of Diagrammatic Image Dataset (DID). We employed a modified version of a VGG neural network to model the relationship between (c) a diagrammatic image of a building parcel and context without the footprint, and (q) a quadrilateral representing the original footprint. The option for simple geometrical output enables direct integration with custom design workflows because it obviates image processing and increases training speed. After training the neural network with a curated dataset, we explore a generative workflow for building massing that integrates contextual and programmatic data. As trained model can suggest a contextual boundary for a new site, we used Massigner (Rhee and Chung 2019) to recommend massing alternatives based on the subtraction of voids inside the contextual boundary that satisfy design constraints and programmatic requirements. This new method suggests the potential that learning-based method can be an alternative of rule-based design methods to grasp the complex relationships between design elements.

Keywords. Deep Learning; Prediction; Building Footprint; Massing; Generative Design.

1. Introduction

Urban context is a fundamental aspect of architectural design and has become more crucial in urban architecture in that it contains complex relationships of various urban elements. It has been explicitly used as the source for form generation in different architectural movements, such as traditional design, critical regionalism or even in contemporary practices based on diagrams. However, the integration of urban context information and design synthesis is still secondary

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 671-680.

in generative design research. For instance, in space planning, CAAD has traditionally employed search and optimization algorithms to explore design alternatives based on internal building requirements, such as areas and adjacencies (Mitchell 1977; Liggett 2000). Building parcels and site geometry are generally treated as constraints for design generation.

Alternatively, agent and rule-based systems have been used to describe the generative logic of a certain design style and also the morphological qualities of existing buildings. Examples that explore the urban context include shape grammars (Ena 2018), L-systems (Parish and Müller 2001), custom urban systems (Hillier and Hanson 1984) and agent-based models such as cellular automata and diffusion-limited aggregation (Koenig 2011). Such systems tend to be harder to integrate with design synthesis because they require an expert to set the design rules or to tune the parameters of existing models.

With current accessibility to abundant urban data, novel approaches can be used to bridge this gap between contextual information and generative logic, without recourse to an expert. For example, machine learning addresses models that can improve in tasks such as regression, classification, clustering, dimensionality reduction and even generation based on data. With deep neural networks, machine learning can address large datasets and provide useful models for design synthesis.

In order to explore the potential of deep learning for space planning, we developed an experiment to capture geometric information from an urban context (represented by a dataset) and translated this into the design of a building on a new site. More specifically, we investigated the analysis and prediction of building footprint, one of the main interfaces between urban and architectural forms. This problem has been addressed in recent research, for example, Chaillou (2019), who trained a GAN on a database of Boston's buildings to generate an image of a building footprint based on the image of a parcel. He further developed a pipeline to partition rooms, define openings and furnish the spaces.

In contrast to Chaillou who creates a GAN-based pipeline from parcel to interior spaces, we focus on the relationship between a larger urban context and the building footprint, with a simpler model. Figure 1 shows the overall process of predicting and generating building footprints using a deep learning model on Pittsburgh in Pennsylvania. We collected Geographic Information System (GIS) data on building footprints and parcels in Pittsburgh and created a large custom dataset that synthesizes the morphological relationships between the target building footprint and its neighbor conditions as contextual information using a diagrammatic representation, Diagrammatic Image Dataset (DID). Next, we formulated the problem as a supervised learning task (regression). A modified version of VGG neural network models the relationship between (c) the diagrammatic image of a building parcel and context without footprint, and (q) a quadrilateral representing the original footprint. The option to use a compact geometric representation for the output simplified the training process, precluding the need for further image processing steps, and provided the required input format for Massigner (Rhee, Cardoso Llach, and Krishnamurti 2019), which is used for the integration between contextual information and architectural massing. The basic idea is that contextual information is not used to define a final building volume, but as a guide for further generative exploration based on the internal requirements of the building.

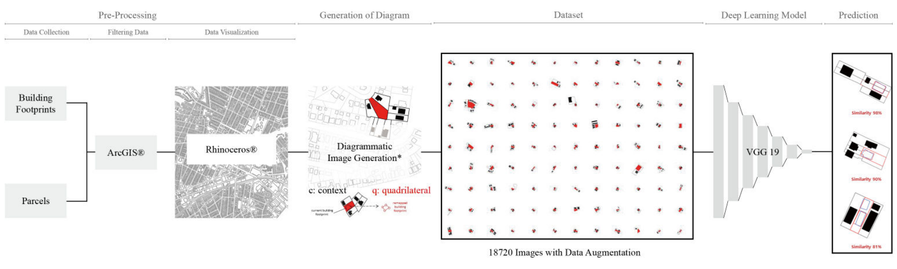

Figure 1. Overall Process of Generating Building Footprints Using Deep Learning and Diagrammatic Image Dataset of Building Occupancy in Pittsburgh, PA.

2. Data, Model, and Learning

2.1. OCCUPANCY MODEL

The diagrammatic image dataset (DID, provisionally patented, developed by Pedro Veloso and Jinmo Rhee) contains images with fixed colors and graphical elements to represent an urban context. The advantage of this type of representation is that designers can choose which aspects of the context to emphasize, thereby reducing the amount of noise from the original data. The image size is 512 × 512 (px). To get a proper range of contextual information to be included in a diagrammatic image, owing to the variety in the shapes of the buildings, the square root (14m) of the average area of all building footprints (202□) was set as the average radius for a target building. Assuming that three neighboring buildings are included on one side of the target building, half of the range of context information is set as 98m and eventually one side of the image range is set as 196m (Rhee, Cardoso Llach, and Krishnamurti 2019).

Based on the DID format, we developed an ‘Occupancy Model’ (see Figure 2), which shows the morphological relationship between the target building and its neighbor conditions. The occupancy model approximates the target building to a quadrilateral, stores its normalized coordinates as a vector, and contains the parcel shape of the target parcel, footprints of neighboring buildings and parcels as a single image (see Figure 3). At the center of a diagrammatic image with an occupancy model, there is an empty parcel filled with a solid color which indicates target parcel information. Around the target parcel, there are geometries representing information on adjacent buildings and parcels. The footprint information for the target building is a vector with the coordinates of the quadrilateral $[x_0, y_0, x_1, y_1, x_2, y_2, x_3, y_3]$, tagged to the diagrammatic images as the label.

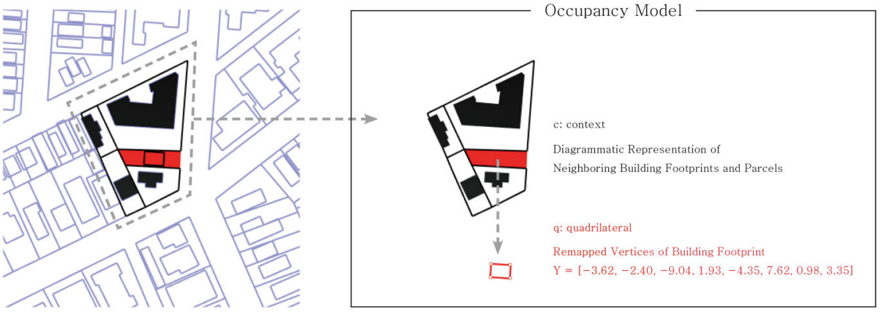

Figure 2. Concept of Occupancy Model.

Figure 3. Using the Context image (c) to Approximate the Quadrilateral of the Target Building Footprint (q). .

2.2. GENERATION FOR DID FOR SHADYSIDE (PITTSBURGH, PENNSYLVANIA, USA)

We used the GIS data provided by Allegheny County, Pennsylvania, for information on building footprints and geometries of parcels: ‘2017 Allegheny County - Building Footprints’ and ‘2017 Allegheny County - Parcels’. After importing .shp files in ArcGIS, we set an area covering about 1.5km around Pittsburgh at an intersection near where several neighborhoods meet: Shadyside, East Liberty, Friendship, Bloomfield, Garfield, Highland Park History District, and Larimer. This site includes 7,598 buildings and 8,459 parcels. After converting building footprints and parcel geometries into .dwg files, Rhinoceros and Grasshopper were used to import these files and generate the DID for the occupancy model. For diagrammatic images, the process requires setting a diagram drawing style using line weights and colors for the geometry. The style can be customized. In this research, target parcels are colored solid red, neighboring buildings colored solid black, and neighboring parcels are represented by 2px wide black lines.

The geometrical information for the footprint of a target building is the label for its diagrammatic image. Each footprint is represented by a vector with the coordinates of its vertices. As the vector size depends on the number of vertices of the footprint, the size of the vector representing the original footprint varies on its shape (see Figure 2). The learning process requires a standardized vector format of a constant length. Figure 3 illustrates this need for a constant length using geometry approximation. The top polyline has four points, which can be represented by a vector of length 8. Another, the bottom polyline has six points, which can be represented by a vector of length 12. The first vector can obviously be represented by a vector of length 12 with four tailing 0's. However, should the footprint contain much more points represented by say a vector of length 100, the data becomes highly distorted (e.g., there are 92 tailing 0's). Therefore, approximating the geometry to a quadrilateral gives a vector that has constant length, and this contributes to more successful learning results.

To approximate the geometry to a quadrilateral, we tested seven different algorithms: the four longest distance, largest area, largest overlapping area, most similar to a rectangle-shape, most similar variance, smallest variance, and a Delaunay triangulation. We chose the Delaunay triangulation because it creates a quadrilateral successfully even in the case of concave geometry (see Figure 4).

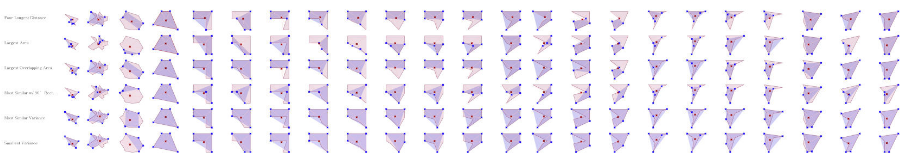

Figure 4. Seven Different Methods to Approximate Footprints into Quadrangles.

In order to validate the dataset for the occupancy model, we checked several conditions:

We first filtered empty target parcel cases. If the target parcel is empty, there is no target building footprint information to be converted to a label. In the same way, cases where there are no neighboring buildings near a target building were excluded. Moreover, we checked the collision cases between geometries: target parcel and neighbor buildings, target parcel and target buildings, target buildings and the window geometry, target parcel and the window geometry, neighbor buildings and the window geometry, and neighbor parcels and the window geometry. If there are any collisions, we excluded the case from the dataset. Lastly, cases where the relative size of the target building (the area of target building / the area of the target parcel $\leq$ e, e $\approx$ 0.15) is very small, such as temporary storage in yard, were also excluded.

After filtering invalid cases, the total number of the diagrammatic images is 2,080. This number of images is not enough to train the deep learning model for a regression problem and may occur overfitting. Therefore, in order to improve learning accuracy and reduce overfitting, we augmented the dataset by rotating the sample images, since we can assume that the relation between context and footprint in Pittsburgh is weakly correlated with orientation. The original building images and labels are rotated 3 degrees apart 8 times counterclockwise. In total, 18,720 images derived from the 2,080 original images by this image augmentation method. Figure 5 shows the part of DID for Shadyside.

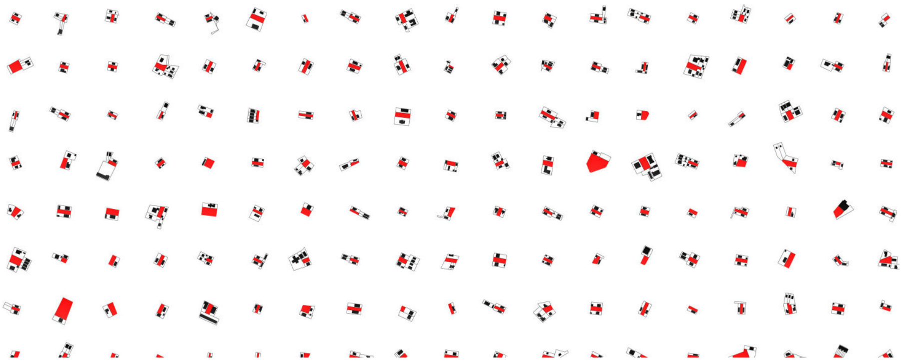

Figure 5. Part of DID for Shadyside.

2.3. MODEL AND LEARNING

Visual Geometry Group 19 (VGG 19, Simonyan and Zisserman 2014), a deep-neural network, was implemented to train the two-dimensional geometrical relationship between a building and its adjacent buildings along with their parcels for predicting building footprints. Considering that a parcel includes a house building and a garage building, the size of its y-value is 16 representing two quadrilaterals. Each quadrilateral has 4 points and each point has 2 coordinates. Therefore, we tweaked VGG19 to receive y-values of the dataset with tensor shape (18720, 16). Also, we added two dropout layers to prevent overfitting cases in learning. We compiled the model with an SGD (Stochastic Gradient Descent) optimizer, MSE (Mean Squared Error) loss function, and 0.00005 learning rate. Batch size is 64 for 800 epochs for learning. This model was trained on a computer with the following specifications: 'Intel(R) Core (TM) i7-8700k @ 3.70GHz', 64GB memory, and two GTX-1080ti graphic cards. It took almost 41 hours to train the data. With this trained model, un-figured images were given to predict the building footprints by considering the given surrounding buildings and parcels.

3. Results and Design Implementation by Building Massing

3.1. LEARNING RESULT AND PREDICTION

In final learning, the model shows a maximum of 94.47% training accuracy and 93.14% validation accuracy (see Figure 6). We remap the predicted footprints on the target parcel and compared the similarity (%) with the original target building by considering the overlapping area and difference of vertices positions. Similarity is expressed through the average of the differences between an actual point (x, y) and predicted point $(\overline{x}, \overline{y})$ (1). The best and worst predicted footprints had respectively 98% and 81% similarity with the cases with one original target building. However, when there is more than one target building in a parcel, it shows only one building footprint with 42% similarity (see Figure 7).

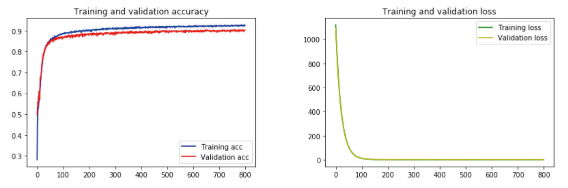

Figure 6. Learning Results, Accuracy and Loss Accuracy and Loss of Training and Validation Dataset.

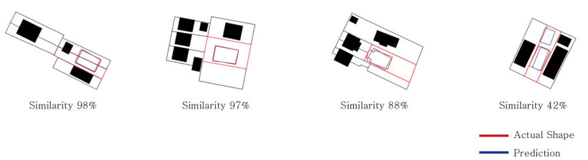

Figure 7. Prediction Result and Similarity to Actual Shapes.

$$S(Similarity) = \left(1 - \frac{1}{n}\sum_{i=0}^{n}\sqrt{(x_i - \overline{x}_i)^2 + (y_i - \overline{y}_i)^2}\right) \cdot 100, n = 3 \tag{1}$$

By visualizing the filters and the feature map of the trained model, we tracked how and what the model learned from the dataset. A filter-applied feature map to input images by layer is one way of visualizing the convolutional neural network. Generally, a convolutional neural network is assumed to be a ‘black box’ and it is hard to provide a reason for a specific decision. However, this visualization can help users of the network have a level of insight and understanding of the internal process of convolutional neural networks.

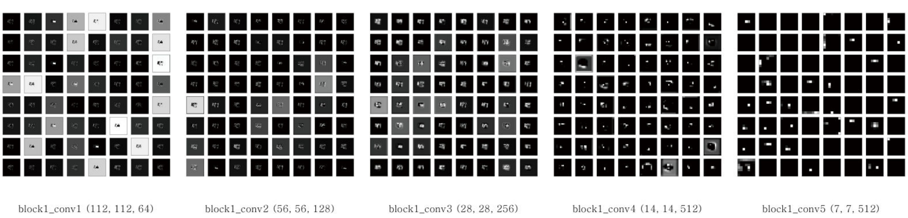

Figure 8. The Result of Filter-Applied Feature Map to a Sample Image by Each Convolutional Max-Pooling Layer.

Figure 8 is the result of filter-applied feature map to a sample image by each convolutional max-pooling layer. The brighter pixel indicates larger weights, and the darker pixel indicates lighter weights. The feature map in the first convolutional max-pooling layer of VGG19 shows the almost same details as the original images. The deeper the convolution layer, the more condensed the information shows. The feature map in the last convolutional max-pooling layer of VGG19 illustrates the pixel-scale white squares. It can mean the model abstracted well the feature of the dataset and trained well to grasp the generalized pattern of the given dataset.

3.2. DESIGN IMPLEMENTATION BY BUILDING MASSING

Prediction of quadrilateral can be decoded as two different ways for building massing: parametric and morphing. (see Figure 9). The parametric approach reconstructs the quadrilateral to the polyline shape by specifying the parameter t on one side of a sloped quadrilateral. If the quadrilateral projections are accurate enough and the original building footprint has parallel walls, its shape can be exactly reconstructed. The middle of the Figure 9 shows the various example masses from parametric decoding method. This method allows architects to grasp the sense of scale, size, and composition of existing mass. If the site does not have existing buildings or their shape is unknown, this decoding method can be used as a restoration tool by providing an inferred shape domain based on their contexts.

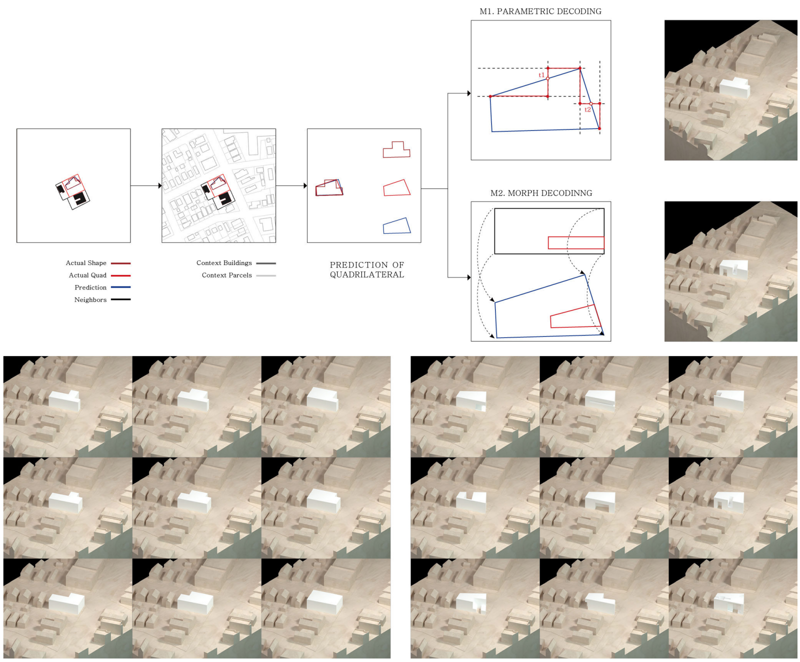

Figure 9. Two Different Methods to Decode Footprint Prediction (Top), Example of Parametric Decoding (Bottom-Left), and Example of Morphing Decoding (Bottom-Right).

The morphing approach is to translate this prediction as a new shape of building footprint or a maximum envelope. In this case, the prediction plays role to provide the size and location of the building within a given site parcel. Due to restriction of building footprints to quadrilaterals, box morphing method can be applied to the prediction shapes for generating new massing.

We used a genetic algorithm-based massing automation tool for housing (Rhee and Chung 2019) to generate an archetype of morphing shape. This tool subtracts voids from a maximum volume and maximizes the usage of within a given conditions, such as building regulations or codes. After generating the optimized volumes from the automation tool, the site volume can be generated by extruding the prediction of quadrilateralized building footprints. Then the optimized volume is morphed to the site volume. The right images of the Figure 9 show the examples of various morphed shapes.

4. Conclusion

In this paper we presented an initial experiment of a novel application of deep learning where we use a simple learning model and geometrical representations to integrate the contextual information with design synthesis. It successfully illustrates how generative systems can extrapolate the dependency of computational synthesis on internal building factors, such as spatial adjacencies, opening location, heat radiation optimization, to incorporate external qualities that are barely captured with the metrics and requirements.

Additionally, in contrast to the conventional hypothetical-deductive logic of the conventional CAAD methods, our approach promotes an alternative inductive approach - i.e. it supports the generalization of the knowledge acquired from data to novel cases with a function approximator (see Cardon, Cointet, and Maziéres 2018 for this distinction). Our model learns a complex function that maps the relation between a certain notion of context (in our case, a diagram of the urban site) and the desired footprint based on a dataset.

In contrast to the direct optimization of a parametric model, our approach enables not only the reconstruction of cases from the dataset but also the generalization of the synthesis for previously unknown sites. Unlike rule-based systems, it does not require an expert to create a grammar or to tune a certain model. Rather than generating a few deterministic rules based on the accessibility or bias of the information of certain experts, patterns from existing data are employed to discover the generative rules. The designer does not have to be an expert in shape grammars or urban morphology. She only must curate a certain dataset representing the context, so the model can learn the desired relationship between context and form.

Finally, thorough and continuous research in various research aspects is still required to understand the broader and deeper applicability of contextual learning in generative design, such as space planning and building massing. Some of the open questions are: How to curate a design dataset?, What aspects of the context can be embedded in DID?, What types of geometry can be learned with simple regression models?, How to incorporate other representations in our method to address other aspects of the context, such as in geometric learning?

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MACHINE LEARNING ASSISTED URBAN FILLING

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Abstract. When drawing urban scale plans, designers should always define the position and the shape of each building. This process usually costs much time in the early design stage when the condition of a city has not been finally determined. Thus the designers spend a lot of time working forward and backward drawing sketches for different characteristics of cities. Meanwhile, machine learning, as a decision-making tool, has been widely used in many fields. Generative Adversarial Network (GAN) is a model frame in machine learning, specially designed to learn and generate image data. Therefore, this research aims to apply GAN in creating urban design plans, helping designers automatically generate the predicted details of buildings configuration with a given condition of cities. Through the machine learning of image pairs, the result shows the relationship between the site conditions (roads, green lands, and rivers) and the configuration of buildings. This automatic design tool can help release the heavy load of urban designers in the early design stage, quickly providing a preview of design solutions for urban design tasks. The analysis of different machine learning models trained by the data from different cities inspires urban designers with design strategies and features in distinct conditions.

Keywords. Artificial Intelligence; Urban Design; Generative Adversarial Networks; Machine Learning.

1. Introduction

1.1. FUNDAMENTAL MECHANISM

Generative adversarial network (GAN) is a model framework in machine learning that is designed to learn and generate image data (Goodfellow, Pouget-Abadie, et al. 2014). In GAN, a network generation candidate is generated, and then the discriminating network evaluates it. The game is organized by data distribution. Typically, the generated network learning maps from the potential space to the data distribution of interest, and the discriminating network distinguishes the candidates generated by the generator from the real data distribution (Wang, Liu,

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 681-690.

et al. 2017) (figure 1). The training goal of the generator is to increase the error rate of the discriminator, for example, to “deceive” the discriminator by generating new candidates that the discriminator considers real. In contrast, the goal of the discriminator is to increase the error of the discriminator.

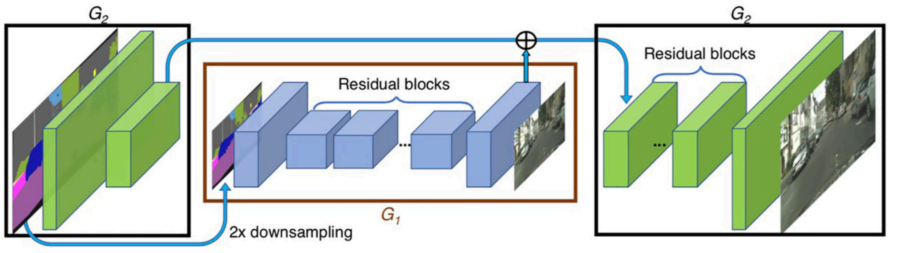

Figure 1. The framework of GANs, by (Wang, Liu et al. 2017).

The training dataset is used as the initial training data for the discriminator. Training involves presenting samples of the training dataset with them until acceptable accuracy is achieved. The generator then is trained with the same dataset to generate the fake images as similar as possible to the real image, and make the discriminator miss-identify the real and the fake images. The backpropagation algorithm updates the network parameters, training the generator to generate better images, while the discriminator can more closely mark the composite images. The generator is typically a combination of convolutional neural networks and deconvolutional neural networks, while the discriminator is made from convolutional neural networks.

1.2. LITERATURE REVIEW

Besides the application in architectural and urban tasks, GAN can be used to create photos of fictional fashion without the need to hire models, photographers, artists or studios and vehicles (Kim and Cho 2000). It can also be used to create fashion campaigns, including a more diverse set of models, which may increase the purchase intention of people (Cheng and Liu 2008). In the scientific field, GAN can improve astronomical images and simulate gravity lenses for dark matter research (Mirabal, Charles, et al. 2016). Researchers successfully simulated the distribution of dark matter in a particular direction in space and predicted the gravitational lens that will occur (Agarwal, Davé, et al. 2018). GANs have also been proposed as a fast and accurate method for generating simulations in calorimeters, granule shower, and high energy physics experiments (Paganini, de Oliveira, et al. 2018).

In design domain, Steinfeld (Steinfeld, Park, et al. 2019) ingeniously transforms 3D architectural forms into 2D three-view data, then uses 2D CNN neural networks as a design evaluator and uses genetic algorithms to find out the current evaluation system (such as the most the optimal housing form solution like banana design). Different from directly giving the model to 3DCNN learning, although the data translation method cannot describe all the forms, it improves the accuracy of the shaped storage and speeds up the algorithm. Also, Zheng (Zheng 2018) uses the transformation of city maps to satellite images, Huang (Huang and Zheng 2018) generates the furniture layout by GAN. Zheng (Zheng and Huang 2018) recognizes different rooms in architectural plans. And Kvochick (Kvochick 2018) applies GAN to recognize different architectural elements (doors, windows, etc.).

1.3. PROJECT GOAL

For the previous research, the image-to-image network only deals with architectural design problems, such as the generation of plan drawings and forms. However, urban design is another widely discussed domain that highly depends on the image-based data. In urban design, designers use simplified city maps to express their design ideas, thus providing a possibility to apply the image-based neural network to assist the design process.

Thus, in the age of Artificial Intelligence, we propose a Machine Learning method to teach the computer to provide the urban plan drawings in the early design stage, releasing the heavy load from the urban designer. Generative Adversarial Network (GAN) supports the learning and generation of images of urban design plans. The final goal of this research is to build a tool that takes images showing the site conditions (roads, green lands, rivers) of a city as the input and outputs images showing the urban design plans (buildings).

2. Methodology

2.1. LABELLING RULES

In urban design, city maps are usually presented as colored images for simplification, in which different colors represent various elements in the maps. In this research, five colors were selected to represent those elements, that is, red (R255G0B0) corresponds to the road, green (R0G255B0) to green land, blue (R0G0B255) to the river, white (R255G255B255) to the building, and black (R0G0B0) to the empty pixels (figure 2). These five colors, as well as their corresponding design elements, can represent most of the situations in urban design tasks.

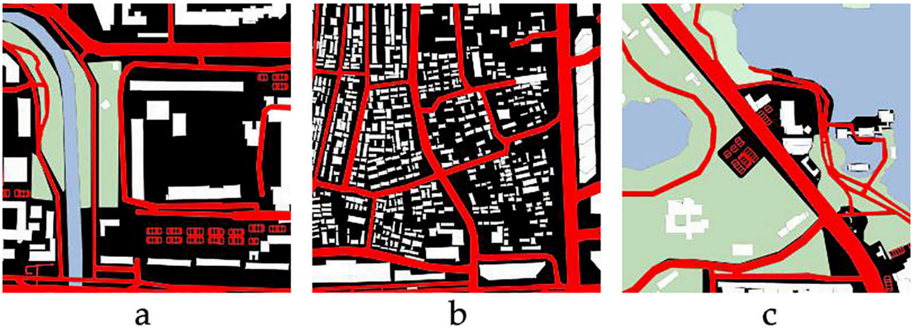

Figure 2. Coloured labelled map, red: road; green: green land; blue: river; white: building; black: empty; a) common city map with all elements; b) condense city map with only roads and buildings; c) loose city map with large green lands and rivers.

2.2. DATA COLLECTING

To train the networks, the dataset of different city maps were collected (figure 3). Eight cities were selected and classified into four tiers, in which the first-tier cities contain Beijing, Shanghai, and Shenzhen. Then, the second-tier cities are Chengdu, Fuzhou, and Guiyang. For the third-tier city and the fourth-tier city, Kunming and Kaifeng were selected. Those eight cities can represent the typical urban design projects in China with different scales, and they have the value to be compared and learned by GAN in machine learning.

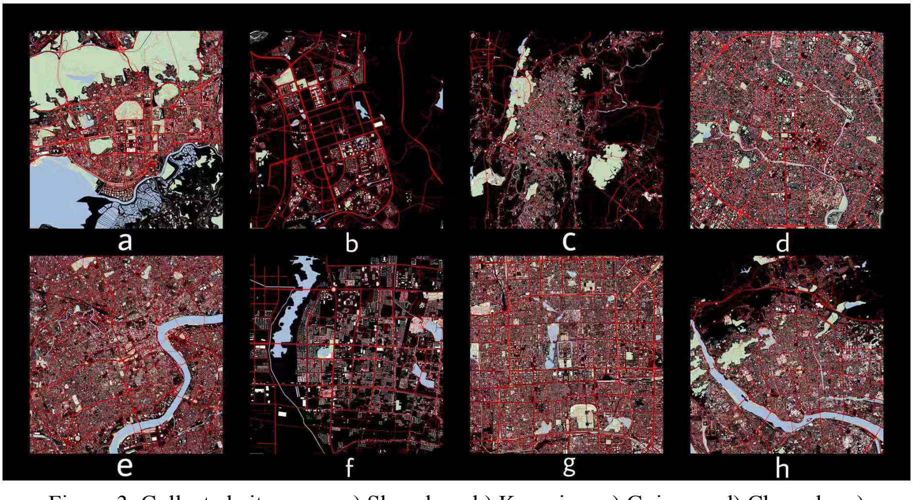

Figure 3. Collected city maps, a) Shenzhen; b) Kunming; c) Guiyang; d) Chengdu; e) Shanghai; f) Kaifeng; g) Beijing; h) Fuzhou.

2.3. NETWORK TRAINING

With the collected data, different neural networks were trained. As mentioned before, the input data contains the required information to start an urban design project, that is, the elements of roads, green lands, and rivers. And the output data reveals the design contents of the project, that is, the designed buildings as well as the environments. Thus, the images of the required information and the images containing buildings of the city are fed into the machine learning neural network separately (figure 4). Also, the large map of the whole city is divided into small samples of 256*256 pixels, while matching the data structure of GAN.

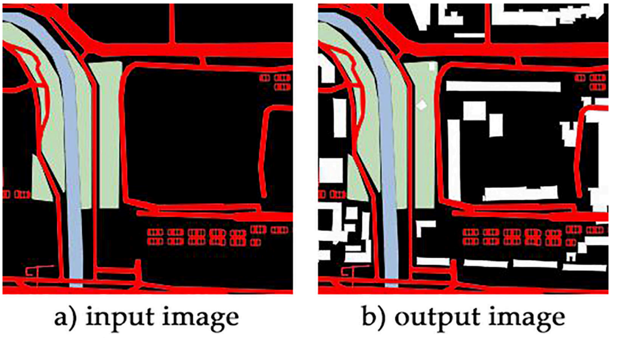

Figure 4. a) the input image; b) the output image.

Taking the training of Beijing city map as an example, figure 5 shows the training loss of the generator and the discriminator. Mentioned before, during the training process, the generator and the discriminator compete with each other to improve the performance. Therefore, the non-convergence of the loss values shows the fact that the generator and the discriminator are evolving with each other to achieve a smaller loss value while being cheated by the other to obtain larger loss values, thus the training is successful.

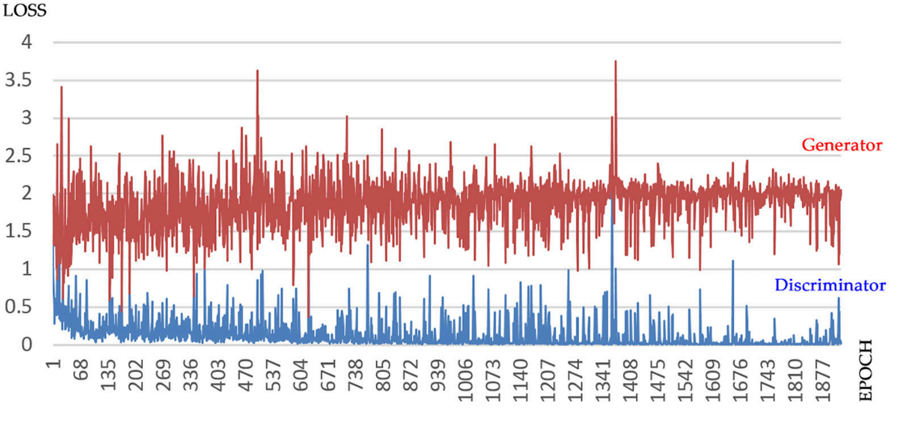

Figure 5. Training loss values of the Generator and the Discriminator.

3. Results

3.1. TRAINING DATA ACCURACY

After training, the neural networks can be used to generate new maps of the city based on the input images. Based on the results, the original input images are firstly be fed into the neural network, and the generated images are compared with the original output image to evaluate the similarity. If the generated images share a significant resemblance to the authentic output images, the urban planning style can be evaluated as characteristic, which is easy to learn. If not, urban planning is uncharacteristic, which is hard to process.

Based on the assumption above, generally speaking, the accuracies of some models are ideal, while some are not. For instance, from the set of the maps by evaluating Fuzhou city, the generated images are similar to the original images of the city (figure 6). Thus, it can be concluded that the urban planning style of Fuzhou city is well-learned by the system, which means the training data has high accuracy. From the perspective of urban planning, this result reveals that the design strategies in Fuzhou city are more uncomplicated and more uniformed.

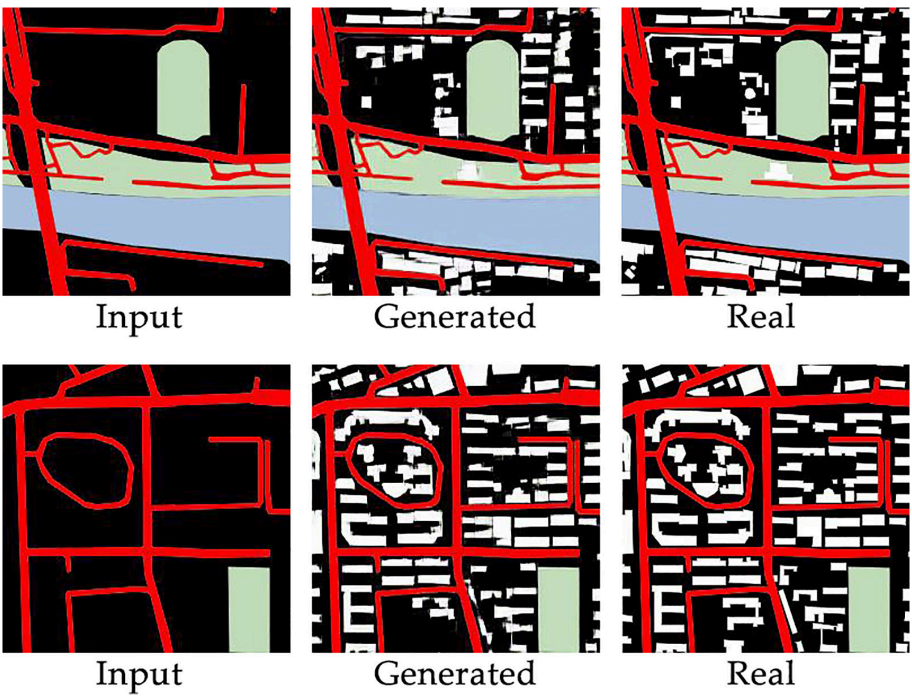

Figure 6. Result comparison of Fuzhou city generated by Fuzhou model.

However, in another case, by evaluating the city maps of Beijing city, the generated images of the city have comparatively less similarity with the original ones (figure 7). For example, the generated buildings and the real buildings in the areas with a yellow box marked are very different; the difference exceeds the acceptable range. Therefore, the urban planning style of Beijing city is not well-manifested on the generated image. Thus, it can be concluded that the learning result has lower accuracy, and the design strategies of the city in different areas are more diverse in larger cities, for example, Beijing.

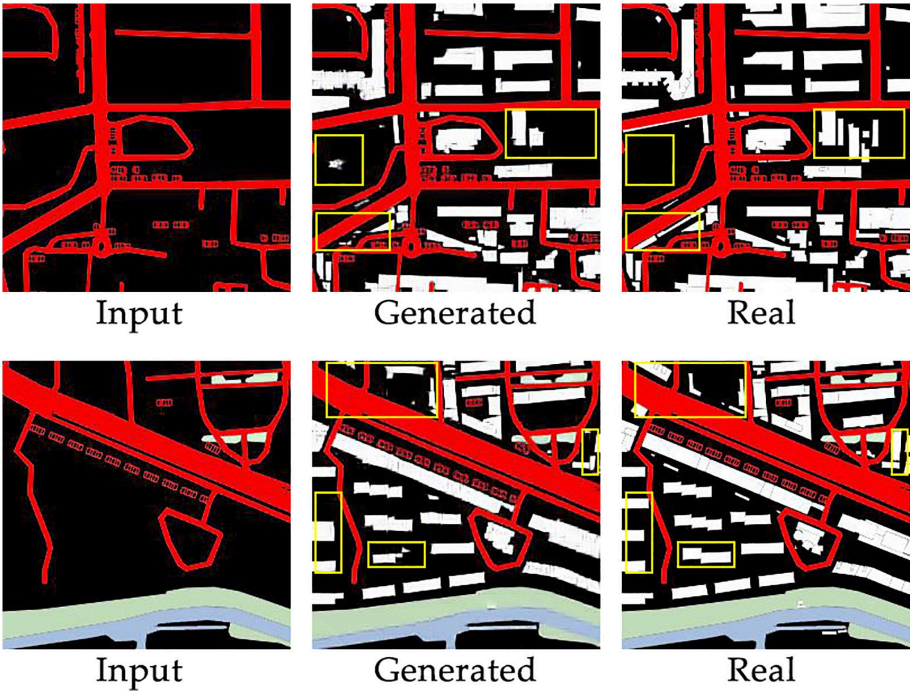

Figure 7. Result comparison of Beijing city generated by Beijing model.

3.2. TESTING DATA ACCURACY

Along the process, cross-validation is also utilized for the evaluation. Firstly, trained by eight different groups of city maps, 8 GAN models representing eight cities are obtained. Then, by feeding all input images of the eight cities to the eight models, 64 groups of output images are generated, representing the predicted urban design solutions based on the corresponding input site conditions and the trained GAN models. Figure 8 shows the selected results of this cross-validation experiment. Four cities from each tier (Shanghai, Chengdu, Kunming, and Kaifeng) are chosen, and their cross-validation results show the generated urban planning solutions by machine learning with different design scales. For example, the generated plans using the site conditions of Chengdu and the model of Shanghai (figure 8 b-1) can be regarded as the urban planning solution with the design strategies from Shanghai but in the area of Chengdu.

To be specific, city maps of the first tiers are used to generate city maps of the second, third, and fourth-tiers based on the input site condition images of the cities (figure 8 b-1, c-1, d-1). The result of generated images can be compared to the original set of city maps of the second, third, and fourth-tier cities (figure 8 b-2, c-3, d-4). In this way, it is easier to tell the distinction between the original and generated images, which is concluded as testing data accuracy. Also, the urban planning style of four tiers is shown on the generated map, which can be compared to the original urban textures of the style image to rule out the accuracy.

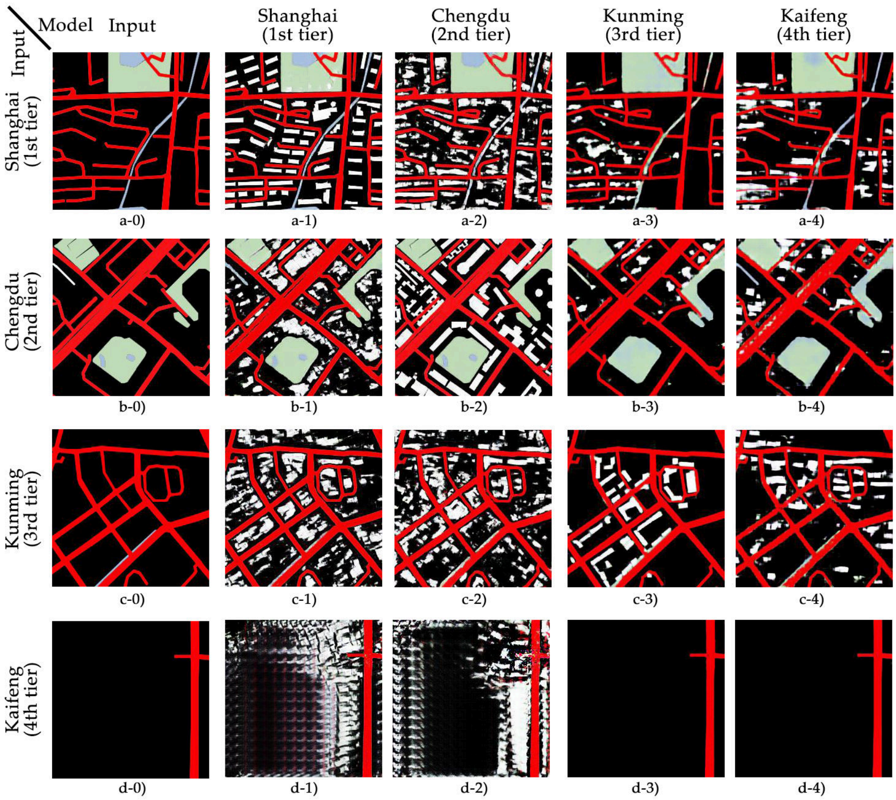

Figure 8. Generated results by different GAN models.

In detail, according to the results shown in figure 8, the design strategies in each city are different. Based on the generated images in each column, they are generated by the same model trained from the same dataset, but with different inputted site condition images. The models in the first and second-tier cities always generate a large number of buildings, for example in figure d-1 and d-2, the generated urban planning images are unable to be understood since the road system is very loose in the fourth tier city, it's hardly seen in the dataset of the first and second cities; thus the models perform poorly. Besides, the models trained by the city images of the third and fourth-tier cities always generate fewer buildings. For example, the generated images in figure a-3 and a-4 are very different than the ground truth image in figure a-1, the building areas are far less than the real situation. Therefore, the most diverse design strategy in urban design in China is the number of buildings that each city will have.

Furthermore, based on the generated images in each row, the site condition image is inputted to different GAN models. The same conclusion of the building density can be reached by visually observing and comparing the results. However, the specific design styles of each city can also be analyzed. For example, by comparing figure a-1, a-2, a-3, and a-4, we can see that the buildings generated by the Shanghai model and the Kaifeng model are placed more related to the road system, while the buildings generated by the Chengdu model and the Kunming model are placed more independently. Also, by comparing figures c-1, c-2, c-3, and c-4, the buildings in the Kunming model and the Kaifeng model are more significant as fewer single units. In contrast, the buildings in the Shanghai model and the Chengdu model are more separated as smaller units. These phenomena reveal the specific design strategies of each city based on the urban planning data.

4. Conclusion

Generally speaking, by comparing the generated images of city maps to the original counterpart, the two sets of images can inspire the urban researchers with different or similar urban planning styles. Therefore, it can be concluded that the learning process of GAN using urban planning dataset is thriving and has high accuracy.

By continually learning the images of all kinds of cities, GAN is capable of conducting urban design. For instance, an urban design plan for a particular area of the city can be generated by importing the aimed city map. Using the trained model by a more substantial city to predict the buildings in a smaller city would give us encouraging results for the future development of the smaller city. This methodology is efficient and accurate to generate urban design plan solutions.

Also, with the development of GAN, the machine learning algorithms may assist more in the future of the urban design process since GAN with a robust database that can be used to customize urban planning of a city in the beginning stage of the urban design.

Besides, the generative analysis based on the generated results with different models and the same site condition provides a method to evaluate an urban design and conclude the design strategies under the same circumstance, which is impossible by the traditional analytical methods.

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A DEEP LEARNING APPROACH FOR BRAND STORE IMAGE AND POSITIONING

Auto-generation of Brand Positioning Maps Using Image Classification

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Abstract. This paper presents a deep learning approach to measuring brand store image and generating positioning maps. The rise of signature brand stores can be explained in terms of brand identity. Store design and architecture have been highlighted as effective communicators of brand identity and position but, in terms of spatial environment, have been studied solely using qualitative approaches. This study adopted a deep learning-based image classification model as an alternative methodology for measuring brand image and positioning, which are conventionally considered highly subjective. The results demonstrate that a consistent, coherent, and strong brand identity can be trained and recognized using deep learning technology. A brand positioning map can also be created based on predicted scores derived by deep learning. This paper also suggests wider uses for this approach to branding and architectural design.

Keywords. Deep Learning; Image Classification; Brand Identity; Brand Positioning Map; Brand Store Design.

1. Introduction

Brand identity and brand positioning have a significant role in dealing with intensifying global competition. Brands strive to achieve desired brand images by designing and controlling brand stores in a particular way. By precisely designing their brand environments, brands seek to differentiate themselves from others. A number of brands have developed iconic architecture and interior design as a means to promote and differentiate themselves. The role of the brand store has thus changed; architecture and store design have become strategic tools of competition, enabling brands to achieve distinctness and recognition. However, brand image and brand positioning are still highly subjective and have been measured using customer opinion. Using deep learning technology, this study explores a new possibility for understanding brand identity, brand image, and brand positioning without relying on individual statements. Using the cases of Starbucks and Bluebottle-two leading global brands creating constant and strong brand identities attached to their brand spaces worldwide-a quantitative

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 691-698.

interpretation of brand image is examined and their brand identities evaluated using a deep learning-based convolutional neural network (CNN) model with brand store images, and a conventional, but still important, positioning map is created thereby. This research could alter traditional ways of measuring brand identity and position, which is currently considered a highly subjective aspect of image perception. This paper also suggests possibilities for further discussions related to deep learning, in-store design, and branding.

2. Related Work

2.1. BRAND IDENTITY, BRAND IMAGE, AND BRAND POSITION

The concept of brand identity is used to set brands apart from competitors in the global marketplace. According to marketing specialist David Aaker (2012), brand identity refers to "how strategists want the brand to be perceived." Brand identity is important because its strategic management is crucial in building a strong brand and thus needs to reflect the brand's value, characteristics, personality, and promise to the customers. Conversely, brand image is about customers' perceptions of the brand; in the process of delivering brand identity through diverse marketing communication channels, a certain type of brand image is generated and positioned in customers' minds. The visual identity of a brand has a particularly significant role in shaping the desired brand identity and delivering it to customers (Balmer, 2001). To survive in a fierce market, brands need to build a competitive brand identity and deliver it successfully. In this context, positioning maps (Trout and Ries, 1986) show the relative positions of market competitors along specific dimensions. The ultimate goal of brand positioning is to set a brand apart from competitors to gain a competitive advantage in the marketplace.

2.2. BRAND STORE AND STORE IMAGE

There has been a significant amount of literature demonstrating that brand store design has a considerable impact on brand identity and forming a particular brand image. Physical store design is a strong communicator of consistent brand identity (Kotler, 1973; Kotler and Rath, 1998; Bitner, 1992; Baker, Grewal and Parasuraman, 1994), and brand stores are a place for delivering the brand's value and identity as well as for selling the product itself. Architects and marketers therefore design the spatial elements and shape the brand experiences of the store space, helping to make brands memorable and unique in customers' minds. Brand space can thus work as a strong medium for brand communication, increasing the brand's value while creating distinct brand positioning (Manovich, 2006). Beyond the traditional way of delivering brand positions, such as services and commodities, brand environments and visual identity have become another level of brand value. In this context, architectural design has become a strategic instrument of brand communication in its own right (Riewoldt, 2002). The brand environment itself expresses value, philosophy, and brand identity by means of architecture and interior design (Messedat, 2005; Kirby, 2010). Brand stores in which consumers experience brand identity use trademark features in stores worldwide (Klingmann, 2007), and an increasing number of brands have moved to creating signature stores with strict brand design standards. Across all stores, the same visual elements of brand identity are consistent, and consumers identify with a particular brand not just because of the goods or services, but also because of the staged environments they offer.

2.3. DEEP LEARNING-BASED ANALYSIS OF STORE IMAGES

In terms of brand environments, both brand image and communication have been studied using qualitative approaches, such as interviews and surveys. Conventionally, measuring market perception of a brand includes the product, service, and all other elements of the brand. The evaluation of brand image-and the corresponding brand positioning map (Trout and Ries, 1986)-use multiple dimensions based on personal evaluation by customers. Even though brand identity has been studied for a long time, it is considered difficult to evaluate and identify a brand image using quantitative approaches without personal help. With emerging interest in deep learning technology and greater availability of digital image data on online platforms, computational image analysis has become possible, such as with AlexNet (Krizhevsky et al., 2012) and diverse CNN models. It has been proven that such models can understand subjective areas, such as style, genre, art, and sentiment, beyond mere image detection and classification (Cetinic et al., 2019). This paper therefore investigates a way of measuring brand identity and generating brand positioning maps by adopting deep learning technology.

3. Research Methodology

To explore the numerical evaluation of store images, this research was based on a quantitative approach adopting deep learning technologies. CNNs are outstanding for dealing with various types of image recognition and classification. Due to the accessibility of pre-trained CNN models, it is possible to get valuable results even with limited data. The proposed method can be divided into two main parts, as illustrated in Figure 1.

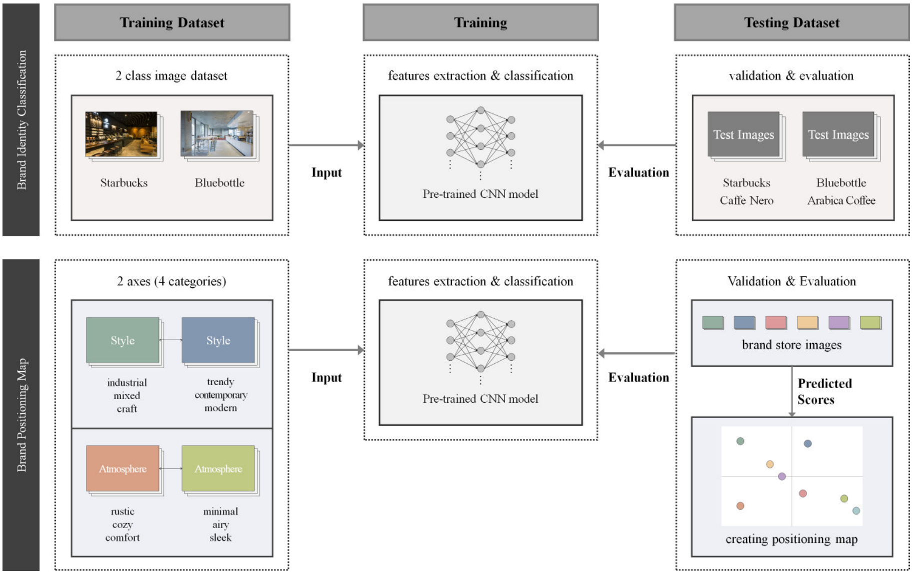


Figure 1. The Research Framework.

This research first investigated the utilization of deep learning-based image classification for classifying brand identity depicted in in-store images. Images that show the in-store design of a coffee shop were collected; Starbucks and Bluebottle were analyzed as cases because they demonstrate successful branding practices in their stores. The collected images were pre-processed under the same conditions so as not to influence training; all images were the same size, included the order counter, and showed at least three sides of the store clearly. In pre-processing the collected data, this research employed a CNN model whose internal design embedded training to evaluate brand identity. Based on previous research, Inception V3-an optimized pre-trained CNN model for understanding contexts-was chosen for the analysis. Parameters were controlled for higher training accuracy.

After training, test images that were not included in the training dataset were tested to validate the classification model. Brand store images in similar positions were analyzed to determine whether the model could capture brand positioning as well. Caffe Nero and Arabica Coffee Shop were chosen as case brands for this stage. The trained model classified the brands that showed similar visual identities, giving probabilistic scores for the brand identities of Starbucks and Bluebottle.

The second section of this research focused on the generation of a positioning map-a perceptual marketing map. After validating the model in the context of brand identity, a second training was conducted to generate a positioning map. The axes of the positioning map were determined by symmetrical words standing for brand attributes. As a typical positioning map is two-dimensional (Sengupta, 2005), two determinant attributes were selected in this research. The horizontal axis (X) indicated design style: industrial/mixed/craft and trendy/contemporary/modern. The vertical axis (Y) denoted atmosphere: rustic/cozy/comfort and minimal/airy/sleek.

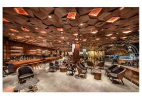
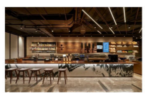
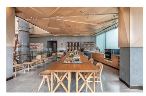
To collect image data that contained the attributes, Pinterest-the most popular social curation site (Hall and Zarro, 2012) based on digital image sharing-was utilized. With the high availability of digital image data on this platform, it was possible to collect large amounts of keyword-related image data at once. Each image also provided brief user comments and thus reflected users' opinions and perceptions (Naaman, 2012). Without social network platforms, it would be hard to gather perceptions of store designs and their associated atmospheres and moods. After training, four scores-for two brands on two axes in the same market-were calculated to determine each brand's position on the two-dimensional map.

4. Findings and Discussion

4.1. BRAND IDENTITY CLASSIFICATION

To ensure that the deep learning could recognize and classify brand identities presented in the store, interior images of Starbucks and Bluebottle were tested. Table 1 shows the images used for classification and the assessed scores.

Table 1. Brand Identity Classification.

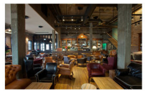
Starbucks Store Images					
Image					
Result (predicted score)	Starbucks (0.999)	Starbucks (0.990)	Starbucks (0.999)	Starbucks (0.930)	Starbucks (0.966)
Bluebottle Store Images					
Image					
Result (predicted score)	Bluebottle (0.991)	Bluebottle (0.998)	Bluebottle (0.998)	Bluebottle (0.971)	Bluebottle (0.941)

The scores represent the probabilistic value for similarity, i.e. the consistency in brand identity. In both cases, the image classification model distinguished brand identity. In the cases of Starbucks and Bluebottle, the results showed an average 98% accuracy, demonstrating that artificial intelligence can learn and evaluate brand identity shaped by the brand store. It can be argued that the deep learning-based image classification successfully detected the characteristics of each brand by extracting and learning signature features and attributes from the store images.

4.2. BRAND POSITION CLASSIFICATION

After training using the interior images of Starbucks and Bluebottle, the test of brands in similar positions was conducted to analyze how the model recognized other brands with similar brand identities. As shown in Table 2, interior images of Caffe Nero and Arabica Coffee were used for evaluation; they do not have the same interior designs, but there is a similarity of evoked moods and styles. The model was trained with 94% accuracy and found similarities in terms of atmosphere and style.

Table 2. Brand Position Classification.

Caffe Nero Store Images					
Image					
Result (predicted score)	Starbucks (0.941)	Starbucks (0.933)	Starbucks (0.999)	Starbucks (0.990)	Starbucks (0.991)

Arabica Coffee Shop Store Images					
Image					
Result (predicted score)	Bluebottle (0.925)	Bluebottle (0.998)	Bluebottle (0.998)	Bluebottle (0.619)	Bluebottle (0.999)

The model therefore recognized the overall style and atmosphere of the space, rather than fragments, such logos, colors, and furniture. It recognized similarities in terms of brand identity and so understood the brands' relative positions.

4.3. DEEP LEARNING BRAND POSITIONING MAP

Coffee shop brand images were collected, from online image platforms, that represented specific styles and atmospheres as defined by individuals. To predict the perceptual attributes-design style and atmosphere-the pre-trained deep learning model was employed again. Style- and atmosphere-related scores were calculated for six coffee shop brands. Table 3 shows the average scores on two axes.

Table 3. Style and Atmosphere Evaluation.

Brands		**Starbucks**	**Caffe Nero**	**Costa**	**Bluebottle**	**Arabica Coffee**	**The Barn**
Image							
X (style)	**industrial**	0.715	0.847	0.838	0.329	0.165	0.854
	trendy	0.285	0.153	0.162	0.671	0.835	0.146
Y (atmosphere)	**rustic**	0.912	0.999	0.997	0.739	0.192	0.540
	minimal	0.088	0.001	0.003	0.261	0.808	0.460

The scores place the specific store images within each category and can thus be used to infer relative positions in two dimensions. The positions of the brands were determined using average scores. Figure 2 shows the final positioning map generated by this model.

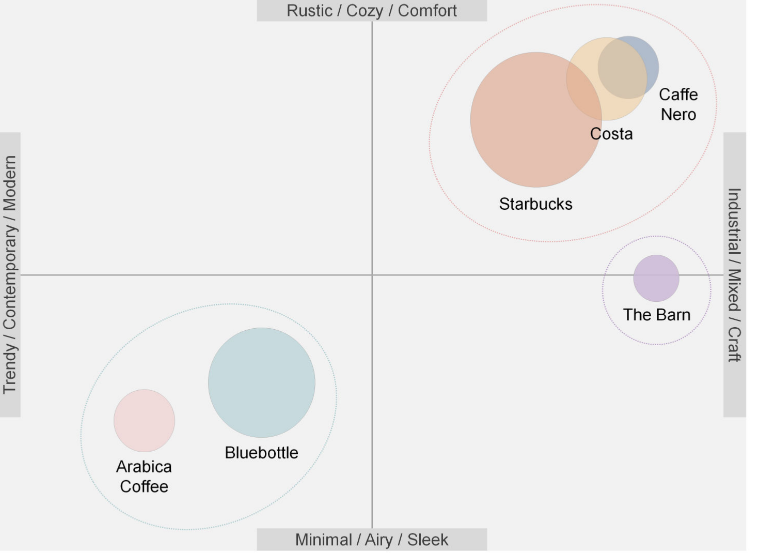


Figure 2. The Brand Positioning Map.

The proposed positioning map shows each brand's position within the four quadrants, reflecting the perceptions of the brand and the possible competitiveness of the brand. This research therefore offers a quantitative evaluation of brand identity, bringing new opportunities for using brand positioning maps.

This model could be used to develop store designs by understanding who the competitors are and where they are positioned. There is no right way to design; much wider consideration and more diverse methodologies are needed. Brands inevitably ask how and to design stores, and this research suggests that quantitative assessment should be broadly considered in in-store design, which could enhance strategies for brand identity and brand environment.

5. Conclusion

A deep learning approach was able to recognize brand identity and automatically generate a brand positioning map. It is evident that brand positioning and brand identity created by design can be trained and identified through deep learning. This research also introduced quantitative evaluation of brand image as an alternative method of creating a perceptual map. While brand identity and brand image have been studied qualitatively, this research argues that a computational approach offers a route to potential competitiveness, but the results still need to be validated through comparison with a qualitative methodology. This new methodology could help corporates and designers beyond industrial boundaries as an evaluation tool for brand identity, an analysis tool for store design, and a design tool for re-branding in line with marketing strategy. Brands building their empires and seeking customer attention look for effective ways to build brand identity and brand space; this novel approach with deep learning offers research evidence of a technological solution currently missing from the literature. Human touch will always be crucial, but artificial intelligence definitely broaden the possibility of design.

Acknowledgement

This work was supported by the BK21 Plus funded by the Ministry of Education of Korea.

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SANITARY SANITY: EVALUATING PRIVACY PRESERVING MACHINE LEARNING METHODS FOR POST-OCCUPANCY EVALUATION

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Abstract. Traditional post-occupancy evaluation (POE) of building performance has typically privileged physical building attributes over human behavioural data. This is due to a lack of capability and is especially the case for private spaces such as Sanitary Facilities (SFs). A privacy-preserving sensor-based system using Machine Learning (ML) was previously developed, however it was limited to basic body position classification. Yet, SF usage behaviour can be significantly more complex. This research accordingly builds on the aforementioned work to expand behavioural classifications using a sensor-based ML system. Specifically, the case study uses a GridEYE thermal sensor array, which is trained on a cubicle location within a workplace SF. A variety of ML algorithms are then evaluated on their behaviour-classifying ability. A detailed analysis of behaviour-classification performance is then provided. A system with greater fidelity is thus demonstrated, albeit hampered by imprecise behaviour definitions. Regardless, this contributes to the capability of the broader field of research that is investigating Evidence Based Design (EBD) by extending the ability to examine human behaviour, especially in private spaces. This further contributes to the growing body of work surrounding SF provision.

Keywords. EBD; Data; Internet of Things; Machine Learning; Post Occupancy Evaluation.

1. Introduction

"Although many architects profess interest in post-occupancy performance, only a handful have taken action to derive more reliable and sophisticated ways to gather data" (Shapiro 2019). Current standards such as the Building Code of Australia (BCA)-the document relevant to the jurisdiction of the case study-are built on minimal data (Doherty et al. 2020). Mathematical queueing models are built, despite little input data or verification. This is especially noticeable in sanitary facilities (SF), as privacy requirements result in minimal data for Evidence Based Design (EBD). Further, architects generally disregard human behavioural data gathering techniques in lieu of a building's physical characteristics, likely due to implementation difficulty (Li et al. 2018).

There are few existing methods to collect high fidelity behavioural post occupancy information. Computer vision techniques that have been successful

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 699-708.

in high fidelity classification cannot be used, especially in private spaces, due to infringements on privacy (Workplace Surveillance Act 2005).

This research addresses these issues by evaluating the potential fidelity of a sensor and machine learning (ML) based privacy preserving behavioural classification system. This uses a SF cubicle as a context for the case study as in Australia it has legal privacy protection; similar concerns are evident internationally. This system develops the ability for architects to understand SF usage and thus improve SF provision, while also developing overall EBD capabilities.

Collecting meaningful data, and thus enabling EBD, allows for truly occupant-addressing design. Findings from this system can be applied to a variety of spaces, even privacy-sensitive spaces, such as a "change room, toilet facility or shower or other bathing facility" (ibid, p.7).

2. Research Aims

The overarching aim of this research is to develop the capability for greater post occupancy evaluation (POE) fidelity, especially in private spaces, with the goal of enabling EBD.

This research also aims to reveal the classifiable behaviours within a SF cubicle context, both to contribute to the field of SF provisions, but also to gain understanding about issues that could occur in private spaces broadly.

3. Research Questions

Given the outlined aims, this paper will address the following questions: What degree of fidelity can be reached when using a combination of sensor technology and ML for a privacy-preserving, data gathering system to measure human behaviour in buildings? Specifically, how can workplace SF usage be quantified with such a system?

4. Literature review

SFs have had great significance to the individual throughout history (Kira 1976, pp.5-6). Despite this, little has been written about the design of these spaces prior to Alexander Kira's 1966 (later revised in 1976) work, "The Bathroom". This work described SF needs qualitatively-only later did Kira (1994) collate quantitative data. Others later performed time-based studies on SF usage using stopwatches and human observation (Reid & Novak 1975, Anthony & Dufresne 2007, Rawls 1988, Gwynne et al. 2019). Rawls (1998) in particular surveyed participants after using the SFs, detailing their self-reported behaviours. In each of these studies there were gaps of knowledge; 34.7% of SF users' behaviours in Rawls' study (1988, p.81) were unaccounted for, Reid and Novak (1975, p.265) only studied urinal usage, and Anthony and Dufresne (2007, p.272-274) only amalgamated others' data.

Given only these data sources, the academic consensus is that current public SF provision is inequitable (Greed 2003, Edwards & McKie 1996, Rawls 1988, Anthony & Dufresne 2007, Molotch & Norén 2010, Banks 1991). Greed (2003, p.8) suggests it is currently unlawful under European Union & Equal Opportunities law. Citing Rawls and Kira among others, Anthony and Dufresne (2007, p.272) alongside Greed (2003) agree that female SF provision equity translates to at least double the amount of fixtures. Despite this, often the opposite is true in England due to the impact of laws enacted less than a century ago (Greed 2019, p.909). Greed (2016, p.1, 5) suggests that public SF policy "is one of the last frontiers of gender inequality", causing great harm including how "50% of girls in Africa do not continue with school because of lack of toilets".

Understanding SF behaviours is an important step towards closing this provisional inequity. Scholars recognise that there are a great variety of behaviours that occur in SFs, however mostly from anecdotal evidence (Kira 1976, p.156, Molotch & Norén 2010, p.9). Users often select SFs to suit their behaviours, with privacy often being important. Studying anonymous homosexual intercourse, Humphreys noted "the most active [SFs for homosexual intercourse] studied were all isolated" (1970, p.31). Rawls' study suggests however that these behaviours are uncommon in SFs, with over 80% of self-reported behaviours listed within "Wash Hands, Urinate, Check Appearance, Straighten Clothes, Comb/Brush Hair, Straighten Tie, Talk" (1988, pp.110-118). This study still faced the challenges of biased reporting due to participant willingness and subjectivity. There is little evidence to suggest from the survey of literature that a study has overcome these barriers in quantifying SF behaviours using sensors.

According to a recent practice review, built environment firms that use POE largely lack quantitative sensor-based behavioural analysis (Li et al. 2018). Over 80% of surveyed POE reports use popular subjective methods, whereas just over 40% made temperature measurements, which was the most popular environmental quality passive measurement (ibid). There were no recordings of behavioural analysis in the Li et al. study.

Table 1. Scholarly mentions of SF behaviours. Those used for this study are marked by an asterisk *. a: (Rawls 1998, p.32), b: (ibid, p.200), c: (ibid, p.201), d: (Molotch & Norén 2010, p.8), e: (Humphreys 1970, p.30), f: (ibid, p.43), g: (Molotch & Norén 2010, p.137), h: (ibid, p.243), i: (Kira 1976, p.207), j: (ibid, p.208).

Breast feeding[*a], Straighten clothes[b], Straighten tie[b], Squat on toilet seat[*g], Comb/brush hair[b], Change diaper[*b], Change pad/tampon[*c], Change clothes[*b], Assist child/children[b], Brush/floss teeth[b], Check Appearance[b], Clean glasses[*b], Take medicine[*b], Drink alcohol[*d], Take phone call[*d], Wait on [for] other person[b], Use toilet paper seat cover[*g], Have a moment of solace[*d], Adjust jewelry / scarf[*c], Put in / take out contacts [b], Use drugs[*d], Nap[*d], Masturbate[d], Vaginal sex[d], Oral sex[e], Anal sex[f], Read[*d], Graffiti[d], Vandalise[*d], Chat[d], Talk[*b], Smoke[*b], Hide[*d], Gamble[h], Wash Face[b], Urinate[*b], Defecate[*b], Shave[h], Wash a pet[h], Eat food[*h], Relax[*h], Exercise[*h], Sing[h], Play rough[i], Rob/mug[i], Bomb[i], Deal drugs[*i], Write notes[*d], Destroy evidence[i], Leave a message[i], Beat up[j], Spy[*j].

There have been a few notable studies that attempt to uncover behaviour through passive data gathering. Herkel et al. (2008) recorded user behaviour regarding the opening and closing of windows relative to weather conditions. Sailer et al. (2013) used RFID tags on participants in a workspace to track movement behaviour, whereas Spinney et al. (2015) extended this with sitting time & physical activity sensors, recommending that RFID systems be avoided due to their low spatial resolution. Wang and Shao (2018) use Wi-Fi instead, noting higher spatial resolution, enabling inferential behaviour classification based on location, albeit with limited accuracy. These aforementioned locating methods require a user to have a device with them, unlike Berry and Park (2017) who employ GridEye thermopile array sensors to track participant movement. This method is a more widely applicable system without infringing privacy, unlike popular computer vision classification techniques (Brunetti et al. 2018). The cost of privacy however is that this technique had little accuracy, with inputs largely deviating from the prediction (Berry & Park 2017, pp.142-143). A potential solution is the combination of several datasets in one ML model, as Han (2012) and Yang (2014) among others have found success in, although in building occupancy rather than behavioural analysis. None of these aforementioned methods have been applied to an SF context.

The recent article by Doherty et al. (2020) is the most pertinent piece of work to this study, using sensor-based technology to quantify presence and behaviour in a workplace SF. In this study a three-class model (sit, stand, absent) was successful for basic body position classification, showing promise for expansion of the list of states. The states can be used to infer further information about potential behaviours (ibid), but with limited detail, especially considering the aforementioned diversity of behaviours that occur in SFs. The focus of this study will be to determine the level of behavioural fidelity and breadth that can be reached using these hybrid sensor-ML techniques, specifically in a workplace SF.

5. Case Study

This research explores using sensors and ML to distinguish between SF behaviours. In order to ensure that privacy is maintained in such a system, a sensor that is unable to infringe on privacy was chosen-the Grid-EYE thermal array sensor. It produces 64 temperatures per reading in an 8×8 grid.

5.1. METHOD

This system reuses the hardware developed by Doherty et al. (2020). Additionally, the software developed includes:

The *sensor-capturer*: This script interfaces with the Grid-EYE. It collects temperature information via the I²C protocol. It continuously translates the readings to Celsius, associates the reading with the *current metadata*, and stores it.

The *behaviour-informer*: This script updates the *current metadata* to the current behaviour as it runs. The operator uses this script during the experiment.

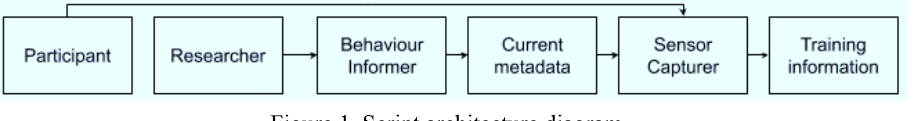

Figure 1. Script architecture diagram.

These scripts must be used together during the running of the experiment, with the *data-capturer* in the background before and the *behaviour-informer* in the foreground. These components together capture the labeled data necessary to train the ML models.

In line with the problems of equitable provision mentioned in the literature review, the participants should be an equitable cross section of the population; no body characteristics should be disproportionately present in the cohort. Recruiting diverse participants is essential to ensure low bias in the system's predictions as the same model will be deployed, agnostic of the users' characteristics.

To prepare for collecting training data: place signs in front of the cubicles as well as outside the bathroom, informing participants and others of the experiment taking place. Then, set the cubicles up in Figure 2's configuration. The prop box contains: Lighter & metal rod (for simulating smoking), eyeglasses, contact lens case, book, pen, beer bottle (filled with chilled water), tampon box, jacket, and a baby-sized water bag (at body temperature).

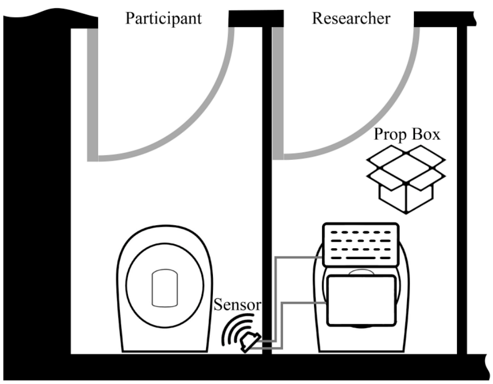

Figure 2. Cubicles layout.

When participants first arrive at the location, introduce them to the items for the exercise. Do not show them how to act out the behaviours, but rather without actions tell them they may use certain items for certain behaviours. Place the items in the researcher's cubicle. Show the participant into their cubicle. Ensure someone is outside to minimise disruptions. Move into the researcher's cubicle and start the system. Note the behaviour that is listed by the script, telling the participant to act out the behaviour. If a prop is required, pass it to the participant.

Start the recording process for that activity after they have started. Train for a total of 20 seconds; stopping early if the participant must. Once the recording has stopped, ask the participant to return any items. Repeat this recording process for all the behaviours. This produces a dataset with 15,530 labeled frames (out of 30610 frames).

This system used a Raspberry Pi, with Python 3.6, SKLearn, Matplotlib, Tensorflow, and Pandas. It used SKLearn to develop a K-Nearest Neighbours (KNN), Support Vector Machine (SVM), and a Logistic Regression (LR) model, and used Tensorflow to develop a ConvLSTM model. These models are explained further in the results (6.2) section. They each accepted 8x8 arrays or 64-length lists of temperatures.

Each model was trained with the information transferred, using an 85% training to 15% validation split. With each of these models, hyperparameters (such as Gamma, Kernel & batch size) were tuned until it obtained a satisfactory validation accuracy. Matplotlib was used to further visualise and understand the results.

5.2. RESULTS

Initially, a list of 7 behaviours was used: sitting, browsing phone, take phone call, standing, straighten clothes, comb/brush hair, absent. Six individuals acted these behaviours out, which trained the ConvLSTM model. The result was a 99.8% validation accuracy between each of the behaviours. This result confirmed that these 7 behaviours could be easily distinguished; thus further behaviours were added.

From the list in the literature review, not all of the 51 behaviours were attempted due to various logistical reasons e.g. 'bombing' the SF would be difficult to replicate safely and cheaply. The authors elected to study only single occupant activities. A list of 27 behaviours (indicated by a * in table 1) was used with 9 participants. The results of using these behaviours for ML model training are varied and have lower accuracies than the initial 7-behaviour results. The highest validation accuracies (VAs) achieved are noted in Table 2.

Table 2. Support Vector Machine (SVM) accuracies. Different kernels are different methods for attempting to split up the data. Gamma/Degree are the 'strengths' used for classification (Degree applies to "Kernel: Poly", Gamma applies to the others).

Gamma	Degree	Kernel: RBF VA	Kernel: Sigmoid VA	Kernel: Poly VA	Kernel: Linear VA
0.001	**2**	31%	4%	48%	49%
0.1	**3**	80%	4%	50%	51%
10	**4**	4%	4%	63%	48%

Table 3. K-Nearest Neighbours (KNN), Logistic Regression (LR), and Convolutional Long Short-Term Memory (ConvLSTM) Validation Accuracies (VA). KNNs average the closest K results to find the correct classification. LRs develop a function that calculate classification probabilities with C strength. ConvLSTMs use convolutions to identify important 'features' and has a batch size (BS) memory is when classifying.

Hyperparameter	Low	Low-med	High-med	High
KNN VA	77% (K=1)	78% (K=10)	63% (K=100)	26% (K=1000)
LR VA	27%(C=0.001)	30% (C=0.1)	28% (C=1)	32% (C=100)
ConvLSTM VA	4% (BS=2)	4% (BS=6)	4% (BS=10)	4% (BS=14)

The best result achieved by any of the models developed is 80% by the SVM with a Radial Basis Function (RBF) kernel and a 0.1 gamma. A confusion matrix identifies the probability that a behaviour will be confused with another. A perfectly performing system's confusion matrix will have 100% for the right/down diagonal, and 0% for all others. Higher percentages in these other areas indicate behaviours that are mistaken for each other, as seen in Figure 3 minimally. Figure 4 ranks behaviour pairs that have a confusion rate of over 3%.

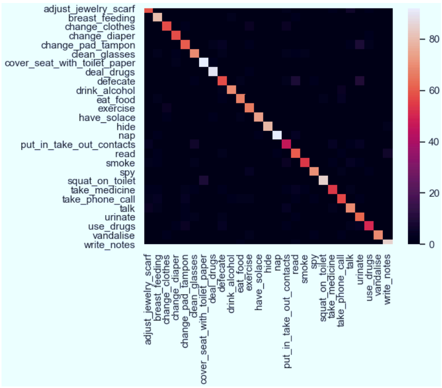

Figure 3. KNN Accuracies (Actual activities vertical, model inferrences horizontal).

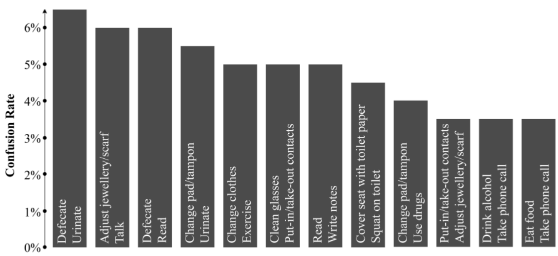

Figure 4. High pair confusion rates (activities that are mistaken for each other).

Some activities, such as defecation, urination, and reading are highly present in wrong inferences. Ranking activities by this metric places urinate first, then read, change pad/tampon, put-in/take-out contacts, and defecate. This list and the mistaken pair list having similar behaviours suggests that certain behaviours are more easily misassociated than others. This trend can be confirmed when viewing other ML models (figure 5A & 5B).

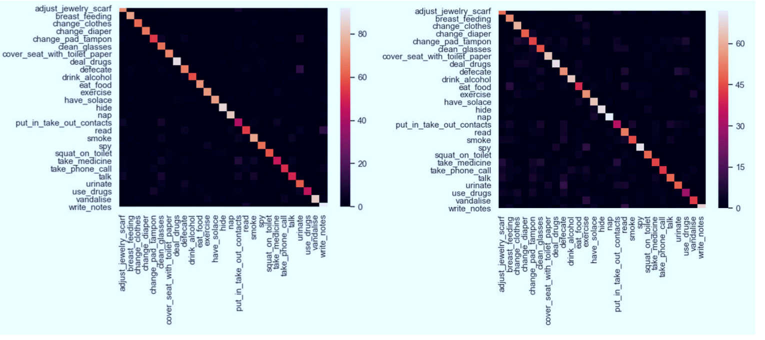

Figure 5. (A) KNN (K: 10) (B) SVM (K: Poly, D: 4).

The most misassociated behaviours in figure 5A are clean glasses, then put-in/take-out glasses, urinate, smoke, and defecate. In figure 5B they are defecate, change pad/tampon, read, exercise, and breastfeeding. Although there is some variance, there is a trend towards certain activities being more difficult to classify. This is confirmed by a pair contrast, which shows the highest validation accuracy achieved for each pair of behaviours:

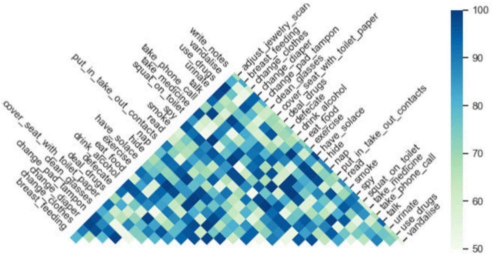

Figure 6. ConvLSTM Pair Contrast. Shows the accuracy percentage of correctly distinguishing between each pair of behaviours.

For example, ‘read’ has low distinguishability, as was seen in other models, whereas ‘spy’ has high distinguishability. There are notable anomalies, such as ‘vandalise’, which appears to have low distinguishability but did not appear in previous figures. It being inferred to be other behaviours is a likely reason, presumably due to the high variability of ‘vandalise’ interpretations; recall that participants aren’t instructed *how* to perform the action. A similar trend can be seen for ‘change clothes’.

6. Discussion

The overarching aim of this research was to evaluate the potential fidelity of a sensor and ML based system for the distinction of behaviours in private spaces. There was also a secondary aim of understanding the identifiable SF behaviours.

With regard to this second aim, minor trends within the data could be identified. Behaviours such as ’read’, ’defecate’, ’urinate’, ’vandalise’, and

’change clothes’ were noted to be difficult to distinguish, with two classes of suggested distinguishability-behavioural similarity (e.g. defecate & urinate), and variability in interpretation (e.g. vandalise). ML models’ overall ability to distinguish between behaviours was high, achieving 80% accuracy.

Having said this, there are definite limitations to the research. The list of behaviours selected is not comprehensive, although it covers a broad range of behaviours. A fully comprehensive system, using this method, is impossible as it would require the system to be pre-trained with infinite classes.

This system has a greater fidelity than previous systems, but still is just one step towards necessary further research. Such research should address questions of which ML models are suited to classifying the data, as well as the most appropriate privacy preserving hardware. The definition of privacy preservation with sensors must be addressed both in a scholarly and legal context. Additionally, as previously noted, a collection of sensors and ML models may be better suited to solving this issue (Han et al. 2012, Yang et al. 2014).

7. Conclusion

This research study has developed the fidelity of a privacy preserving sensor-based ML system. It has iteratively improved ML algorithms for a sensor placed within an SF cubicle. The research demonstrates that a wide range of activities are possible to distinguish between in a SF setting, albeit with limited by behaviours that have little physical differences and those that have a wide range of interpretations. This contributes to the tools for EBD, while also aiding the growing discourse on SF provision.

The initial question regarding the behavioural fidelity that can be reached by the system (using a SF as a case study) resulted in a high accuracy, albeit with further investigation into ML models and the hardware being necessary. Further, the study includes only a partial list of cubicle behaviours, with a holistic list being potentially impossible. The implications of pre-training a model to classify into set behaviours to capture cubicle behaviours should be further considered. For example, its inability to classify new behaviours.

Regardless, there are many further directions this research suggests. Primarily, some data should be collected with this system to further SF EBD, before then applying this system to broader contexts as a method for private, effective EBD. Overall, the research provides a useful method for high-fidelity, privacy preserving, sensor-based EBD applications using ML, a step towards further research in a potentially high impact field.

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MACHINE LEARNING NEURAL NETWORKS CONSTRUCTION AND ANALYSIS IN VECTORIZED DESIGN DRAWINGS

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Abstract. Machine Learning, a recently prevalent research domain in data prediction and analysis, has been widely used in a variety of fields. In the design field, especially for architectural design, a machine learning method to learn and generate design data as pixelized images has been developed in previous researches. However, proceeding pixelized image data will cause the problems of precision loss and calculation waste, since the geometric architectural design data is efficiently stored and presented as vectorized CAD files. Thus, in this article, the author developed a specific machine learning neural network to learn and predict design drawings as vectorized data, speeding up the learning and predicting process, while improving the accuracy. First, two necessary geometric tests have been successfully done, which shows the central concept of neural network construct. Then, a design rule prediction model was built to demonstrate the methods to optimize the neural network and data structure. Lastly, a generation model based on human-made design data was constructed, which can be used to predict and generate the bedroom furniture positions by inputting the boundary data of the room, door, and window.

Keywords. Machine Learning; Artificial Intelligence; Generative Design; Geometric Design.

1. Introduction

1.1. MACHINE LEARNING ALGORITHMS

The name Machine Learning was first introduced by Samuel (1959) to represent a computational learning theory in Artificial Intelligence, but without being explicitly programmed. However, the concept of Machine Learning, a computational model for neural networks, was firstly invented by McCulloch and Pitts (1943) based on threshold logic, a mathematical algorithm. According to the model, the activation status (0 or 1) of neuron in the current layer is calculated through that in the previous layer, based on the logic operation rules. Thus, by inputting an initial status of neurons in the first layer, the computation graph will feedback on an output status of neurons in the last layer. This theory not only

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 709-718.

established the foundations in the biologic processes of the brain but also inspired the neural network structure of Artificial Intelligence.

Then, Werbos (1974) developed a method call Back Propagation to accelerate the training of multi-layer neural networks, which feeds the error term back to the neural network to modify the parameters in each neuron. By calculating the gradient of the loss function between the ground truth value and the predicted value, such as mean square error, the parameters in the hidden layers will be updated and gradually approach the optimal values. With enough data and processing power of computers, the weights of each neuron in the neural network will finally reach a condition that the total error value (loss function) is minimized.

The neural structure and the backpropagation algorithm together form the basic unit of the neural network, which further inspired the development of Recurrent Neural Networks (RNN), repeatedly applying the basic unit to proceed sequential data (language model), and Convolutional Neural Networks (CNN), extending the dimension of the basic unit to proceed matrix data (image model) (figure 1).

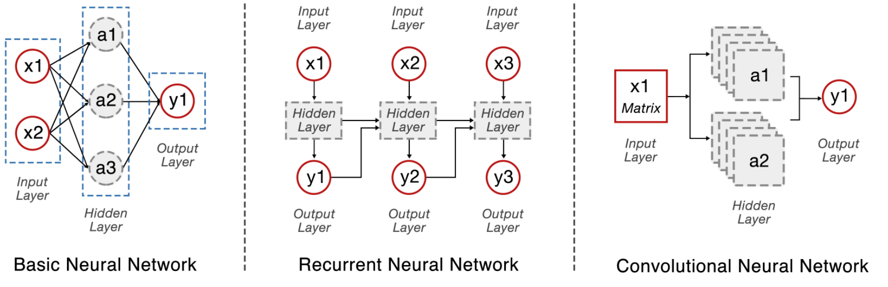

Figure 1. Neural Network Structures of Different Machine Learning Algorithms.

1.2. PREVIOUS WORK IN DESIGN DRAWINGS

Images, especially drawings, as the representative of design, have been commonly used to store and present design data. Huang and Zheng (2018) applied a Generative Adversarial Network (GAN), a refined version of CNN, to train and predict architectural image data in pairs, mapping the parameters between two images. However, there are still blurry and unclear areas, and the furniture is not recognizable as it should be. What's more, the most significant limitation of CNN is that it regards design data as pixelized images. Hence, the precision is limited, and it depends on the number of pixels in the image. Enlarging the size of the image can improve its performance, but will also increase the training time. Similar research of applying image-based neural networks in generative tasks includes (Kinugawa and Takizawa 2019, Newton 2019, Steinfeld, Park, et al. 2019, Thomsen, Nicholas, et al. 2019, Turlock and Steinfeld 2019, Zandavali and García 2019).

However, Zheng and Huang (2018) also proposed a method in their paper to visualize the parameters in the neural network. The convolution layers in CNN work to detect the boundary information from the original image, and then combine features into a chaotic system for calculation.

Thus, CNN firstly translates image data into vector-like data (but still stored as a matrix), by creating continuous white or black pixels, then links the pixel data to essential neural networks for outputting a single value (image classifier) or to deconvolution layers for outputting another image (image generator). A large amount of processing power is used to update millions of parameters, which only act to transform images into vectorized data. Thus, it's unnecessary to train CNNs if vectorized data already exists in CAD files in most of the architectural design cases.

2. Methodology

2.1. BASIC GEOMETRIC TEST - INSCRIBED CIRCLE

Inspired by the facts above, two tests in constructing neural networks to train simple geometric data were carried out firstly, validating the feasibility of training and predicting vectorized data.

First, a sample neural network was built to predict the inscribed circle by inputting a rectangle. As figure 2 shows, the inputted square is represented by the coordinates of its two vertexes as $(x1, y1)$ and $(x2, y2)$. Using the same rule, its inscribed circle is represented by the coordinate of the center point $(x3, y3)$ and the radius r. Therefore, the first layer in the neural network should contain four neurons, and the last layer should contain three neurons.

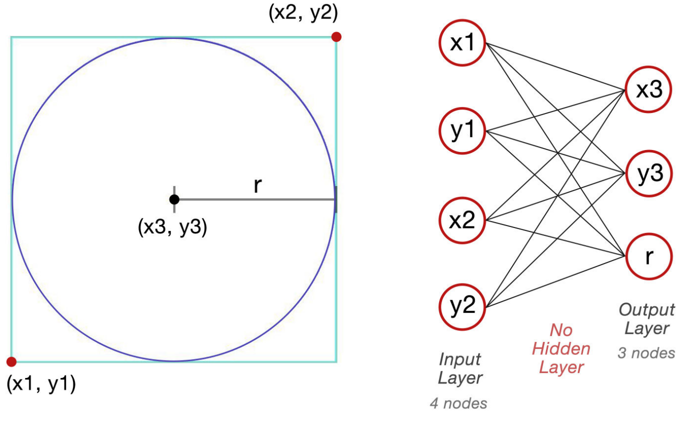

Figure 2. Geometric Statement and Network Structure of Inscribed Circle Prediction.

Before defining how many hidden layers the neural network should have, mathematically, the value of $x1$, $y1$, $x2$, $y2$, $x3$, $y3$, and r can be expressed as a linear formula. Compared to the activation function, which describes the calculation method from the current layer neurons to the next layer neurons, the indexes of the ground truth formula and the activation function for one layer are both 1. There is no need to change the activation function to increase the index or to add any hidden layers to complicate the neural network, a neural network without hidden layers should perform better to avoid the overfitting problem.

Thus, after training with a dataset of 3000 pairs of rectangles and circles, which only took 2 seconds to loop 5000 times without GPU support, the network performed nicely to predict the values. This case demonstrates that, rather than directly applying complex neural networks to the problems, analyzing and referring the possible mathematical solution is very important for simplifying the neural networks and improving its efficiency.

2.2. ADVANCED GEOMETRIC TEST - SPLINE INTERPOLATION

Next, a neural network to predict the cubic spline interpolation by inputting three control points was built. As figure 3 shows, to simplify the problem, a spline is divided into 25 points, which approximately represents the curve. Therefore, the first layer of the neural network should be the coordinates of the three control points with six input neurons, while the last layer should be the coordinates of the 25 divided points with 50 output neurons.

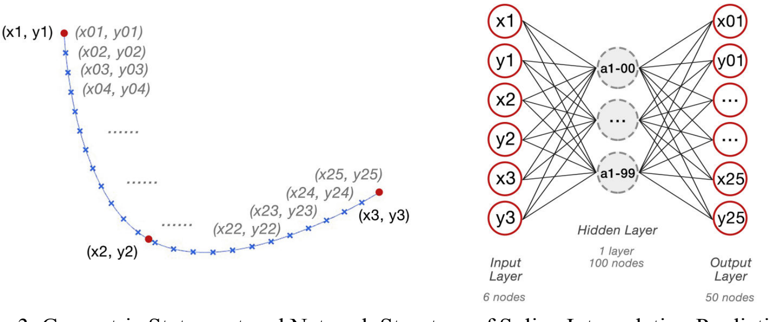

Figure 3. Geometric Statement and Network Structure of Spline Interpolation Prediction.

Before constructing the hidden layer, the mathematical expression of cubic spline interpolation, in this case, is the formula as following:

$$y_i = a_{i1} \cdot (x_i - x_1)^3 + b_{i1} \cdot (x_i - x_1)^2 + c_{i1} \cdot (x_i - x_1)^1 + d_{i1} \qquad (1)$$

Generally speaking, to calculate the output neuron values $x(i)$ and $y(i)$, after passing through the neural network, the index of the input neuron values should be a combination of 1, 2, and 3, which means the activation function should not still be linear, but a polynomial function as:

$$y_1 = w_1 \cdot x_1^3 + w_2 \cdot x_1^2 + w_3 \cdot x_1^1 + b_1 \qquad (2)$$

Also, for every spline, the neural network parameters are different. Thus, to cover all situations as far as possible, a hidden layer with 100 neurons is needed, so that the combination of parameters will be enlarged to match more data. The activation function for the hidden layer is the sigmoid function, increasing the gradient and speeding up the training process.

After training, this neural network reached very high accuracy. Thus, in conclusion, the neural network to predict spline interpolation contains one input layer, one hidden layer, and one output layer, but what's important is that the activation function is customized to solve this problem especially. This case demonstrates that functions in the neural networks, such as the activation function and the loss function, should also be considered and customized to optimize the neural networks.

2.3. DESIGN RULE TEST - RECTANGLE PATTERN

Other than directly creating simple geometric data like inscribed circle or spline interpolation, figure 4 shows a pattern design that, for a given boundary with the vertexes of $(x1, y1)$, $(x2, y2)$, $(x3, y3)$, and $(x4, y4)$, rectangles with side lengths of $r1$ and $r2$ should be fitted into the boundary as many as possible. Still, a gap with the length of 0.01 unit should remain between rectangles, and the center points of the rectangles are marked as $(x11, y11)$, ..., $(x14, y14)$, $(x21, y21)$, ..., $(x24, y24)$, and so on, by the numbers of rows and columns.

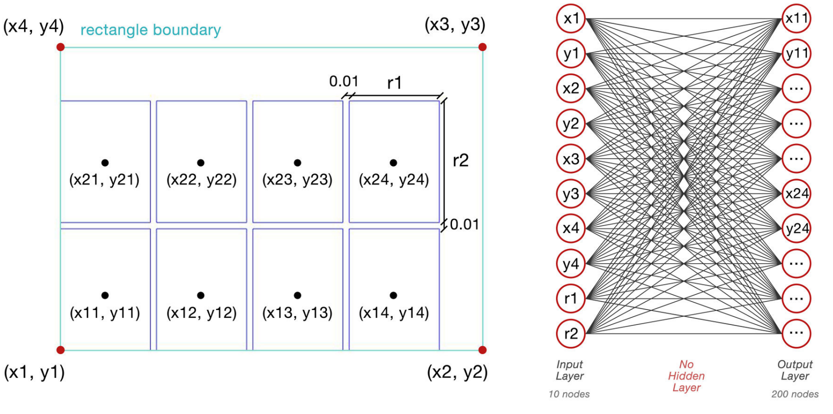

Figure 4. Geometric Statement and Network Structure of Spline Rectangle Pattern.

According to the variables described above, a neural network with the input layer of 10 neurons, which represent the coordinates of the four vertexes and the values of $r1$ and $r2$, was proposed at first. But the problem is the number of neurons in the output layer. As we know, the total number of rectangles that can be fitted into the boundary is different for every input data. But the neural network model requires a certain amount of neurons. So, the solution is that an output layer with 200 neurons was constructed in the neural network, to represent a maximum of 100 center points. Other than assigning the coordinates of the existing points to the neurons, the values of the rest neurons will be -1 to indicate the invalid points.

Also, instead of sorting valid values together, the output layer arranges the data by its row and columns. Every 20 neurons represent the rectangles in one row, so only the neurons for the rectangles in the same row and column will share the same parameters. Then the invalid value of '-1' will not influence the training process.

The later successful training of the neural network, in this case, presents a prospect that, with suitable network frame, data structure, activation function, and loss function, design, as long as it is data, has the potential to be learned and predicted through Machine Learning.

3. Application

3.1. LEARNING AND GENERATING MAN-MADE DESIGN DATA

Previous tests are all based on clear design rules and auto-generated datasets. With the successful experiments, a similar neural network was built to learn and predict human design data. The neural network parameters were also analyzed to summarize the possible formulas of human-made design.

In the test of the rectangle pattern, the neural network model can predict 2D geometries. Therefore, a neural network with similar structure and functions should work when being applied to the 2D architectural drawings, which in fact, are the primary communication tools between architects.

To simplify the question, a dataset of floor plans of bedroom design was collected from lianjia.com for training and testing. First, the elements in the bedroom design were marked as figure 5 shows. Red for the bedroom boundary, cyan for the door, purple for the window, blue for the bed, green for bed stand, and orange for the TV set. Every mark is a rectangle, representing a specific area.

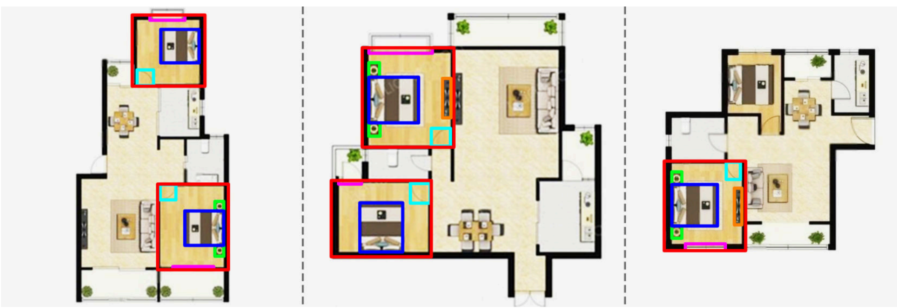

Figure 5. Labelling Rules of Bedroom Plan Drawings.

The neural network should take in the information of bedroom boundary, door, and window, as the room's situation under design, then output the rectangles of bed, bed stands (if existing), and TV set (if existing), as the design data. Thus, there should be three rectangles in the input layer and 1 to 4 rectangles in the output layer.

3.2. NEURAL NETWORK STRUCTURE

To prepare the data for training, as figure 6 shows, the geometries were first moved to the original point based on the left-down vertex of the bedroom boundary so that the bedroom boundary can be represented as $(x1, y1)$. Then for the door and the window, $(x2, y2)$ and $(x3, y3)$ represent their center points, while $r21$, $r22$, $r31$, and $r32$ represent their side lengths. Therefore, the input layer should contain 10 neurons, $(x1, y1, x2, y2, r21, r22, x3, y3, r31, r32)$.

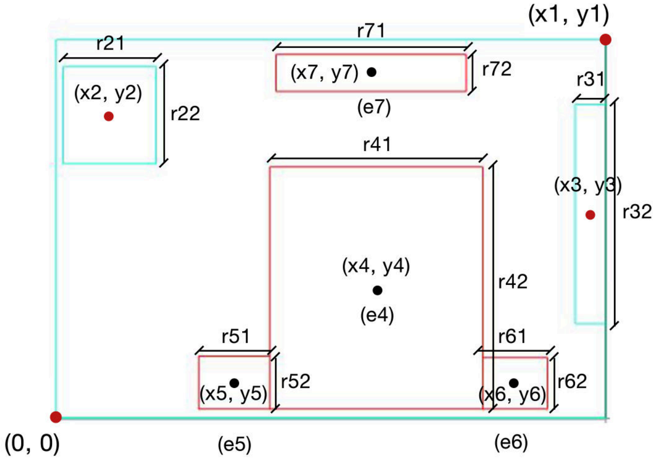

Figure 6. Variables and Meanings of Bedroom Plan Generation.

For the output layer, it's uncertain how many items should be contained in the room. Therefore, in addition to using the same rule to record the rectangle as the center point and side lengths, a variable e is introduced as the first neuron, which represents the possibility that the rectangle below exists. That means, in the training dataset, a data of $(0, -1, -1, -1, -1)$ means there is no rectangles, a data of $(1, 0.5, 0.5, 0.2, 0.2)$ means there is a rectangle, whose centric point is $(0.5, 0.5)$ and side lengths are both 0.2. Thus, if a testing result shows an e value smaller than 0.5, we can assume that there should not be an item, and we should ignore the values in the following four neurons. After arranging the output 20 neurons as $(e4, x4, y4, r41, r42, e5, x5, y5, r51, r52, e6, x6, y6, r61, r62, e7, x7, y7, r71, r72)$, the neural network structure is shown in figure 7.

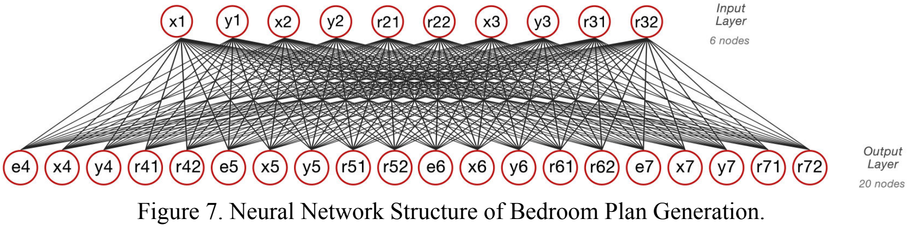

Figure 7. Neural Network Structure of Bedroom Plan Generation.

According to the previous test, the activation function and the loss function of the neural network should be the same as those of the rectangle pattern:

$$y = w \cdot x + b \tag{3}$$

$$LOSS(y, \hat{y}) = \frac{1}{n}\sum_{i=1}^{n}(y_i - (\hat{y}_i))^2 \quad y \geq 0 \tag{4}$$

$$LOSS(y, \hat{y}) = 0 \quad y < 0 \tag{5}$$

3.3. RESULT ANALYSIS

With a dataset of 179 bedroom plan drawings, 150 of them were chosen as the training set, and the remaining 29 of them were tested as the evaluating set. The training process only took 20 seconds to loop 20000 times without GPU support, since the neural network is quite simple, and the training data is tiny.

Figure 8 shows the selected generation results, which indicates a fact that the predicted designs are not always the same as the ground truth designs. To be specific, in no.152, no.164, and no.167, while the predicted positions of the bed and bed stands are highly similar to the ground truth design, the neural network generated an additional TV set, which does not appear in the ground truth design but is reasonable. In no.161 and no.170, the model also generated a TV set, but the position is slightly different, which is closer to the center axis of the room. For small rooms like no.157, no.163, and no.169, there are no TV sets both in the generated and the ground truth designs.

As for the bed and the bed stands, in the training set, there is always a bed in a bedroom, so it's no doubt that there should also be a bed in every room if the input data in the testing set is reasonable. However, there are either two bed stands, which neighbor with the bed or no bed stands in the training set, so the variable 'e' acts as the main role to tell whether there should be bed stands or not. In no.157, rather than generating two bed stands, the neural network prefers to output a more massive bed without bed stands. Also, in no.163, the bed stands disappear from the ground truth data to the generated data, which might be caused by the short side length of the room. Further, the position of the bed (and the bed stands) are closer to the center axis, for example in the situation for the TV set, especially in no.161, there is a massive shift between the ground truth data and the generated data. However, the generated results are more reasonable. And from the mathematical aspect, the parameters in the neural network represent the weighted results of all the data in the training set. Thus, the neural network should always output the most optimized solution based on the training data.

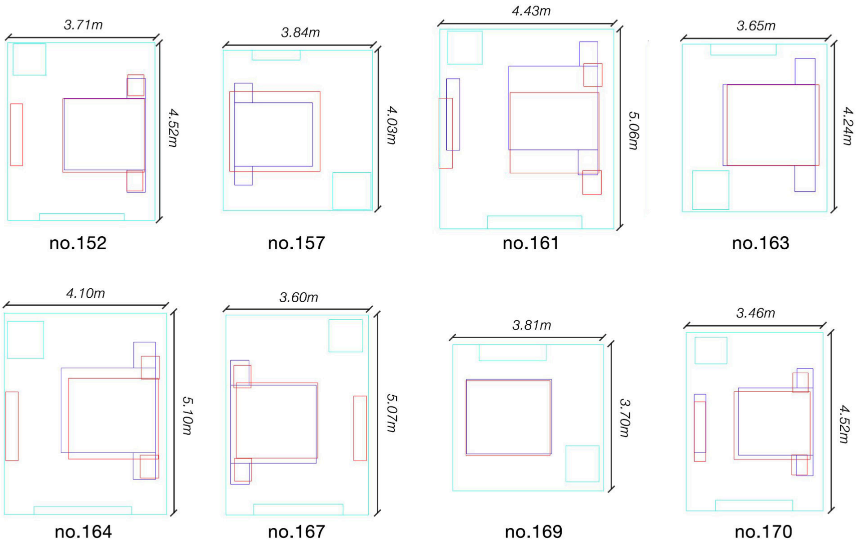

Figure 8. Performance. Cyan for Input, Blue for Ground Truth, Red for Generation.

Figure 9 shows the comparison of the results between the image-based neural network and our vector-based neural network. For the upper bedroom, both two neural networks generated two bed stands, which is different from the original design. However, for the lower bedroom, the image-based neural network outputted a noise image, while our vector-based neural network fed back a rectangle showing the position and size of the bed. This result demonstrates the stability of our vector-based neural network.

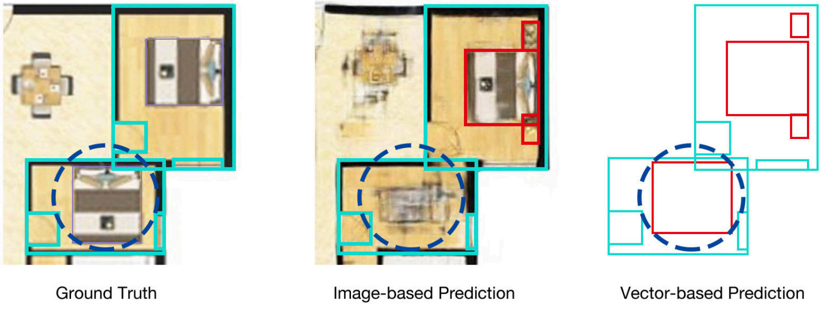

Figure 9. Image-based Prediction and Vector-based Prediction.

4. Conclusion

Machine Learning is a powerful tool for processing design data, especially for architectural design drawings. Learning and predicting architectural drawings as vectorized data is more efficient and accurate than that as image data. For simple tasks, such as generating plan drawings of interior design, a primary neural network can act correctly to satisfy the design requirements, which shows the potential of Machine Learning in design practice.

In the future, the tendency of the design cooperation between humans and machines will become more apparent. The machine will assist the design process not only in simple repeated work but also in creative work by learning the design examples from the human. Architecture design is a vast topic, however, by dividing the whole design process into several small and straightforward tasks, and using specially-trained neural networks to solve each of them, design by machine will exceed the human ability. Therefore, the following research of this paper is to develop specific neural networks to deal with different types of design tasks and finally build a "master designer" by machine.

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RECOGNIZING ARCHITECTURAL OBJECTS IN FLOOR-PLAN DRAWINGS USING DEEP-LEARNING STYLE-TRANSFER ALGORITHMS

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Abstract. This paper describes an approach of recognizing floor plans by assorting essential objects of the plan using deep-learning based style transfer algorithms. Previously, the recognition of floor plans in the design and remodeling phase was labor-intensive, requiring expert-dependent and manual interpretation. For a computer to take in the imaged architectural plan information, the symbols in the plan must be understood. However, the computer has difficulty in extracting information directly from the preexisting plans due to the different conditions of the plans. The goal is to change the preexisting plans to an integrated format to improve the readability by transferring their style into a comprehensible way using Conditional Generative Adversarial Networks (cGAN). About 100-floor plans were used for the dataset which was previously constructed by the Ministry of Land, Infrastructure, and Transport of Korea. The proposed approach has such two steps: (1) to define the important objects contained in the floor plan which needs to be extracted and (2) to use the defined objects as training input data for the cGAN style transfer model. In this paper, wall, door, and window objects were selected as the target for extraction. The preexisting floor plans would be segmented into each part, altered into a consistent format which would then contribute to automatically extracting information for further utilization.

Keywords. Architectural objects; floor plan recognition; deep-learning; style-transfer.

1. Introduction

Architectural drawing is the set of meaningful information needed for designing, narrating, and executing a construction project. Recognizing the information contained in the traditional drawings, which exists as forms of papers, CAD files,

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 2, 719-727.

etc., will help future architects for better designs. The work is time-consuming and labor-intensive, making it more efficient if the computer, not a human, can automatically interpret the drawings. Traditional drawings, however, are in a form that only humans can understand, and thus, there must be some tasks preceded for the computer to understand. To figure out the preceding work, architectural drawings were manually analyzed, and this led to the conclusion that the main reason the computer could not understand the drawings was due to the difficulty of recognizing the various symbols corresponding to one represented object in the drawing. For example, wall objects mainly consist of a pair of lines, but in some drawings, they may be represented in a color-filled form. Therefore, in this paper, a new strategy will be suggested to integrate the various styles of drawings by unifying the symbols that represent a single object for the better understanding of architectural drawings by the computer.

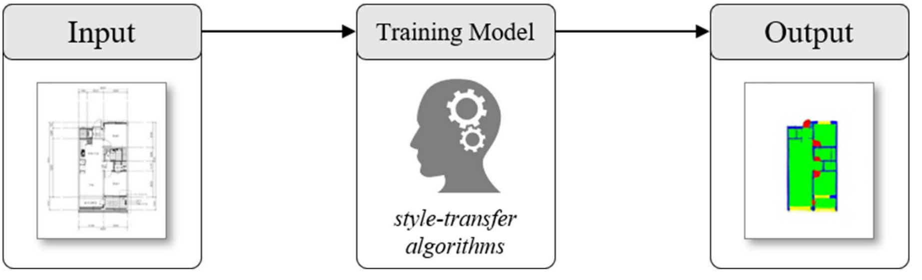

Figure 1. Outline of the study.

2. Background

2.1. ARCHITECTURAL DRAWINGS

Architectural drawings have been a symbolic language to communicate building design for a long time. They have standard representations for the building objects and design descriptions, which allow the integrating focus of the building process today. However, the problem of these architectural drawings is that the standard representation is only human-readable. The contents are conventionally 'semantic' which makes it only understandable by designers. Humans may find similar expressions between different drawings, but from a computer's point of view, difficulties exist to recognize the same symbols with slightly different expressions because the symbols are not identical.

There are several reasons for the different representations of the drawings, depending on the 1) type of drawings, 2) design phase, 3) designer's intention. Types of drawings include a floor plan showing an orthographic top-down view, an elevation and cross-section plan showing longitudinal views, reflective ceiling plans, etc. Since these drawings show different views, the representation of one object is inevitably distinct. Also, the level of detail of the drawings varies depending on the design phase of the drawing. The most complex drawing is the construction structure drawing (CSD). It is detailed enough to show internal steel bars and concrete structures since it is intended for design engineers and construction managers to use. The detail included in the drawings would differ when comparing CSDs and drawings from the preliminary design phase. Lastly, according to the intention of the designer, the emphasized object would differ, making a change in the representation.

This paper focuses on the use of floor plans in all design phases to develop a method for the computer to recognize different representations. The expression methods of different types of drawings differ so greatly, making it a challenge to use them uniformly, but the drawings according to all the design phases can all be utilized because they differ only in the degree of detail, which could be accepted.

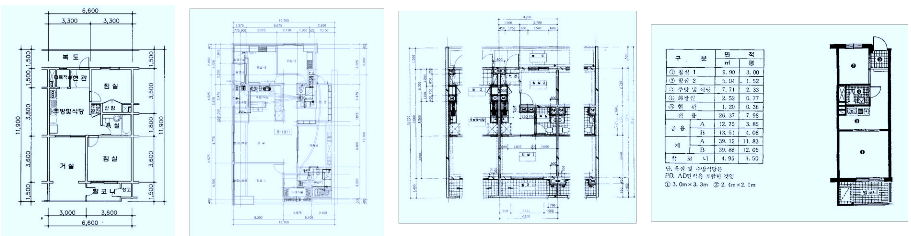

Figure 2. Various formats of floor plans: format with simplified walls, format with electronic wirings, format which includes other residences, format with large drawing tables .

2.2. OBJECTS REPRESENTED IN FLOOR PLANS

Floor plans contain a lot of information in various forms such as letters, numbers, lines, symbols, etc. The question of which information to use is one of the main points in floor plan analysis. Many of the literature have classified the information by texts and graphics, and only applied graphics in their work. However, the graphics recognized by the algorithm-based method might have unnecessary pixels, making segmentation difficult between noise and useful pixels. There is a need, thus, for a standard and a technique that can select and read only the necessary pixels instead of all the pixels.

In this paper, we suggest a standard for classifying information as design data and annotation data. Design data consists of structural and functional objects which have a contribution to the actual building. For instance, walls, doors, windows, floors, columns, beams, etc. On the other hand, annotation data consists of data that is needed for precisional comprehension of the floor plan. Annotation leading lines, dimension lines, hatchings, drawing tables, hardware symbols, etc. are included here. Annotation data is regarded as unnecessary information in the recognition of a computer because it mainly exists for the human understanding of plans. Thus, design data should be considered to a great extent in segmentation, which is a more computer-friendly data to recognize.

The scope of this paper focuses on recognizing several selected objects of the design data. The object-oriented recognition is based on objects that are important in the traditional construction industry and are likely to be used in BIM. The importance of an object in the traditional construction industry is determined by how it affects the construction of a building or the occupants of a building. On the other hand, the availability of the object in the BIM authoring tool is determined by how much it can contribute to modeling a building.

Annotation Data	Design Data
• Texts	• Wall
• Annotation leading lines	• Door ***Target Objects***
• Dimension lines	• Window
• Hatchings	• Floor
• Drawing tables	• Column
• Hardware symbols	• Beam
• …	• …

Figure 3. Scope of research.

2.3. AUTOMATING FLOOR PLAN RECOGNITION

Research on automating the recognition of floor plans has been going on for quite some time. Previous studies have been performed for the applications of recognized floor plans such as re-utilization of preexisting designs, 3D modeling, generation of new designs, etc. In these studies, for recognition, objects were defined mathematically in an algorithm-based method, which made the problem of considering all unnecessary pixels. Due to this reason, preliminary work, such as noise removal and text extraction, were needed to remove the elements that interfered with the objects. These tasks were error-prone and took a long time, which led to more efficient methods for dealing with floor plans.

Subsequent machine-learning-based recognition shows how preliminary works can be omitted by transferring the style of the format. The domain of image style transfer has enhanced by the growth of generative network models. Huang and Zheng introduced a way of implementing Generative Adversarial Network (GAN) in the field for the recognition and generation of floor plans. They parsed floor plans by segmenting areas with different functions to design by data. S. Kim et al. proposed a method to convert diverse floor plans into an integrated format also based on GAN in the vectorization process.

3. Classification of Objects for Automating Floor Plan Recognition

3.1. WALL OBJECTS

Wall objects are physical structures that define the space by surrounding a building. It is a continuous structure that divides the space into different areas. Recognition of the main walls gives an overview of the entire building structure and limits the location of the doors and windows. In designing, the preexistence of the wall is necessary, since the alteration of the wall's location will affect the overall structure, appearance and functional aspects of the building. Even within BIM, other objects such as doors, windows, openings, etc. can exist only if the wall is modeled before, making wall objects worth being selected as a target object for this research.

3.2. DOOR AND WINDOW OBJECTS

Doors and windows are objects located between walls. They have limited location since they cannot exist without walls and work mutually with the walls. Door objects are openable boundaries that give access to the building and rooms inside it. They play a role of breaking through the blocked walls and enable movement between spaces, which greatly affects the movement of people. For this reason, door objects are closely related to circulation analysis areas making it likely to be utilized in BIM.

Window objects are openings in buildings for the ingress of light, air, sound, etc. They work as an object to split walls like door objects but differ with the fact that both the appearance and functional aspects are important in window objects. Environmental factors such as visual comfort due to light, thermal comfort due to ventilation and temperature have significant effects on the human body. In addition, unlike the door objects, the window objects are located on the outside of the building, affecting the appearance of the building a lot. Therefore, window objects are likely to be used in fields such as energy analysis of façade design in BIM.

4. Recognizing Objects Using Machine Learning

In this research, the integration progress for floor plan recognition was conducted based on the recognition of the segmented target objects. The whole process of training was carried out by conditional GAN (cGAN) in Colaboratory. Before training the model, pre-tasks are necessary.

4.1. DATA PREPARATION AND PRE-PROCESSING

The training data consists of a pair of input and output data. About 100 existing floor plans were used as the input data, provided by the Ministry of Land, Infrastructure, and Transport of Korea. They show typical Korean residence and have relatively few obstacles hindering the representation of target objects. As output data, the integrated version of the floor plan was used. The integrated floor plans are color-coded with the target objects having different RGB values. RGB values of only 0 or 255 were used for labeling the objects to differentiate the objects as far as possible.

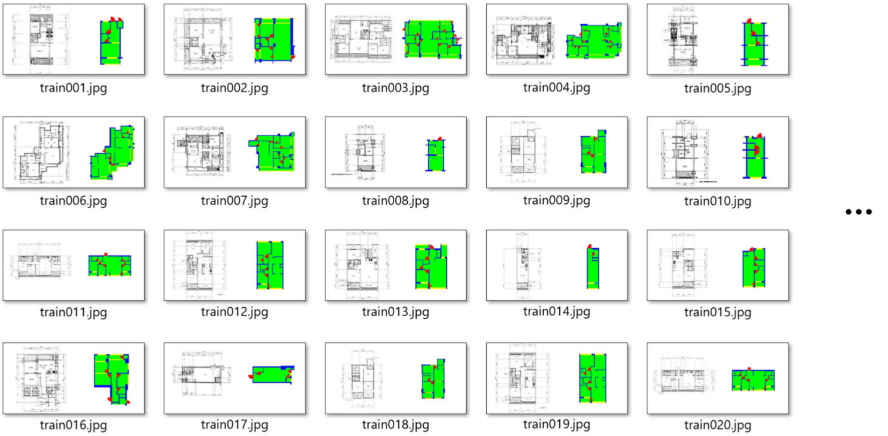

Figure 4. Samples of training data.

4.2. TRAINING AND EVALUATING STYLE TRANSFER MODEL

Conditional GAN (cGAN) proposed by Isola et. al is a powerful network that transfers style preserving the main features. This type of network was chosen for the need to maintain the underlying structure and represented objects in the floor plan. Other types of style transfer algorithms were tried, like CNN, but has failed to keep the structures in a floor plan style. For the utilization of cGAN in this process, some of the structure of the network and parameters were altered.

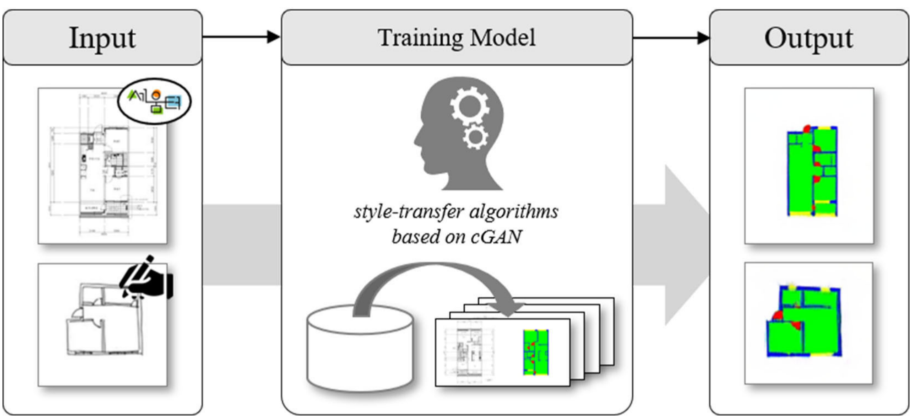

Figure 5. Training style transfer model.

Fig.5 shows the process of the style transfer model. The training model is given a dataset that consists of a pair of original datasets and an integrated version of it. The model is trained in a way to take in a preexisting floor plan and recognize it by producing an integrated format map with colors that represent the different objects.

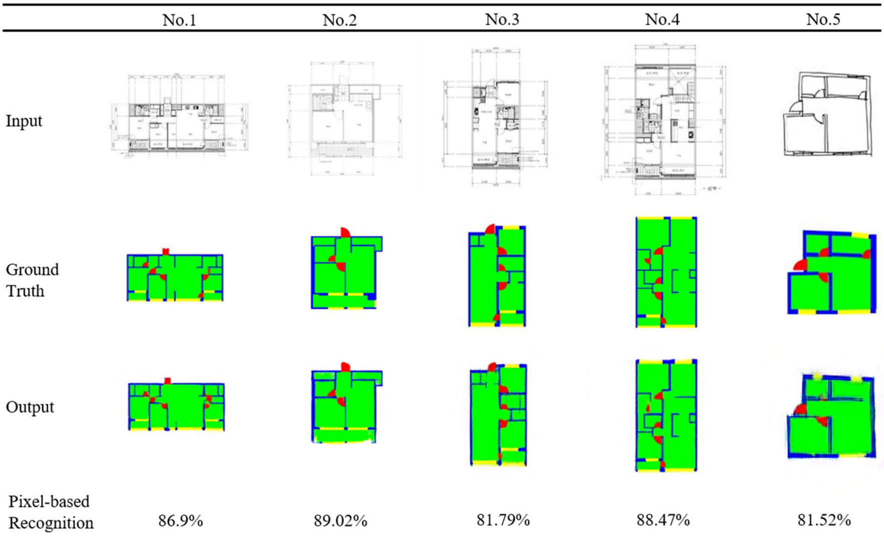

Figure 6. Results of style transfer model.

Figure 6 shows some of the selected results from the testing set. Wall and floor objects are relatively well recognized. Wall objects usually consist of two lines, making them easier to recognize, and floor objects may have high recognition accuracy because of the obvious boundaries of wall objects. In the case of window objects, the recognition rate is quite high because it also has an exact boundary because it always exists between walls. In the case of door objects, it was often only recognized for their location, which may be because they were indistinguishable from other objects that are not the target ones. In the case of No.5, it’s a hand-drawn floor plan which is recognized quite well, thereby increasing the possibility of future use of such a training model.

The evaluation of the recognized figures was made in a way that compares each pixel of the ground truth and the predicted output. Similar to object detection, the segmentation process contains a ‘Ground Truth’ which has labels that indicate the physical location of the object. In object detection, for region representing a particular object in the predicted output, and for the zone corresponding object in the ground truth, the intersection over union (IOU) can be used to assess how much the two overlap each other. Unlike object detection, the evaluation method for segmentation is different in that the classification progress is required for all pixels, and that the overall level of performance is relatively lower than that of other problems. For the recognition of objects in the floor plan, this model was used because it is most important to obtain the results of accurate recognition of the position of the objects. In PASCAL VOC Challenge, the threshold for the IOU is set as 0.5. This means that only when the ratio of overlapping areas between the ground truth and the predicted output exceeds 50% will the reliability score be evaluated for the predicted output. As shown in Figure 6, the recognition rate of the style transfer model used in this study is generally over 80%, showing relatively high accuracy in the domain.

5. Conclusion

This study focuses on a method of transforming various types of drawings into one unified form using a style-transfer model and shows that the computer can automatically and classify the target objects. Through the automatic drawing recognition, the method and applicability of the deep-learning technology, which has been used in various fields, can be applied to the architectural design field. Subsequent research is required to improve the recognition rate and accuracy, and the research on the application of the drawings in the integrated style with a clear standard for the target object that needs recognition. This study is the basis for future automation related applications such as automatic BIM modeling, circulation analysis, spatial relationship analysis, etc. from existing drawings. In future studies, you can just select only the objects you need from an integrated drawing to extract the information and then proceed to the study. This approach to drawings is expected to help with the use of many existing drawings that are currently difficult to utilize as BIM data.

Acknowledgement: This research was supported by a grant(20AUDP-B127891-04) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure, and Transport of Korean government.

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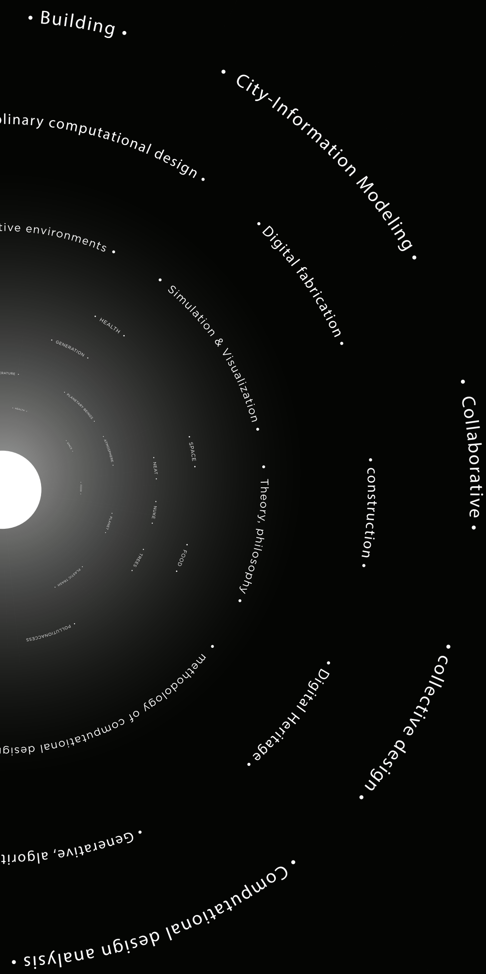
RE: ANTHROPOCENE

Design in the Age of Humans

International Program in Design and Architecture (INDA)
Faculty of Architecture, Chulalongkorn University



What if we are already in the Anthropocene epoch where the function of the Earth system is being impacted by human activities? What if our actions indeed are significant enough to have a critical force on the Earth as a system? The term Anthropocene (the Age of Humans) has gained increasing recognition as a description of a crucial geological stage of our planet as we face the consequences of our own events on the earth's ecosystem. While we are beginning to address the predominant challenges of sustainability and ecology, the environments we built have also shaped our behaviours.

To celebrate CAADRIA's 25th Anniversary, we challenge ourselves with these questions, asking what we want our future to look like, in the next 25, 50, or even 100 years? If human creations are substantial enough to start a new geological epoch, what does this imply for our explorations of the realm of computational design, and how will advanced technologies shape our futures? With the theme RE: Anthropocene, we challenge ourselves to REgard this new geological age as the main meaningful site for exploration into the future, REthink what our planet could become, REvisit our actions and behaviours to foster the REsponsibilities for the planet existence, and perhaps & importantly, REspond to whatever magnitudes happen to the built-environments and other planetary beings.

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ISBN 978-988-78917-4-1