# LIVING SYSTEMS AND MICRO-UTOPIAS: TOWARDS CONTINUOUS DESIGNING

Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016)

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**Living Systems and Micro-Utopias: Towards Continuous Designing**
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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 wider Australasian region, and has members on six continents.

CAADRIA was founded in 1996 with the following objectives:
- To facilitate the dissemination of information about CAAD among Australasian 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 annual conferences, the first of which was held in 1996 in Hong Kong. Since then, 20 conferences have been held in Australia, China, Hong Kong, India, Japan, Korea, Malaysia, Singapore, Taiwan, and Thailand. The 21st conference in 2016 is held at The University of Melbourne, Australia. The conferences provide an opportunity for teachers, students, researchers, and practitioners to meet each other and learn about the latest research in the field compiled under a unique theme reflecting the state-of-the-art research and undertakings in the field. The proceedings of the conferences are available both online and in research libraries around the world.

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 Multi-Science in both paper and electronic versions.

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**CONFERENCE THEME**

# Living Systems and Micro-Utopias: Towards Continuous Designing

Today, human activities constitute the primary environmental impact on the planet. In this context, commitments to sustainability, or minimization of damage, prove insufficient. To develop regenerative, futuring[1] capabilities, architectural design needs to extend beyond the form and function of things in contained projects and engage with the management of complex systems. Such systems involve multiple types of dynamic phenomena – biotic and abiotic, technical and cultural – and can be understood as living. Engagement with such living systems implies manipulation of pervasive and unceasing change, irrespective of whether it is accepted by design stakeholders or actively managed towards homeostatic or homeorhetic conditions. Manipulation of continuity requires holistic and persistent design involvements. In other words, "designers should become the facilitators of flow, rather than the originators of maintainable 'things' such as discrete products or images"[2].

Responding to this challenge, CAADRIA 2016 seeks to interrogate the notion of continuity and the applicable architectural toolsets in order to map and discover opportunities for innovation. Can architecture utilize computing to dynamically specify services and allocate resources to control flows of matter, energy, money or people[3]? Can architecture overcome the impossibility of perfect design by focusing on the co-emergence of technical systems and their user communities? Can it extend and radicalize the idea of lifecycle management, for example towards the inclusion of non-human stakeholders?

Engagement with complex dynamic systems poses difficult conceptual, technical and ethical challenges. To mention but a few: How can the longevity of living systems be affected through technologies for the capturing

[1] Fry, T.: 2008, *Design Futuring: Sustainability, Ethics and New Practice*, Berg, Oxford.
[2] Wood, J.: 2007, Design for Micro-Utopias: Making the Unthinkable Possible, Gower, Aldershot.
[3] Thackara, J.: 2005, *In the Bubble: Designing in a Complex World*, MIT Press, Cambridge, MA.

and sharing of knowledge, including BIM, APIs or technical standards? How do living systems equip and curtail design action, for example through interactions in creative programming, open hardware and parametric modelling communities? How does stabilization of technical knowledge in data types, algorithms, computational objects, languages or user interfaces affect the capability of designers to imagine alternative futures? Can modelling and simulation tools of architectural design cope with the inherent unpredictability of complex systems by integrating such approaches as big data analysis or pervasive computing? Can advances in fabrication and mechatronics support design that functions analogously with the mechanism that evolutionary biologists call adaptive niche construction? What educational approaches are appropriate and future-ready in a world of global and accelerating change? This list of questions could be readily extended.

Crucially, research into more holistic, ecological approaches to architectural design must overcome a methodological mismatch of spatial, temporal and organizational scales. The ecologies of real-world living systems are incalculably more extensive than the bounded experimental prototypes that are possible in research and education. What strategies and technologies can be employed to overcome this dilemma?

CAADRIA 2016 proposes to interrogate whether and how designers' capacity to create micro-utopias[2] can illuminate or redirect complex, longer-term processes and probe into alternative futures. Examples of relevant methods include, but are not limited to, critical making[4] and critical technical practice[5], interrogative[6], critical and speculative design[7] and wild or feral computing[8].

CAADRIA 2016's theme of *Continuous Designing* offers a viewpoint for interrogation of all research in design and computation, including, for example: theory, philosophy and methodology of design research; education; collaborative and interdisciplinary design strategies; stakeholder participation; design innovation and creativity; generative, parametric and evolutionary design; visualisation, virtualisation modelling, simulation and prediction; city,

[4] Ratto, M.: 2011, 'Critical Making: Conceptual and Material Studies in Technology and Social Life', *The Information Society*, **27**(4), 252–260.
[5] Agre, P. E.: 1997, Toward a Critical Technical Practice: Lessons Learned in Trying to Reform AI, *in* G. Bowker, L. Gasser, L. Star & B. Turner (eds.), *Bridging the Great Divide: Social Science, Technical Systems, and Cooperative Work*, Erlbaum, Hillsdale, NJ, 131–158.
[6] Wodiczko, K.: 1999, Interrogative Design, *in* K. Wodiczko (ed.), *Critical Vehicles: Writings, Projects, Interviews*, MIT Press, Cambridge, MA; London, 16–17.
[7] Dunne, A. & Raby, F.: 2013, *Speculative Everything: Design, Fiction, and Social Dreaming*, MIT Press, Cambridge, MA.
[8] Fuller, M. & Matos, S.: 2011, 'Feral Computing: From Ubiquitous Calculation to Wild Interactions', *Fibreculture Journal*, 135, 144–163.

site and building information modelling; human-computer interaction; ubiquitous and pervasive computing; sensing; artificial autonomy and intelligence; mechatronics; fabrication, construction, optimization, mass customisation, and others.

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KEYNOTE I

## SOME CRITERIA FOR MAPPING CONSCIOUSNESS IN LIVING BUILDINGS

JOHN WOOD
*Goldsmiths, University of London, London, United Kingdom*

In discussing ways to re-direct the current Building Information Modelling (BIM) agenda, John draws upon theories of living systems furnished by Maturana & Varela and Jakob von Uexküll. He asks whether BIM could be developed to make future buildings come to life? By regarding buildings as inanimate, we accept them as fundamentally dissipative. This is because the passive idea of 'conserving' building reflects the pessimistic logic of classical thermodynamics. By contrast, the life sciences depict living creatures as systems that maintain their collective survival by resisting entropy. The reason why thermostats and clocks are the dumbest gadgets on the planet is because they are expressly designed to ignore their own role and context. If BIM files were to be interactively updated by the metabolic states of a given building, this might help it to acquire a level of consciousness that includes its own presence and interdependency with the habitat. Ultimately, perhaps living buildings will learn to share tasks with their inhabitants on a symbiotic basis.

KEYNOTE II

# BEYOND BIM – DIGITAL PLANNING AND CONSTRUCTION AS CONTINUOUS DESIGNING

FABIAN SCHEURER
*designtoproduction, Zürich, Switzerland*

Discussions around Digital Practice and Building Information Modelling (BIM) are currently omnipresent across the building industry.

Drawing from application in practice, the Zürich-based studio designtoproduction has successfully been investigating the consequent shift towards digital approaches in construction over the past 10 years. Working predominantly on the back-end of project execution, the interdisciplinary team around architect Arnold Walz and computer scientist Fabian Scheurer helps architects, designers, engineers, and manufacturers bridge the gap between idea and realization when it comes to so-called "Non-Standard-Architecture". At CAADRIA 2016 designtoproduction's founding member Fabian Scheurer will (based on a select number of reference projects) reflect on the fact that the future trend of 'digital construction' has – in effect - long been a reality in contemporary practice.

In his keynote address, Fabian will explain the paths designtoproduction takes in the efficient and high-quality planning and realization of designs whose complex shapes could be neither described with conventional methods nor built from standard components. The services of designtoproduction range from consulting for parametric planning, detailing, optimization and digital manufacturing, to the development of parametric CAD-models and the implementation of complete digital production chains, from design through fabrication, logistics and assembly.

The CAADRIA keynote will highlight how, during the past years, designtoproduction has successfully worked on projects by renowned architects like Zaha Hadid, Renzo Piano, Daniel Libeskind, SANAA, Shigeru Ban, and UN Studio, including the Mercedes Benz Museum in Stuttgart, the Rolex Learning Center at the EPF Lausanne, and the Centre Pompidou in Metz.

KEYNOTE III

# FALLS THE SHADOW

DREW WILLIAMSON
*McBride Charles Ryan, Melbourne, Australia*

There have always been barriers between conception and realisation across all spheres of creative endeavour. In architecture, historically, visions of the future – from Piranesi and Josph Gandy to Boullée, from Sant'Elia and Bruno Taut to Lebbeus Woods – were captured in the representational media of their time, but often not translated into the actuality they depict. Indeed, such 'visions' were inherently perspectival and resisted realisation, either through limitations of translation (communication, orthographic representation, geometric description), industry (material engineering, construction techniques), opportunity (demand, brief, budget) or any combination of these factors. Between the idea and the reality fell the shadow. Over time technologies have developed to overcome these barriers and facilitate each 'project's' delivery. Applying Robin Evans's definition of design as 'action at a distance', increasingly that distance is being reduced.

Advances in this regard have been evident over the last twenty years as practicing architects have become increasingly conversant in the digital generation of three-dimensional form. Limitations to architectural expression have been less one of geometric description as one of communication between the professions and contractors involved in delivering the projects through to completion. The shift was one from 'computation-enabling-expression' to 'computation-enabling-collaboration'.

Bill Mitchell articulated his observations on this period as a relationship between 'design complexity' on the one hand and 'construction complexity' on the other, and foresaw how the development and application of digital design technologies were enabling the realisation of design complexity in built projects. Yet the experience in practice at delivering innovative architecture with an increasing richness of expression has shown that conceiving of non-conventional geometries and material assemblies and describing the buildability of these to clients, consultants and contractors, only addresses part of the problem. Fundamental barriers still remain, specifically in regard to project viability due to construction cost. 'Complexity' in design intent is still synonymous with 'difficult' and therefore 'expensive'. In practice, such barriers appear to have been amplified by the same processes that have, con-

versely, elsewhere enabled complexity and diversity: management, simplification, efficiencies… If these cannot be solved through computation alone, where should the focus of our research now be?

# FOREWORD

The theme of Living Systems and Micro-Utopias: Towards Continuous Designing – the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016) – seeks to challenge the use of computation in architecture by interrogating how designers' capacity to redirect complex processes and probe into alternative futures. Hosted by Melbourne School of Design at The University of Melbourne, CAADRIA 2016 conference provides an international forum where academics and practitioners share their novel, multidisciplinary research.

These Proceedings include 86 full-length papers that were rigorously reviewed by at least three anonymous peers from the International Review Committee. The contribution of the 104 expert members of this committee and the overall selection process uphold CAADRIA's highly respected international standing as one of the leading conferences in computer aided design. The call for extended abstracts that was issued in July 2015 attracted 256 submissions. The Paper Selection Committee reviewed all initial submissions and accepted 195 abstract for further development. These abstracts resulted in 136 full-length papers. Each of these papers was then assessed by the International Review Committee that provided anonymous feedback and recommendations for improvement. Following the reviewers' recommendations, 93 papers were accepted by the conference, of which 86 are finally included in this volume and presented at CAADRIA 2016.

Collectively, these 86 papers interrogate Continuous Designing from the following research viewpoints: Big Data and Precinct/City/Spatial Modelling; Practice-Based and Collaborative Computational Design and Research; Shape Studies; Generative, Parametric and Evolutionary Design; Computational Design Analysis; Human-Computer Interaction; Simulation and Visualisation; New Digital Design Concepts and Strategies; Building Information Modelling; 3D Printing and Robotic Assemblies; Theory, Philosophy and Methodology of Computational Design Research;

Virtual/Augmented Reality and Interactive Environments; Digital Fabrication and Construction; Computational Design Research and Education; and Design Cognition and Creativity. The following pages present the wide range of scholarly papers organized under these rubrics.

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## BIG DATA AND PRECINCT/CITY/SPATIAL MODELLING

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# ANTHROPOCENTRIC

## *Real-time data to encourage social interaction and way finding in mass transit spaces*

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**Abstract.** This research aims to demonstrate the use of commonplace technologies within an architectural system to produce unique real-time user experiences, within the context of a design-led thesis. The result is a personalised real time way finding system, incorporating embodied physical architectural elements and virtual simulation projections with a supporting mobile application. The developed spaces are immersive and ever changing, representing live data inputs and movement of users in space specific to location, through the development of a data representing software.

**Keywords.** Embodied interaction; way finding; real-time data; mixed reality.

## 1. Introduction

Data flows are increasingly embedded in systems throughout society, facilitating the world around us. This ‘big data’ is rarely seen, accessed or understood directly by members of society. However, this data contains important trends that, if accessed, provide insights and cause implications beyond their original use. Methods of accessing this data are usually done via dedicated computing devices, often using web browsers or applications.

This research proposes the use of ubiquitous (McCullough, 2004) and emerging (Achten, 2015) technologies and mixed realities (Anders, 2007) to spatialise data. A case study of a novel airport way finding system is used as a response to the following question: How can data be used to alter architecture to produce an authentic human centric experience and to facilitate a socially responsive space?

Designing Mixed Reality outlines ‘cybrids’, integrated inhabits of mixed reality which form a physical/virtual object (Anders, 2007). Digital-physical translations, local human data and API data about users in space will produce mixed reality cybrid architectures (Anders, 2007). Ubiquitous mobile technologies (Hansen, 2015), embodied interaction techniques and attributes, (Rahaman and Tan, 2009; Schnabel et al, 2007) and graphic representations (Achten, 1997) will produce real time, responsive experiences. Representing Inputs overviews the translation of live streaming data into a 3D form. Personalised Way Finding System produces a spatial simulation linked to humans via smartphone applications and architectural projections, providing a real-time, personal way finding system, connecting users to data and each other. Other projects in the CAAD community have explored the use of human computer interactions to inform mixed reality space (Anders, 2007; Chiu and Chiang, 2006; Kuo et al, 2004).

The experiments will be placed within Milgram and Kishino’s Reality-Virtuality Continuum, between actuality to simulation, with Anders’ (2007) principals of Mixed Reality Design produce an Interactive Design Index on which to access outcomes. This framework is chosen based on the research aims, to develop a unique solution. They are the following:

- Comprehensive space between material, cognitive and symbolic,
- Corroboration and reciprocity,
- Extension of a coherent spatial experience and social context, and
- Anthropic Design (Anders, 2007).

## 2. Representing inputs

Translating data about people to information is initially done in two sections, first to represent data in informative 2D graphics via generic forms, second to spatialise the developed logic, creating a human-centric architecture.

### 2.1. GRAPHICAL 2D REPRESENTATION

Investigating methods of translating live streaming data into graphic information is done using Fry’s interactive visualisation design principles of data representation. Information is extracted from personalised user centric data, including flight information, weather, geographical and human motion via motion capture, forming a depth of context and location. Data choices are made based on its centricity to users. A generic representation is designed around input data, encoding sequences to display multiple types of data inputs visually (Achten, 1997). Each variable is mapped to a geometry’s loca-

tion, size or hue. Grasshopper is used to transform data, with specific plugins to parse API and motion capture feeds.

#### *2.1.1. Flight data input*

Real-time arrival and departure data gives four key outputs: time of flight, aircraft, gate and destination/origin. Using geometry's size, location and movement as variables, flight data is mapped showing dynamic movement of users instead of traditional, static way finding systems.

#### *2.1.2. Weather input*

Temperature or wind speed at the destination or origin is overlaid, adding contextual information. Colour coding explores the relative temperature level at the destination compared to the current location. This acclimatises users physically and mentally, allowing passengers to change their clothing or prepare for the destination through a simple graphic and a real time awareness of destinations' environment. This links locations to users based on their journey not physical distance.

#### *2.1.3. Geographical input*

Adding a geological contour map overlay of destinations' topography helps to further understand of the visualisation. Topological data is pulled from a file based on the destination/origin and becomes the surface. Logic begins to become artistic, adding fluidity into a data driven system.

#### *2.1.4. Kinect input*

A simple interaction method was devised where the location of a person is motion captured and mapped to the visualisation as a negative attractor to shift data around. This introduces of embodied interaction with virtual forms.

### 2.2. RESPONSIVE 3D REPRESENTATION

3D Representation creates a kinetic space that responds to people via input of data based on the 2D graphic method above. Wu and Clayton (2015) define a 3D visualisation of data sources. Using similar methods, in a kinetic form, responsive architecture can be created to develop a central concourse form. These are:

- Gate links flight to pathway which are designer defined,
- Time until flight arrives/departs is calculates point on path, and

- Point and curve creates a curve using 2D metaballs.

Curves inform extrusions. Inside the floor is flat, allowing more space for users. Outside the curve forms are extruded by an amount proportional to the distance to the curve. Circulation, acoustic, light and material properties change as the space does. The result extends and retracts creating enclosed or exposed space, seating or walls, and helping people navigate spatial zones.

### *2.2.1. Responsive architecture from data about users*

Architectural form responds to users' needs at different times of the day, informed by flows of people through space, represented in data. Using big data indirectly from user's movements, architecture becomes a compound of a user's path, responding to trends with awareness for future events, 'corresponding to certain time frames' (Hansen, 2015). The process provides an extension of social groupings and spatial flows beyond pre-existing norms.

This initial project meets some of the performance index, explained below:

- Movement of physical forms skew towards reality,
- Logical ability for the user to understand data,
- Digital data informs physical movements,
- Sociality and experience of a user doesn't affect others, and
- Based on human data is intrinsically anthropic.

Source data inputs effect the spatial outputs. As there is no data distinction between visitors and residents, the design cannot respond to these data changes. Such inputs would change performance when more visitors were exiting or entering the city compared to residents, creating more complex logic but a refined form. Real-time changes in data allow proportions of seating, social and circulation areas to alter in real-time. Responsiveness creates social areas, but as personal data isn't used as an input, social interaction is not highlighted. Colour coding funnels users based on flows and changing lighting in key pathways gives space a transformative directionality to it.

## 2.3. SUMMARY

The initial design stage provides bidirectional navigation for a single airport space. Parameters change based on the current data, accurately suiting the needs of the users. Many way finding techniques have not been included, instead focusing on abstraction of data inputs into simple and ergonomic forms.

It developed a language for understanding data in physically inhabitable, three dimensional ways, however these highlighted difficulties of translating real-time data at an appropriate level of detail while remaining responsive to all users' needs. The need for kinetic architecture is questioned. Information can be relayed through material, light and sound but is data output is not clear. Interaction between people and space is to be improved though including more real-time human inputs and a composite system between traditional way finding mechanisms and the real time personalisation available with technology.

## 3. Personalised way finding

The project shifts focus, to using ubiquitous technologies to create a spatial technological system centred on personalised social interaction. Humans are central to the project. A sense of individuality must remain throughout the experience of a shared space. It could be considered the developed system is a form of cybrid, with physical hardware and a digital virtual display. The projection mapping of digital form onto physical surface will form augmented reality through iterations, adding detail and intelligence.

### 3.1. VISUALISATION

Processing, an IDE and language often used for interactive graphics, is used to develop a simulation of space as a Cartesian coordinate system. Design iterations develop a logic of detailed display data. The initial logic is the following, producing ever changing forms, depending on data:

- Using flight data, each flight is assigned a colour, each passenger is represented by a point.
- Points have a random position and velocity (between -1 and 1 pixel/frame).
- Attractor points are set up based on the physical location of gates.
- As the flight gets closer to departing, the attractor attracts the points from the departing flight.
- As more points reach the departing flight, a ring gets larger.

#### *3.1.1. Flocking algorithm*

The initial logic provides a framework for a spatial understanding of people moving through space. A flocking algorithm provides cohesion, separation and alignment, simulating movement through space. Lines between points on the same flight groups people visually.

### *3.1.2. Interpretation*

Locations of individuals as points provide detailed information of the social movement of users, but needs to be conveyed quickly at a glance. To understand the location of groups of people, coloured trends overlay the graphic showing groups of 10 or more people within a set radius on the same flight. This awareness notifies users when they are in 'the pack' or falling behind. Abstraction of data produces a clear set of information that isn't seen in the raw data inputs (Achten, 1997).

### *3.1.3. Visualisation on specific architectures*

The architectural representation is a simulation of a plan but doesn't denote a specific point in space. Based on the initial program, an additional function calculates the distance of abstracted points to a set point in physical space, creating a simulated, augmented, panoramic view from that point. The result is a context specific visualisation within the space, providing an extension of 'coherent spatial experience' (Anders, 2007) through a logical and simple method. When a physical point is close to a gate and that gate is boarding, the visualisation becomes the colour associated with that flight.

### *3.1.4. Dealing with mixed reality*

The various technologies and mediums allow the projects to inhabit multiple points of the Reality-Virtuality Continuum, engaging the human audience whether through personal devices, in social situations or circulating the space.

The projection is augmented to a physical form allowing 'a user to work in a real world environment while visually receiving additional computer generated or modelled information to support the task at hand' (McCullough, 2004). The project adds virtual elements to the physical world, allowing equal experiences by everyone in the space without special equipment or software (Anders, 2007). Hence, virtualised data about humans occupying the space digitally fixes itself onto the physical building, creating a cybrid of the activity happening within.

## 3.2. HUMAN LOCATION

Achten (2015) overviews ubiquitous and developed technologies allowing interactive space to become more sophisticated. These are divided into three areas – Internet of Things, Wearable Technology and Cloud Computing. Location systems, Indoor Positioning Systems (IPS) and Global Positioning Systems (GPS), integrated with wearable technology into a mobile software

application allow a user to feed personal data anonymously into the system. They can then receive updates and get an awareness of everyone else in the system, helping users navigate and time manage better. GPS has been prototyped on an android phone, working to relay the distance to a server and deliver the user to their destination. Based on real-time feedback the application visually changes. IPS integration is yet to be prototyped, using Bluetooth LE beacons in space. Projected, abstracted, individualised data helps all users understand the space, its trends, flows and its relationship to users.

A Collaborative Virtual Environment is embodied through the proposed system (Segard et al, 2013) allowing physical communities of users to interact in virtuality while solving a physical problem of spatial circulation. Taking big data and local data, and have these converge, can change the way people used space provides localised, customised, efficient and specific spatial experiences (Achten, 1997). Location models are representation of 'activity and organisation' of space (McCullough, 2004), the sharing of which has the ability to help those in space via a shared understanding of personalised experiences. Human computer interaction is done socially, the communication is first mediated by computer systems but is then transcended into the physical. The end result is an improved physical experience than one without computation.

### 3.3. PERSONAL DEVICES

Smartphones are ubiquitous and often seen airports. Spatialising interactions with these devices, using built in technologies, IPS through Bluetooth and GPS, we can increase the immediate social and physical connections. A colour coded application interface (figure 1) matches personalised flight visualisation cybrid, visually linking together phone screens to each other, communicating and interacting with nearby users, and to the architectural projections. Duality between the personal devices and architectural space provides a set of real and virtual engagement that can be used in three ways; Personal device as an indoor way finding app for a building, Architecture as a work of installation art for space, or Combination as an immersive experience.

Though two points of interaction with the Reality-Virtuality Continuum, opportunity arises for a greater level of interaction between users. Physical sociality expanded into the virtual world creates an easier interaction with a lower social threshold. User tracking with provision of a virtual real-time representation of realty extends the social boundaries beyond that of the physical social constraints. (Kuo et al, 2004).

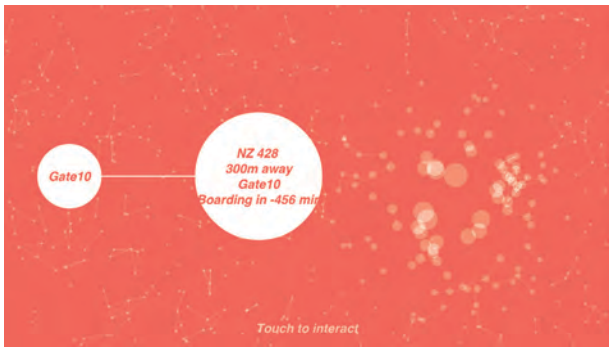



*Figure 1. Application Screenshot.*

The physical – virtual duality of the system uses interfaces between the two realms, made up of sensors for system inputs and displays for system outputs. Each integrates with a section of the overall system, specifically responding to part of the environment, either individually or globally. Sensor data can be considered to be based around the Internet of Things, 'computational representations of physical objects' 'manipulated by virtual entities'. These connected physical objects can then stream data to be used influence interactive space (Anders, 2007). A server/client network allows a supply of data from smartphones to an architectural client, producing projections, presenting a smart architecture. Personal devices become another input for spatialisation.

### 3.4. PROJECTION MAPPING

Projecting on a surface, digital 2D media is 'calibrated to match the depth and details' to become part of the forms and facades, linking the mediums (CreativeApplications.net, 2014). Physical form is installed in space, becoming floors, ceilings, facades lighting etc., to create a constant experience throughout. The physical surface's material perception changes depending on the way it is projected on, for example, shadows cast across the surface creates areas of light and dark. Alteration of surface qualities in real-time provides a virtual mapping of the physical world. The physical surface reflects light around space depending on material qualities and what is being projected (figure 2). This displays corroboration between realties with intrinsic connection between form and projection, ensuring cohesive design.

In order to achieve architecture that is relevant to the needs of people, a series of form related experiments takes place, transforming human-centric data sources into a 3D form. Data in constant flux is not used as it is dynamic, instead data of a meaningful point in time is chosen. Two experiments take place with two sets of data, using a mapping of values to coordinates in

a 3D grid (Wu and Clayton, 2015). Projections then respond to form through mapping and attractor point locations



*Figure 2. Projection Mapping on Data Surfaces.*

This project works to meet the performance index (figure 3). Physical and digital elements have corroboration and reciprocity through their intrinsic link to user specific data sources. This data usage also gives it an anthropic design that creates a unique and informative human computer interaction. The space acts as an extension to the usual social happenings in the space, amplifying the understanding of circulation in the space while remaining discrete.

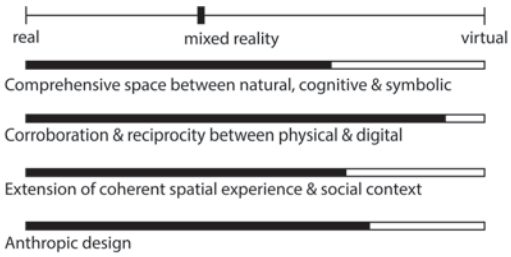



*Figure 3. Interactive Design Index for Developed Design.*

## 3.5. SUMMARY

This phase devises new ways to experience space through physical and virtual worlds simultaneously. Using the design index, a unified experience to help users to understand data, and other people through data is created. Following this, the project requires further prototyping and testing to develop a fully aware system. The system adherers to understanding of spatial computation, taking computing from a task to a layer of reality with ‘a comprehension of physical space which is related to that of the user’ (McCullough, 2004).

Personal devices are universal devices, the architecture is a situated device, and this link covers interaction methods based on personal and social preferences. Smartphones are portable and location based, whereas the architecture is responsive, embodied and activity based, inserting the user within the architecture creation process in real-time. By comparing these, their

technologies complement each other, the phone is an extension of the human, and the projection is an extension of the architecture.

## 4. Conclusions

This paper describes a real-time data influenced way finding system and its use of mixed reality and technologies to spatialise data. By using principles of physical/virtual architecture, a greater level of customised human centric spatial experiences can be gained, increasing authenticity, navigation and socialisation.

Each stage explored a new set of technologies. First real-time data inputs from API's and humans, the second translation and processing, and the third location and mobile application design. This compounding iterative effect resulted in a system-situated between interactive architecture and mobile navigation systems, highlighting the need for cybrid, dual reality thinking in the development of data-spatial systems. Embodied interaction created people-to-people relationships through digital interaction, extending social locations, acting as a social motivator to connect humans and improving the use of space.

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# NEIGHBOURHOOD DETECTION WITH ANALYTICAL TOOLS

## *Identifying neighbourhoods from geospatial and transportation data though graph evaluation and learning algorithms*

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**Abstract.** The increasing population size of cities makes the urban fabric ever more complex and more disintegrated into smaller areas, called neighbourhoods. This project applies methods from geoscience and software engineering to the process of identification of those neighbourhoods. Neighbourhoods, by nature, are defined by connectivity, centrality and similarity. Transport and geospatial datasets are used to detect the characteristics of places. An unsupervised learning algorithm is then applied to sort places according to their characteristics and detect areas with similar make up: the neighbourhood. The attributes can be static like land use or space syntax attributes as well as dynamic like transportation patterns over the course of a day. An unsupervised learning algorithm called Self Organizing Map is applied to project this high dimensional space constituting of places and their attributes to a two dimensional space where proximity is similarity and patterns can be detected – the neighbourhoods. To summarize, the proposed approach yields interesting insights into the structure of the urban fabric generated by human movement, interactions and the built environment. The approach represents a quantitative approach to urban analysis. It reveals that the city is not a polychotomy of neighbourhoods but that neighbourhoods overlap and don't have a sharp edge.

**Keywords.** Data analytics; urban; learning algorithms; neighbourhood delineation.

## 1. Introduction

Understanding the urban fabric depends on understanding the underlying structure. Urban structure is the arrangement of urban spaces, the relationships that the urban fabric permits and the interactions that comprise of people, freight and materials, and information (Rodrigue et al, 2013). These interactions influence transportation, economic growth, social equity, and urban development. The urban form therefore has a direct impact on the configuration of the city through local efficiency, equity, quality of life and health. The form of human settlements develops from a central market towards a polycentric; decentralizing form due to increased equity, mobility, transfer of information and population. This can lead to heterogonous urban sprawl with a complex hierarchy of centres, neighbourhoods, and communities connected through transport and information systems. The question this paper addresses is how can we detect and represent this complex system of centres and neighbourhoods? This has implications for governance, planning and design.

The development of the urban fabric is driven by changes to the transportation and information systems that allow urban dwellers to be connected to any place and makes places more accessible (Anas et al, 1998). With an increasing complexity of human movement the urban space is under constant reconfiguration. Urban dwellers are the carrier and transporter of materials, money, and information between places. Travel and the travel infrastructure is therefore a proxy to understand the spatial configuration of neighbourhoods. To explore this further, this paper tries to identify the following elements of the urban fabric:

- **Connectivity:** the relative ease of travel from a place to places
- **Centrality:** the number of transportation routes that travel through a particular place, as well as the relevance of the area with respect to other places
- **Similarity:** the rate of change in urban indicators between places
- **Boarders:** the socioeconomic boundaries that are can be detected by aggregated travel location choices that subdivide the city

To identify connectivity, centrality, similarity and borders a combination of transportation and geospatial data is used. This paper applies urban analytics approaches that borrow methods from informatics, statistics and geoscience augmenting them with spatial information. One of the contributions of this paper is the combination of data sources with different properties, such as temporal data and static data that are not usually combined.

To identify connectivity, the existing physical road network is used to perform graph analysis. In particular the integration of each of the >1.45 mil-

lion links with respect to the rest of the network, i.e. its proximity to all other links in the network, and its centrality, i.e. the number of shortest paths every link to all other links going through a particular link. The transportation data for a single day is a representative sample of the population of Victoria (~5.8 million) collected by the Department of Transport containing 151,713 trips for a day in 2007 and 163,299 for a day in 2009 that also contain additional information on the purpose of the trip (DOT, n.d.).

The analysis presented in this paper is applicable in two ways. First, we apply a myriad of established methods on the state of Victoria and validate our ideas on 'what constitutes a neighbourhood' from novel insights into the actual structure of Victoria. Second, we introduce a learning algorithm to evaluate urban configurations including the workflow that combines not only attributes of locations or networks and flows but all of the above.

The rest of the paper is organized as follows. Section 2 provides a review of existing research in the field, leading to the conclusion that the presented approach is novel in its use of multiple sources of data and methods. Section 3 introduces and elaborates on the methods applied and invented in this paper. Section 4 presents the example application on the state of Victoria, Australia, the data sets used and the results. Section 5 concludes with a critical discussion and an outlook on unsolved problems.

## 2. Related research

Although this research is motivated by recent development in both software tools and availability data, it addresses a classic problem of decomposing the city into smaller neighbourhoods. In spatial analysis this problem is known as 'aggregation problem' where researchers are either decomposing spatially aggregated data or aggregate data from individual observations to spatial areas or zones. The methods use commonly characteristics based on demographic, economic, or ethnographic structures and apply methods from fields like transportation planning, mathematics, statistics, or geography.

In the 1960s a formal tool to derive mutually exclusive or overlapping hierarchies in large data sets was pioneered by Berry (1967) and extended to interaction data including densities, volumes, and directions of flows, which is the basis from which to create a spatial system based on aggregation (Slater, 1976; Batty, 1978). Approaches using stochastic models to predict land use exist since the early 19$^{th}$ century (von Thunen, 1875) and have seen a revival through the implementation in cellular automata (CA) (Batty, 2007). CA has provided intriguing results since their conception in the 1950s (Von Neumann, 1951). The increase in computing power allowed for an ever-increasing refinement of the individual cells. The availability of more

longitudinal data helps to define the underlying function. Problematic in this approach is the ‘one size (of raster and time) fits all’ that does not differentiate between areas of high heterogeneous activity or change within a city.

Network based analysis was pioneered by Nysten and Dacey in the 1960s using graph theory to spatially partition the city. This approach was very rudimentary and it took until the development of network science in the last two decades for these methods to appear.

Increased sensor density and storage of urban data has created a momentum in the analysis of networks and flows in cities. These ‘big’ data sets are investigated to gain insights into the dynamics of human movement and activity (Zhong et al, 2014). Methods are borrowed from other fields such as the statistical analysis of human travel behaviour on transportation data (Park et al, 2008; Liu et al, 2009; Kang et al, 2013; Munizaga and Palma, 2012). Over time these evaluations of activity and travel patterns led to the detections and identification of the fine urban spatial structure. In London Roth et al (2011) used Oyster Card data and in Singapore Ordóñez and Erath (2013) used stochastic models to estimate workplaces. Machine learning methods are implemented to derive land use from mobile phone use patterns (Toole et al, 2012). These datasets allow us to discover patterns in the urban fabric useful for a variety of application (Jiang et al, 2012; Song et al, 2010; Noulas et al, 2012; Simini et al, 2012).

Detecting a pattern in the urban fabric is the first step in evaluating the impact of change over time though planning and design interventions. These changes are important to estimate the impact of changed activity and transport patterns on social, environmental, and economic systems (Páez and Scott, 2005).

Current approaches use either geospatial or transportation data to detect networks of flow and activities. This paper aims to extend the current system by extending the analysis from a single data set to a multitude of data sets regardless of their structure.

## 3. Method

This project proposes the integration of network graph analysis, spatial analysis and temporal transportation data through an unsupervised learning algorithm. Therefore the rest of this section is organized starting with the data sources, elaborates on the graph generations for network analysis and explains the applied methods for evaluations.

## 3.1. CONNECTIVITY AND CENTRALITY

To identify centrality $C_{integration}$ or $C_{choice}$ the existing road network is used to create a graph. The road networtk is divided into segments of 5m lengths that contain only the geometric value of angular change to all connecting links. This enables us to create shortest paths with angular change as a cost function. The number of all shortest path from a particular link to all other is the centrality of integration of the particular link $k$.

$$C_{choice}(k) = \sum_{ij} \delta_{ij}(k)/\delta_{ij} \quad (1)$$

where $\delta_{ij}(k)$ is the number of paths between any two links $i$ and $j$ going through $k$. Since the shortest path from each link to all others is available the number of shortest paths going through each link can be counted. This represents the 'busyness' of a link (Hillier and Hanson, 1984).

Summing up the distance of shortest paths to all other links in the network is an indicator on how well a link k is integrated within a graph.

$$C_{integration}(k) = \frac{2(\sum_i^n a_{ik}-1)}{n-2} \quad (2)$$

with $a_{ik}$ being the shortest distance between the links $i$ and $k$ and $n$ denoting the total number of links.

## 3.2. SELF ORGANISING MAP

In order to incorporate multiple datasets with different characteristics and to derive a model an unsupervised learning algorithm is applied called 'Self Organizing Map' (SOM). SOM is a data-driven modelling method introduced by (Kohonen, 1982). The method transforms an n-dimensional space into a low-dimensional space (two in this case) while keeping the topology of the n-dimensional space. This means that two points that were close in the n-dimensional space will be close in the lower dimensional space. The low-dimensional space is called map. The map consists of nodes with coordinate $(x_{i1}, x_{i2})$ and a high-dimensional vector $W_i = (w_{i1}, \dots, w_{in})$ that contains the original data from the n-dimensional space.

This data transformation delivers two-dimensional maps with smoothly changing patterns of data. This method allows integrating incomplete datasets, e.g. vectors with missing values $w_{ij}$ by inferring values through non-linear approximation.

The two dimensional maps lend themselves to find clusters of similarity by a k-nearest neighbour algorithm (KNN). This method returns a cluster membership for each node depending on the vector $W_i$ (Moosavi et al, 2015).

## 4. Application to Victoria, Australia

### 4.1. SALIENT CHARACTERISTICS OF VICTORIA

Victoria is a state of Australia that covers 237,629 $km^2$ and has a population of ~5.9 million which are mainly living around the Port Philip bay and includes the principal settlements of Melbourne and Geelong, respectively the State's largest and second largest cities. The urbanization of the area commenced with the discovery of gold and lead to the rapid increase of population through migration to gold mining towns like Ballaarat and Bendigo. The state is divided into 9,306 census districts.

### 4.2. MULTI DIMENSIONAL MAPPING

The initial investigation into both transport and geospatial data uses a multi-dimensional interactive visualization to represent the temporal patterns of different modes of transportation (bus, car, public transport, cycling, walking), the motivation of trips for the years 2007 and 2009. This visualization renders each of the dimensions mentioned above on the level of a CCD. The data is aggregated in 15min intervals. The representation dynamically represents the transportation data and allows selecting different modes of transportation and their origin and destinations. The ground plane represents the different functions present in each CCD and can change.

### 4.3. CENTRALITY EVALUATION OF THE STREETNETWORK

The investigation to identify centrality and centres uses the street network as basis. The Integration and Choice calculation method is applied to a network of 1,267,318 links.

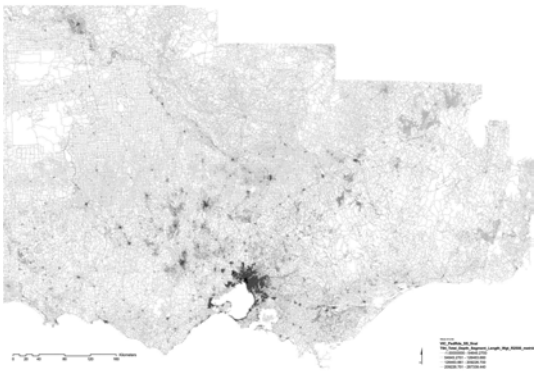


*Figure 1. Integration measures on the Victoria street network with a radius of 2,500m colour indicating the relative value of integration light grey to black (high)*

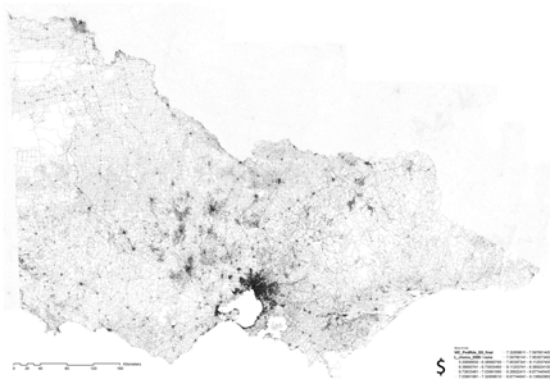


*Figure 2. Choice measure on the Victorian street network with radius of 1,000m colour indicating the relative value of choice from light grey to black (high)*

The integration (radius of 25km) map highlights the state capital Melbourne. By reducing the radius down to 5km and 2.5km sub-centres are highlighted.

Choice shows an even more refined representation of sub centres that even highlights particular neighbourhoods within the metropolitan area that are local hubs.

## 4.4. SIMILARITY DETECTION WITH SOM

To find places with similar characteristics the data-driven method SOM is applied to transform the data space where similarity can be detected. This requires the following 3 steps: data aggregation; data transformation from a high to a 2D-map; identifying clusters.

First multidimensional vector is generated for each CCD that contained the static information about the street network and the modes of transportation used to start or end trips in each CCD. The selection of dimension was driven by the availability and can be extended. Second, a SOM is applied that delivers a 2D-map with a smoothly changing pattern. This is true for all dimensions of the high-dimensional data space allowing us to apply pattern recognition on the map. Third, to find similarities a k-nearest neighbour algorithm is applied that find clusters of similarity. This involves a random starting position and iterate until the clusters boundaries stabilize. The cluster membership is then exported and shown on the map (see Figure 3 and Figure 4)




*Figure 3: Cluster membership in the metropolitan area of Melbourne derived from transport data through a SOM.*

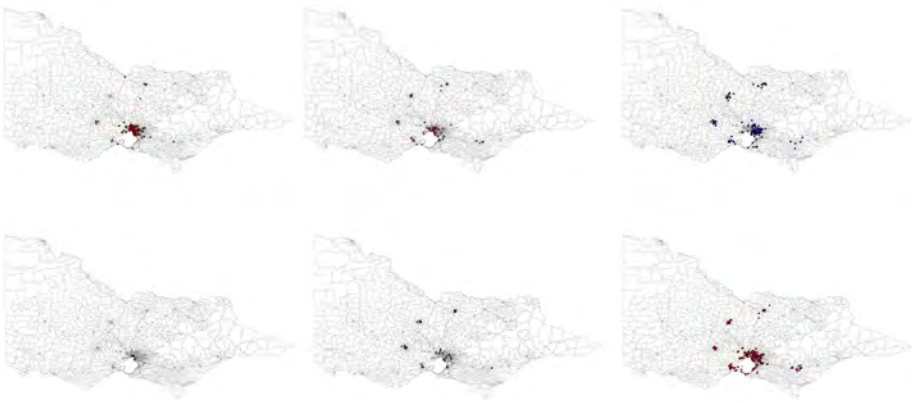


*Figure 4: Cluster membership in victoria derived from transport data by applying SOM.*

Similarity in does not lead to geographically congruent clusters. This is to be expected since several properties appear in different areas.

## 5. Conclusion and Discussion

The capability of analytical tools to evaluate the urban fabric and provide guidance to urban designers, planners and politicians was shown in this project by using transportation and geospatial data to infer neighbourhoods. It also highlighted the requirement to go beyond multidimensional mapping since evaluating multidimensional data streams in real-time is beyond human capability.

The choice of using multimodal transport data, geospatial data as well as network evaluations to detect neighbourhoods has shown promising results. That the urban environment drives 'transportation mode choice' is a known fact; inverting this fact to derive neighbourhood qualities is interesting but requires further research. The evaluation of street graphs has provided a set of very clear neighbourhoods that are very similar to the settlement clusters in Victoria. The street graph evaluation also provides insights into the local centrality by highlighting streets that are more frequented which correlate with street life and commercial activity. This is essential for the choice and location of urban interventions.

All of the evaluation methods only provide a single point of view and require more than combining combined method to gain a more holistic view on the city. The capability of the SOM as a data-driven modelling method to combine and structure multidimensional data has helped to overcome this limitation. This is particularly true since it allows us to overcome excessive dimensionality and incompleteness of data problems. Even though the SOM is a robust method, the application of evaluation methods described earlier in this paper is not a complete set of evaluation tools.

The results show that the clusters and network centres are not necessarily congruent, indicating that urban locations are used by multiple communities and are not only connected in one direction. This shows that the city cannot be understood as a polychotomy but as a collection of distinct neighbourhoods, and as a multi-layered conglomerate of many separated and interactive communities.

## Acknowledgements

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# A TALE OF TWO CITIES

*A cost-driven design optimisation in Addis Ababa & Honolulu*

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**Abstract.** A cost-driven design optimisation is introduced through two case studies: 1) a design prototype of a large scale housing community for social mix of its tenants in Addis Ababa, Ethiopia, and 2) the one of a luxurious high-rise condominium with maintaining a decent level of its maintenance fee in Honolulu, Hawaii, USA. For both cases, the computation of the optimisation was performed with regards to targeted financial concerns which are as following: 1) marketing value, construction cost, and government subsidy (incentives) for the case in Addis Ababa and 2) maintenance fee and construction cost for the case in Honolulu. Design factors are employed as a guide for computational outcomes in the optimisation of both architectural problems. The computational outcomes become the basis for projecting three-dimensional forms as design alternatives. Its application process is delineated within the integrated environment of parametric modelling applications.

**Keywords.** Optimisation; financial model; social mix; design feasibility; parametric modelling.

## 1. Introduction

Design optimisation has been employed as a rigorous methodology in the search for design solutions under an objective (fitness) function in a given problem domain with defining its boundary condition (Papalambros and Wilde, 2009). The application of design optimisation has been expanded to architecture through industrial design from mechanical or manufacturing engineering. In architecture, the design optimisation has been developed for

various objective functions, such as environmental, structural, financial, and so on. Their design outcomes include building façades & envelopes, truss systems, and single & multi-family housing projects (Caldas, 2003; Shea and Cagan, 1999; Lee and Hovestadt, 2011). As the complexity of a given architectural problem increases in the optimisation process, the prioritization of the multi-objective functions is made by ranking or weighting their efficient and effective man-agement (Neema and Ohgai, 2008). The outcomes generated from the computation of the weighted functions then become the parameters for projecting design alternatives. In order to guarantee the generation of meaningful projections, design factors found in the analysis of a given site and precedent studies become critical constraints in the objective functions. The design factors regulate possible exponential growth resulting from the computational search efforts in the optimisation process. These simulated projections provide the practical value of the optimisation in architecture, and serve not only as the visual proof of the search but also as the justification of its boundary condition. In this paper, a design optimisation methodology is introduced by employing cost as the primary objective function in the development of 1) a large scale housing community for social mix in Addis Ababa, Ethiopia, and 2) a luxurious high-rise condominium in Honolulu, Hawaii, USA.

## 2. Addis Ababa: large scale housing development

The project site is located in one of the oldest informal settlements in Lideta, a sub-city of Addis Ababa, Ethiopia. The average family size in the city is 4.5 people in average 20 $m^2$ space per family. This large-scale housing development is aimed at improving these informal settlements while providing affordable housing to low-income urban dwellers with encouraging social mix. The design factors in the cost-driven optimisation for this project include a neighbourhood model and building unit types, while its financial factors include marketing value, construction cost, government subsidy (incentives). The outcomes of the optimisation are represented within a parametric modelling environment supported by Rhinoceros 3D, Grasshopper and its plug-ins in order to enhance design feasibility studies.

### 2.1. DESIGN FACTORS

A spatial analysis of the given site condition identified circulation, in-between spaces, and buildings as the main components of the neighbourhood model that serves as the basis of the site design. The building unit types include studio, one bedroom, and two bedroom units. The unit types are proposed for accommodating the tenants of the informal settlements and respect

the multi-generational relationship found in each family unit. The project site is a 43,103 $m^2$ plot of land which is divided into six neighbourhood models, as shown in Figure 1. Existing circulation paths within the property are retained and improved upon for meeting municipal code. Based on the given FAR of 2 and maximum site coverage of 50%, 80,000 $m^2$ living space is required.




*Figure 1. Site with six neighbourhoods models.*

The average living area of each neighbourhood model in a given site is 13,333 $m^2$. Zoning regulations allow for housing and communal buildings in newly developed communities to be a maximum of 7 stories tall. The required building unit types are studio, one bedroom and two bedroom units. The building unit types are based on a 5 meter square grid. The size of a studio unit is 25 $m^2$, a one bedroom unit 50 $m^2$, and a two bedroom unit 75 $m^2$. The studio is the basic unit. The number of the building types and the combinations of the types are computed using g financial factors. Accordingly, the project's financial feasibility is evaluated.

## 2.2. FINANCIAL FACTORS

Market value, construction cost, land cost, and government subsidy (incentives) are translated into mathematical models for computing the tangible benefits for encouraging various income groups to participate in this social mix large-scale housing community. The main objective of this mathematical model is to maximize the profits P with respect to the input variables necessary for the market value ($M$), the total construction cost ($C$), land cost ($L$), and government subsidy ($G$). Government subsidy includes tax credit ($T$), land cost ($L$), construction site development ($C_D$). These variables are controlled by the combinations of building types. They are crucial factors in the creation of social mix. The variables used to analyse the financial factors are based upon the input data gathered from current market analysis.

$P = M - (C + L - G)$ (1)

$M$ = Total market value (2)

$C$ = Total construction cost = $C_A + C_C + C_D$ such that (3)

$C_A$ = Living area ($A_L$) construction cost = $A_L \times 4{,}000$ ETB/ $m^2$

$C_C$ = Common area ($A_C$) construction cost = $A_C \times 1{,}000$ ETB/$m^2$

$C_D$ = Construction site development cost = $A_S \times 1{,}500$ ETB/ $m^2$

$L$ = Land price = $A_S$ x 3,000 ETB/ $m^2$ (4)

$A_L$ = Living area = 80,000 $m^2$

$A_C$ = Common area = 36,000 $m^2$ = $S_A + H_C + V_C$ such that

$S_A$= Semi-private area = 25% of Building area (0.25 × A) = 20,000 $m^2$

$H_C$ = Horizontal circulation area = 10% of Building area (0.1× A) =8,000 $m^2$

$V_C$ = Vertical circulation area = 10% of Building area (0.1× A) = 8,000 $m^2$

$M$ = Market Value = $M_x + M_y + M_z$ (5)

$M_x$= Studio unit market value = $A_x$ x 4,000 ETB/$m^2$

$M_y$= One Bedroom unit market value = $A_y \times 6{,}000$ ETB/$m^2$

$M_z$= Two Bedroom unit market value = $A_z \times 9{,}000$ ETB/$m^2$

$G$ = Government Subsidy (Incentive) (6)

$T$ = Tax Credit = 40% of Market value = 0.4 x $M$

$G = (T + L + C_D) \times (W_x \times R_x + W_y \times R_y + W_z \times R_z)$

such that $W_x = 1.25$, $W_y = 0.75$, and $W_x = 0$

$W_x$ = Weight value per studio unit type

$W_y$ = Weight value per one bedroom unit type

$W_z$ = Weight value per two bedroom unit type

Ratio among different unit types such that $1 = R_x + R_y + R_z$ (7)

$R_x$ = Studio unit ratio

$R_y$= One Bedroom unit ratio

$R_z$= Two Bedroom unit ratio

Area per unit type (8)

$A_x$ = Studio area = $A_L$ x $R_x$

$A_y$ = One Bedroom area = $A_L$ x $R_y$

$A_z$ =Two Bedroom area = $A_L$ x $R_z$

Size of each unit (9)

$S_x$ = Studio unit size = 25 $m^2$

$S_y$ = One Bedroom unit size = 50 $m^2$

$S_z$ = Two Bedroom unit size = 75 $m^2$

Number of each unit (10)

$U_x$= Number of Studio unit = $A_x/S_x$

$U_x$= Number of One Bedroom unit = $A_y/S_y$

$U_x$=Number of Two Bedroom unit = $A_z/S_z$

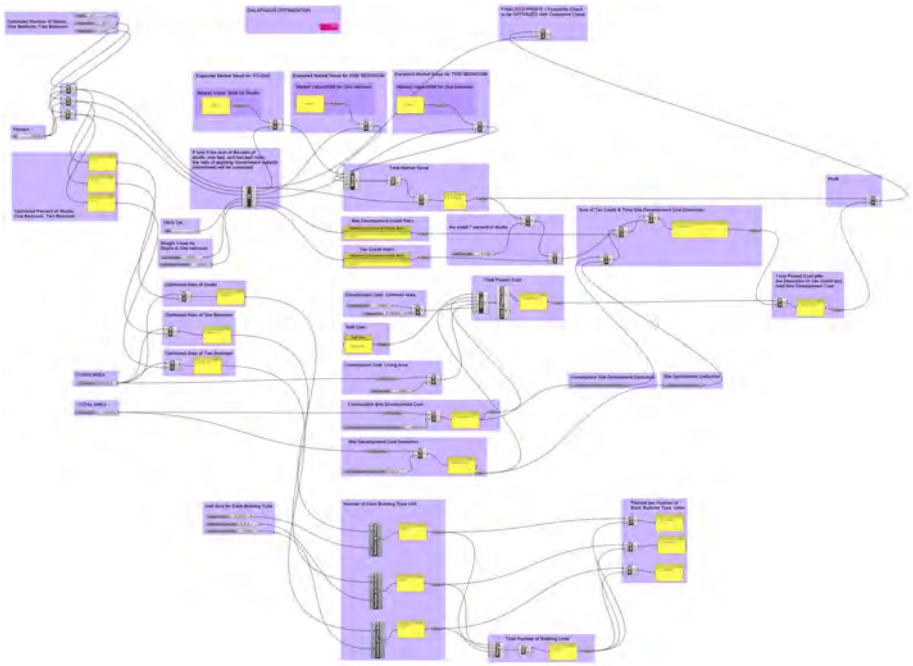


*Figure 2. Optimisation in Grasshopper.*

By optimising for the financial factors, it is found that, given a living area of 80,000 $m^2$, the studio unit type should account for 23% of given living area (18,400 $m^2$), the one bedroom unit type should account for 46% (36,800 $m^2$), and the two bedroom type should account for 31% (24,800 $m^2$). The computed areas out of 80,000 $m^2$ per each building unit type are then translated into the number of each unit type given that the size of studio is 25 $m^2$, one bedroom 50 $m^2$, and two bedroom 75 $m^2$. Therefore there should be 736 studio type units, 736 one bedroom units, and 330 two bedroom units. The optimised profit is then calculated to be 141,346,846 ETB, which is 22% of total project cost. The initial marketing value is 517,600,000 ETB, total project cost 629,887,867 ETB, government subsidy 253,630,000 ETB (the sum of 63% of Land cost, 63% of construction site development cost, and 63% of 40 % tax on the initial marketing value).

## 2.3. PROJECTIONS

Design decision making based on the financial feasibility of the project is then developed using simulated projections of design alternatives found in the optimisation process.

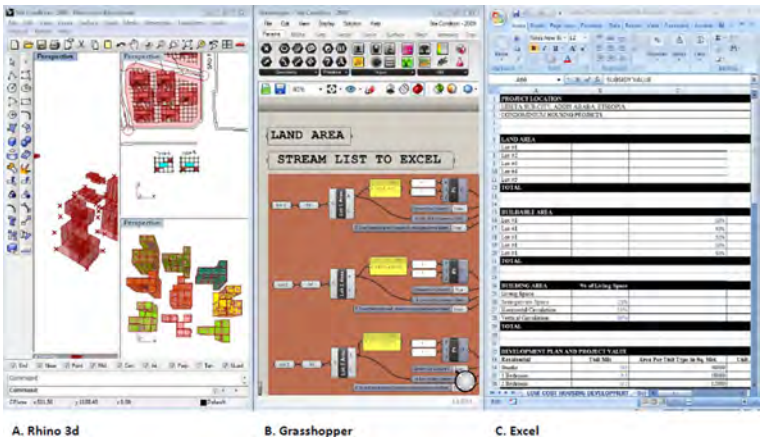



*Figure 3. Integrated Projection Module.*

Lot 2 is selected as one of the neighbourhood models for a demonstration as shown in Figure 4. Its living area is defined as 12,600 $m^2$. Using the optimised division of living area stated in 2.2 Financial Factors, there should be 116 studio units (23% of 12,600 $m^2$ is 2,898 $m^2$), 116 one bedroom units (46% of 12,600 $m^2$ is 5,796 $m^2$), and 52 two bedroom units from 3,906 $m^2$ (31% of 12,600 $m^2$ is 3,906 $m^2$). Then, given that a total of 504 basic units are to be assigned to Lot 2 and considering 2 people live in 20 $m^2$, it is validated that 1,268 people are able to reside in Lot 2. This is a 120% increase in the number of residents compared to the number of original residents 1,054 where 4.5 people live in 20 $m^2$. Based upon the analysis of the existing context, 5×5 $m^2$ grid patterns, circulations and open areas are overlaid on top of the neighbourhood model of Lot 2, as shown in Figure 4.

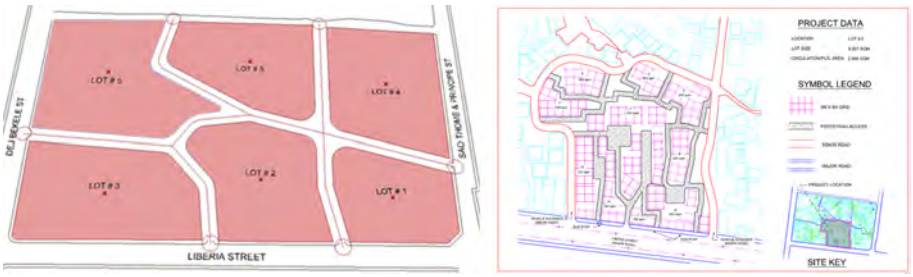



*Figure 4. Generated 6 neighbourhood models and overlaid 5×5 $m^2$ grid patterns on Lot 2.*

77 basic square units are 5 stories (G+5) and 17 basic units are 7 stories (G+7). 385 basic units are available in G+5, and 119 basic units in G+7, as shown in Figure 5.



*Figure 5. Overall building height distribution. Maps from left to right: Building height distribution; G+5 (5 stories); G+7 (7 stories); Retails (2 stories).*

According to the optimised proportion, studio units account 23% of 119 basic units (28) when a basic unit is 5m x 5m and its size is 25 $m^2$. One bedroom units account for 46 % (56 basic units), and two bedroom units 31% (36 basic units). This means that G+7 should have 28 studios, 28 one bedrooms, 12 two bedrooms. Each level needs 4 studios, 4 one bedrooms, and 1 or 2 two bedrooms. The combination of three building unit types, horizontal & vertical circulation, and semi-private area are defined in as shown in Figure 6.



*Figure 6. Three building unit type combinations with circulations.*

The projections of the building unit types in Lot 2 are generated in Rhinoceros 3d with Grasshopper are shown in Figure 7.

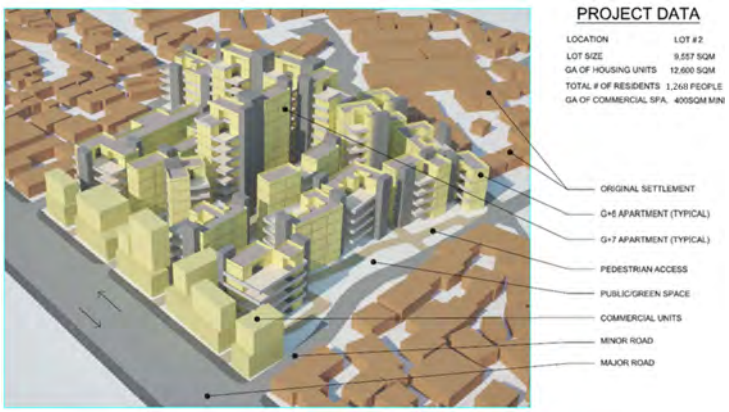



*Figure 7. Projected Buildings in Lot 2.*

## 3. Honolulu: high-rise condominium

In the real estate industry, the optimisation of building maintenance fee along with maintaining maximum tenant living condition is regarded as an instrumental Unique Selling Proposition (USP) for increasing a building's market value. A design prototype for a condominium in Honolulu, Hawaii is projected using a cost-driven design optimisation methodology. This cost-driven optimisation integrates an early stage design synthesis for a high-rise condominium with its construction cost estimation when its design alternatives are constrained by design factors known to optimise for its maintenance fee. When the maintenance fee is adjusted by the design factors, the optimisation is focused on the construction costs.

### 3.1. DESIGN FACTORS

Design and financial factors are defined through an analysis of the maintenance fee for 17 buildings in Hawaii and 6 buildings in Florida. The design factors are the possible variables found in a building's design which decrease expenses and increase incomes while maintaining a high level of user satisfaction and building security. These design factors include 1) building floor plans, sections and site plans, 2) number of units in a building, 3) land acre size, 4) location and land value, 5) year, 6) amenities, and 7) extra revenue facilities.

### 3.2. FINANCIAL FACTORS

Maintenance fee, and construction cost are translated in mathematical models in order to check financial feasibility of the condominium project. Total project cost is defined as a constant value in the computation of Net Present Value (*NPV*) which represents Internal Rate of Return (*IRR*) in the current marketing value estimation for the high-rise condominium. With maintaining the decent level of maintenance, a construction cost is regarded as a variable for minimizing the total project cost. The fitness function on the design alternative is focused on minimizing $f(_i)$ with respect to the input variables necessary for the total construction cost ($T_i$) of the design alternative with subject to the set of construction tasks constrained by the design factors and the input variables necessary for each task. Given $i$ = index of task, $p$ = project id, $D$ = total direct field cost, and $H$ = total overhead cost,

$$f(i) = M_p + \sum_{i=1}^{n} T_i \tag{11}$$

$$T = \sum_{i=1}^{n} T_i = D + H \tag{12}$$

$$T_i = \{F_i + Q_i(M_i + E_i + W_i L_i)\} + H_i \tag{13}$$

Computation of the fitness function starts with gathering the cost of individual tasks. The input variables of individual task includes field supervision ($F_i$), materials ($M_i$), equipment ($E_i$), labor ($L_i$), wage rate ($W_i$), overhead ($H_i$) and labour cost per each field work ($Q_i$).The cost of the individual task ($B_i$) is calculated according to “Building Construction Cost Data” in MasterFormat 2009. In the middle of the computation, various design options, including size, numbers, types, and construction methods per each task are searched for in order to minimize the total cost.

### 3.3. PROJECTIONS

Using the given formula, one of the condominiums with high maintenance fee in Hawaii is selected and its design alternative is developed with the goal for minimizing its construction cost as shown in Figure 8.

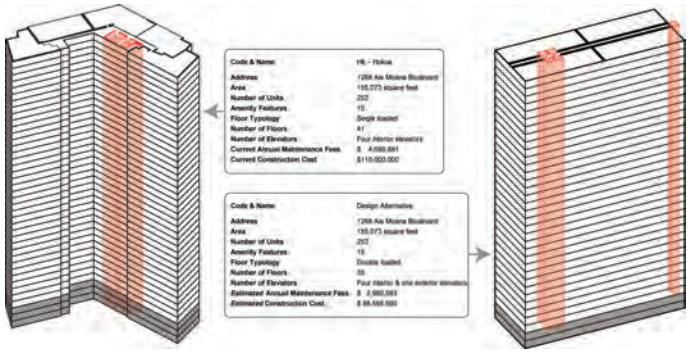


*Figure 8. (a) $H_8$ – Hokua in Honolulu, (b) a design alternative by the design factors.*

The construction of the original design was $110,000,000 with $ 4,689,881 annual maintenance fee when it has 1) single loaded corridor, 2) 41 floors, and 3) four interior elevators. By combining the design options an optimised alternative is then generated in Rhinoceros 3D using Grasshopper. This design alternative has 1) double loaded corridor, 2) 35 floors, and 3) four interior elevators & one exterior elevator. The estimated construction cost of this alternative is estimated to be $ 98,595,000. Its maintenance fee is the average of other buildings' which have design factors similar to the ones in the alternative. This comes out to be $ 2,980,093. Therefore this design alternative finds a 10.3% reduction in its construction cost build and a 36.4% reduction in its maintenance fees when compared to the original building.

## 4. Discussion

A cost-driven design optimisation was applied to 1) the design of a large scale housing community in order to maximize a project's profit and encour-

age social mix in a community, and 2) the design of a luxurious high-rise condominium prototype in order to minimize a project's construction cost while maintaining a decent maintenance fee. The outcomes of the large scale housing community project in Addis Ababa were 1) an optimised profit which came out to be 22% of total project cost, 2) the social mix regarding building unit types (studio units: 41% of total units, one bedroom units: 41 %, and two bedroom units: 18%), and 3) a 120% increase in the number of residents. The outcomes of the high-rise condominium project in Honolulu were 1) a 10.3% reduction in the building's construction cost and 2) a 36.4% reduction in the maintenance fee. The proposed cost-driven design optimisation was composed of 1) design factors, 2) financial factors, and 3) projections. The design factors were defined using the analysis of existing site context and precedents. The possible exponential growth of the computation was able to be regulated by the design factors. Furthermore, the design factors were used as the guiding force when defining the boundary condition of a given project. The outcomes computed using the financial factors became the basis for projecting simulated design alternatives. These projections provided interactive responses to various financial changes, and therefore could be utilized by not only designers but also developers in order to make more informed design decision.

## Acknowledgements

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# FORM-BASED CODE IN PARAMETRIC MODELLING FOR CONTINUOUS URBAN DESIGN

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**Abstract.** This paper analyses parametric modelling in connection with the Form-based Code (FBC) methodology to support continuous design in an urban scale. FBC is an approach to optimize conventional zoning regulations and has been implemented by a number of cities. Akin to a utopian urban design solution, we argue that the FBC is crucial to develop main objectives, characteristics, trends and impacts in a design process systematically and logically. Zoning emphasizes excessively on land use and intensity control, however, FBC promotes to (re-)create and predict urban-rural environments through controlling forms. FBC is developing and offers opportunities for flexible coding processes, adjustment of density and seamless public participation. Parametric modelling, being rule based, is a significant step towards a continuous urban design creating a mechanism for FBC. This paper presents a framework to connect parametric modelling with FBC processes, and how parametric modelling methodologies allow the form-based coding processes to be more impeccable hence being more appropriate in the process of continuous design flow.

**Keywords.** Form-based code; continuous urban design; parametric modelling; utopian design solution.

## 1. Introduction

With the New Urbanism arising in 1980s, people began to rethink urban problems caused by rigid segregation zoning, such as the decline of pedestrian and use public transport, disappearing of public realms, damage of natural environment and decay of central areas. Yet there are still many problems leading to a more holistic and persistent design involvement. Form-based Code (FBC) is considered as a more appropriate method to analysis urban space and environment than traditional zoning, which is a “new city-making

approach" (Marshall, 2011) basing on Smart Growth, New Urbanism and Transect (Figure 1).

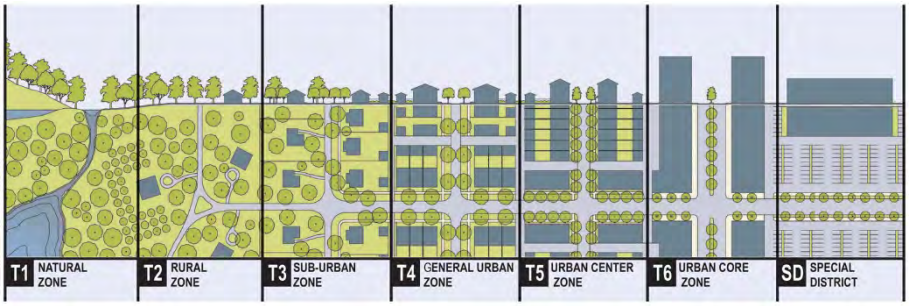



*Figure 1: Transect diagram with six normative Transect Zones (T-zones) used for the zoning of urban areas as well as natural lands (taken from Duany Plater-Zyberk, 2008).*

Unlike traditional zoning emphasizing land use and intensity control excessively, FBC promotes to predict built environment through controlling and regulating forms. FBC offers a more contemporary method for continuous designing of urban and rural regions in different scales and types. Thus, akin like a utopian urban design solution, FBC is crucial to demonstrate the destinations, characteristics, trends and impacts of a design project from its original concept to implementation. This allows us to interrogate the notion of continuity in order to map and discover opportunities for further design innovation.

In 1982, the development of the town of Seaside, Florida, is "significant for its use of codes; in particular, the reinvention or revival of codes prescribing three-dimensional forms and urban components" (Parolek et al, 2008). The Seaside development designed by Duany Plater-Zyberk (DPZ) can be regarded as the beginning of the FBC practice. In 2004, the *Form-based Codes Institute* was founded, which dedicated to advancing the understanding and use of FBC. Up to now, there are nearly 500 urbans and regions have formulated their FBC system in the USA. FBC enables diversity with local identity by using *Smart Codes, Transect FBCs* and *FBC Guides,* whereby Smart Code has the biggest impact on FBC. Smart code was originally developed by DPZ and the first implementation of Smart Code was an overlay control plan in Petaluma, California in 2003. In the following developing stage, Smart code worked as a creative way to regulate urban planning in Gulfport, Montgomery and Mississippi region. Smart Code clarifies the standard of "region-urban-community-architecture" in variety of scales and typologies in rigorous view processes. Besides, they make the Smart Code approach more modularized and easy-manufactured.

At the meantime, the use of parametric modelling turns into a mainstream technique in architecture design processing. It offers architects and urban designers immense opportunities to tie various building elements imbedded with information together. Parameters are “manipulable” and allow different sectors to collaborate and communicate intentions. Basing on this kind of property, parametric modelling has a potential to act as a supporter for FBC implementation by optimizing the procedures and public participation. Our research aims to achieve flexible and continuous urban design by using form-based coding, and developing the parametric model to fulfil the goal.

## 2. Challenges of FBC

The raising of FBC is a critical reflection of conventional zoning which aims to improve the use-based design approach. FBCs have proven to prescribe urban form, implement mixed-use developments, and address place-based characteristics of sites (Parolek et al, 2008). Current FBC has five components, including regulating plans, public space standards, building form standards, administration and definitions. In form-based coding procedure, “transect code” always represents “form code”. Because transects show actual development requirements such as building location, set back lines, or allowable building heights (Kim and Clayton, 2010).

FBC can be divided into three phases, documenting, visioning and assembling. At the documenting phase, designers collect data of a target region or community, and translate an illustration plan into a regulation plan. Data collection contains neighbourhoods, zones and galleries, architecture typologies, layouts, street space details, public green realms and so on. In the second phase, designers code or recode the building typologies, streetscapes, blocks contexts to build a FBC model. In this phase, designers need to adjust or refine the program and coding grammar continuously to match the urban development requirement. In the last phase, designers translate FBC models into visual 3D layouts to offer interfaces for public participations that is a user-friendly and interactive. Compare with the zoning method, FBC is more flexible. It allows designers easily renew or alter programs, layouts and typologies basing on public comments.

Although FBC has been tested in hundreds of cities and regions, it still has some challenges, or opportunities. First, high density cities are ignored by FBC applications and Floor Area Ratio (FAR) is omitted. However, density is one of the most vital indicators in urban development analysis. FAR is also important to value environment and growth capacities. At this point, FBC should be expected to accomplish more preciseness and comprehensiveness by dealing with density. Besides, FBC is not just a text-based de-

sign approach. Prescribing urban form needs visual files and graphics. How to express form-based coding more intuitively has the direct bearing on communications between different sectors. FBC needs an effective and smart platform to share data and allow people to access design information in multiple ways.

## 3. Parametric modelling in FBC

The introduction of digital tools and the related processes for dynamic architectural pieces has been increasingly important in designing a project. Parametric modelling differs from traditional hand sketching, building physical models and manual models by adding to the modelling procedure the ability to change, during all the design process, allowing the production and experimenting of several versions of the same, within a controlled design environment, by simply changing the values of specific parameters. Since Architecture, Engineering and Construction (AEC) Industries already have accumulated experiments by taking the idea of parametric modelling techniques, it has become clear that parametric tools could bring similar benefits to urban design projects, having even effectiveness in higher scale urban cases (Nagy, 2009).

Using parameter to define land use and fabric in region or city scale is more aptly in contemporary urban development in last decades. In parametric urbanism methodology, urban design is controlled by the distribution of existing urban fabric instead of the objects position; by the compositional gradients instead of axial forces. For the purpose of see the parametric modelling applied in city, for example the Kartal Pendik Masterplan can be chosen as a relative mature project to study. It presents a grid structure as the basis of the master plan's organization. Using a Cartesian grid for the organization of space is a very common approach, however the grid employed in the Kartal Pendik Masterplan is not Cartesian but topological. The streets and axes are shaped and adapted according to the terrain features and other exterior conditions, in order to facilitate access and promote connections (Pinto et al, 2013).

In FBC, parametric modelling has a potential to support making FBC both in procedures and expressions. Since FBC aims to create or recreate physical urban environment, considerable data represented space form information should be collected, as mentioned before. In addition, FBC is a numeric-based design approach. Some related illustrations have to be changed when values in sections are changed. That makes FBC less flexible. Parametric modelling can help FBC overcome these kind of limitations. It becomes easier for planners to update models by changing parameters in

form-based coding, avoiding spending time to re-edit illustrations. Besides, sharing database to sectors is another benefit parametric modelling offers for FBC. Additionally public participation has become an important aspect of contemporary urban planning and design. In a parametric model making process, public sectors can check the block geometries and transects; allowing members of the communities to understand the future development via three-dimensional models more directly; giving planners and designers the opportunities to refine their FBC models basing on the public feedbacks.

## 4. Application of FBCs in continuous urban design

The concept of continuous urban design provides an associative framework for design implementation. It proposes that a city development should be "edible". Different from the conventional and narrow urban design which is decided only by specific groups, like government officers, designers and experts, continuous urban design is more like a kind of public policy. The design procedure should guarantee a variety of interest subjects participate into the course, no matter policy makers, designers, developers or community neighbourhoods. Continuous urban design flow more respects to citizen's experience. Each region has a unique set of conditions, however, the conditions can be changed with the change of developing situation. So continuous urban design methodology is appropriate and flexible to meet the requirement of contemporary urban growth.

As a response of zoning pattern, FBC has potentials to be applied in continuous urban design. Firstly, FBC is supported by existing form and fabric to create physical environment, which helps this new approach get solid foundation of data and materials to support continuous design flow. Secondly, FBC is concerned with creating public-open mechanism. FBC makers tend to use interlinked platform to obtain relevance feedbacks from communities. That's beneficial to achieve sustainable urban development. Thirdly, FBC is a method of emphasising on coherent visible outcomes, "one-size-fits-all" approach will never be displayed in continuous urban design practice.

Making a successful FBC system needs a smart tool, as mentioned, parametric modelling is able to support the implementation. For our research we choose *Esri CityEngine* as a parametric analysis tool. The purpose of rising CityEngine is to transform 2D GIS data into smart 3D models for urban planning, architecture and design. CityEngine provides opportunities to turn zoning laws into vivid 3D visualizations and change the way to understand future environment. It consists of several procedural and interactive ways to layout street networks, align and subdivide shapes. On the one hand, streets

is grown according to different patterns and edited in an interactive way. For example, street-crossings can be moved, streets can be deleted or selected and the street growth wizard can be applied again on the selection. On the other hand, tools for the editing of lot shapes are available, such as aligning building lots to a terrain etc. The tools usually work on the selection done in the 3D view window, the viewport, or operate on the whole layer.

We choose Hong Kong to conduct a pilot study of FBC. Actually, there are no mature applications of FBC in high dense cities of Asia, however, high dense urban environments are in much greater need of an interactive tool to predict urban developments. With the rapid urbanization and population aggregation, high dense cities need a more efficient and practical way to meet urban development requirement, no matter in land-use intensification, public participation or urban form rationalization. There is a blank in the field using FBC in urban planning and design in high dense cities. Whether FBC can be used smoothly in high dense cities in Asia and how it can be used is our hypothesis of our research.

Before making FBCs, a rural-to-urban transect has to be prepared, which describes basic information of neighbourhood characteristics and architecture diversity. Hong Kong is a highly compounded city and it does not have a common pattern that can be summarized in a single district (Figure 2).



*Figure 2: High-dense neighbourhoods in Hong Kong. Row by row from left: Tsuen King, North Point, Tai Koo, Sai Ying Pun, Sham Shui Po and Tai Po (taken from Kandt, 2011).*

High-rise urban form and extreme population density make government to be cautious with the regulation plan policy and the developing strategies of diverse regions. Obviously, the development situation in the core of Hong Kong Island differs from other areas such as the New Territories. Therefore, it is a challenge to generalize the six transect zones as Parolek proposed before. There is a rough transect summary to explain the transect zones of Hong Kong (Figure 3).

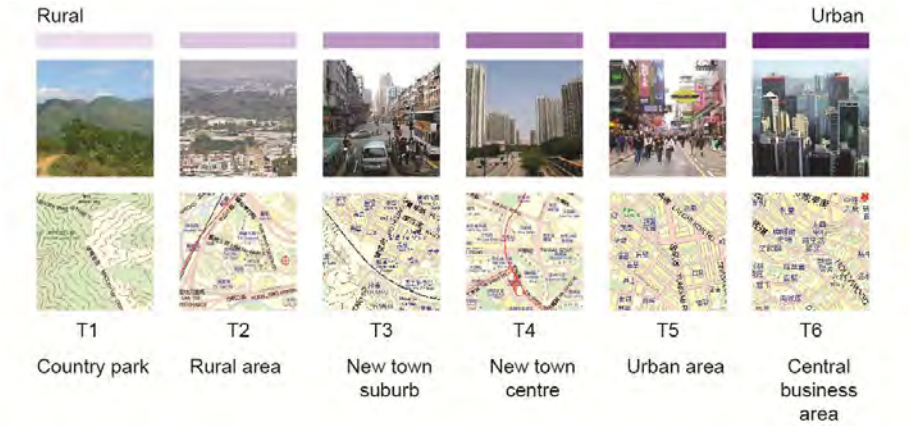



*Figure 3: Territorial-wide transect of Hong Kong (taken from Kan, 2012).*

By using CityEngine as the parametric model-making tool (Figure 4), designers and programmers compose platforms, or websites, to make urban form code information more visualized and public participating more convenient (Figure 5).

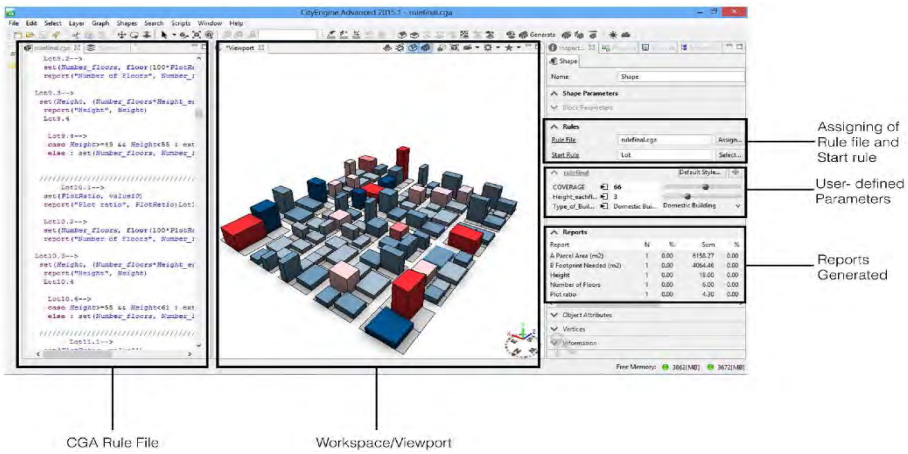



*Figure 4: Working interface of CityEngine in Sai Ying Pun, Hong Kong (taken from Diwan, 2015).*

Different interest groups, such as government, policy makers, developers and neighbourhoods, all have a chance to search information as they want, or try to change the virtual model parameters under simple guide, which is meaningful for strengthening the sense of space identity and belonging. Continuous urban design is not only a “result”, but also a “process”.

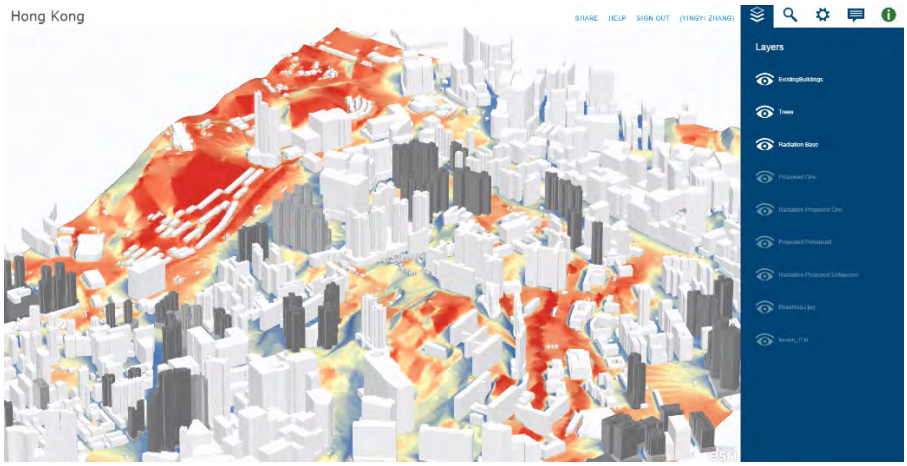



*Figure 5: Online platform for public participation by using CityEngine (taken from https://www.arcgis.com).*

## 5. Discussion

Through the analysis of FBC development and utility of parametric modelling tools, we propose that FBC methodology is utopian for continuous urban design by generating proposals that work based on physical urban form and fabric. However, FBC is a relative "young" approach in urban development research realm, designers and FBC makers need effective, smart and flexible tools to implement it into real practice. Parametric modelling, as a computer aided design tool, is able to fulfil the requirement.

- Continuous urban design describes the vision of sustainable urban-rural development and impacts on the space qualitatively. It becomes a tendency of contemporary urban design with dynamic and "processing" property.
- As a replacement of conventional zoning, FBC is noted as a positive design methodology for creating the edible, predictable and reasonable outcome of the built environment in planning process.
- Parametric modelling is a new way to conceive design because of its property, that is, the nature of an element in a parametric family won't be changed with the value changing. In urban scale, parametric urbanism studies already have been practiced around the world.

Parametric modelling is a broad category. In statistics, a parametric model or parametric family is a codes group that can be created using a number of parameters. In architecture and urban design, architects use parameters predefined before design process to code and create scenarios by specific software. In our research, we employ CityEngine work as the parametric

modelling tool. The core concept of CityEngine is the 'procedural' way for modelling efficiently. Layouts become a dynamic process and user-friendly platform. People can change the options and create interactive streets, buildings, public spaces in real time.

Our application of parametric modelling tools in FBC is at an early stage. Since FBC is a critical response of zoning in the USA, there are not many mature cases in the rest regions and cities in the world, especially in high density cities like Hong Kong. Yet, high density cites are in urgent need of flexible and continuous planning implementation mechanism as public participation platform supported by parametric modelling. The application of FBC in high density cities has great potential and prospect. Besides, current FBC making method still depends on manual data collection, community investigation and designers' experience. Popularizing parametric modelling and creating evaluation system in FBC making processes need more time and practice.

## 6. Conclusion

In the past decades a shift happened and how planning and zoning are developed and employed are redeveloped to facilitate sustainable development and continuous growth. This became a crucial instrument of urban evaluation standards no matter in urban-rural spaces, economy and society. As reaction to New Urbanism and Smart Growth, FBC aims to (re-)create regulations and controlling (re-)developing scenarios by setting a more flexible and interactive urban design framework to support sustainable and continuous design flow.

From the study of the preceding expressions, it appears that parametric modelling is an appropriate tool to support and expand the development and implementation of FBC. By using parametric design methodologies, designers can explore a variety of space form components type, to draw up dynamic equilibrium modularized systems to guide design practices. This is especially valuable in high density cities like Hong Kong. Furthermore, parametric modelling tools and platforms provide visualized 3D scenarios to professionals and laypersons. Subsequently, it contributes to create effective communication between FBC makers, stakeholders and the general public through allowing real time feedback of different stakeholders. Although still in a developing stage, parametric FBC has potentials to set up a synergistic urban design mechanism and result in a continuous urban environment.

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**PRACTICE-BASED AND COLLABORATIVE COMPUTATIONAL DESIGN AND RESEARCH**

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# ENABELING LOW COST HUMAN PRESENCE TRACKING

*Using commodity hardware to monitor human presence in workplaces*

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**Abstract.** Finding automated methods to track the presence of humans can help designers understand workplaces. Methods to understand the patterns of human movement in workplaces using beacons, badges and sensors are being developed. Whilst the results are promising, they can be costly and may require the manual setup of expensive equipment. The Global Positioning System (GPS) is widely adopted due to its high degree of accuracy, however, is inapplicable in indoor environments due to the physical limitations of satellite attenuation. There is no comparably ubiquitous positioning system that can be used to make device-driven position tracking that is specifically adapted to indoor environments. With the increasing popularity of phones, watches and fitness tracking bands with WiFi and Bluetooth connectivity, we explore the potential of these wireless radios as a low-cost alternative to monitor human movement. As the costs of technology continue to decrease, the means to build a low-cost tracker through WiFi and Bluetooth enabled devices in an indoor environment become possible. Furthermore, is it possible to develop a low-cost tracking device using only commodity hardware that is able to accurately automate and record presence in space with sufficient veracity?

**Keywords.** Movement tracking; workplace environment; wireless.

## 1. Introduction

Tracking the presence of humans can help designers create effective workplaces (Sailer 2013). This paper describes experiments to determine the ef-

fectiveness of a low-cost tracking device in an indoor environment. It describes the advantages and limitations of using such devices in providing understanding of human movement patterns. This in turn, can be used as a tool to inform designers that improve productivity and social interactions in workplaces. Indoor movement research has relied on manual data gathering to track human movement. It is based on speculation, drawing from personal experiences, newspaper stories, early empirical psychological and, sociological studies (Sailer 2009). However, the need to repeat experiments is time-consuming, laborious and involves a lot of manual data (Hillier 1996, Sailer 2013). Methods to understand the patterns of human presence in workplaces using beacons, badges and sensors are being developed (Khoury et al. 2008). Whilst the results are promising, they can be costly and may require the manual setup of expensive equipment (Fleuret et. al. 2008). The Global Positioning System (GPS) is widely adopted due to its high degree of accuracy, however, is inapplicable in indoor environments due to the physical limitations of satellite attenuation (Mautz 2008). There is no comparably ubiquitous positioning system that can be used to make device-driven position tracking that is specifically adapted to indoor environments. With the increasing popularity of phones, watches and fitness tracking bands with WiFi and Bluetooth connectivity, it has been suggested to use these wireless radios as a low-cost alternative to monitor human movement (Mautz 2012, Scheerens 2012). As the costs of technology continue to decrease, building a low-cost tracker that has the ability to detect human movement through the WiFi and Bluetooth enabled devices in an indoor environment becomes possible. The research will: Develop a low-cost tracking device that is capable to establish the presence of humans in an area using WiFi and Bluetooth technology; evaluate the correlation between measured data and reality using video surveillance. Hence determine accuracy and viability of this method.

## 2. Methodology

The research deploys a tracker device, a low-cost, off-the-shelf component. WiFi and Bluetooth technologies with ‘sniffing’ software measure the incoming and outgoing traffic. Movement data is recorded when a signal with a WiFi or Bluetooth enabled device is detected and update quickly enough to capture the movement of people into and out of the surveyed area. To evaluate the accuracy of the tracker device, a camera was placed to capture the number of people in the area. The experiment considers a specific attractor point (kitchen) of architecture firm BVN, as it is an open space that constitutes as a main area for social interaction and meetings with project teams. Still there are confounding factors as people being studied may have zero or

more transmitting devices with them as they enter the area. This may bias the data, by not counting, or double-counting, a person. A video camera will act as a control to evaluate the impact of data collection during experiment.

*Multiple Devices* – An individual that may carry a laptop, phone and a tablet at the same time as they enter the area can cause an increase in numbers and bias the counting analytics of the results.

*Discoverable Mode* – For the agent to collect any data, the WiFi or Bluetooth enabled device must have these wireless connections on. If the user has never accessed the WiFi Access Point (AP) in the past, the packets of data that are sent to detect known networks are not transmitted. This would make the person with the device invisible to the tracker device.

## 3. Background research

An indoor environment's structure can have a significant impact on the range and accuracy of any tracking device. Several case studies have evaluated a variety of indoor tracking technologies and indicated that accurate estimation of Bluetooth and WiFi localization is a challenge in indoor spaces (Kaemarungsi 2005, Khoury et al. 2008, Mautz 2012). Signal propagation loss is a significant cause of unreliable results, due to different building materials, furniture and radio interference from microwave-ovens and refrigerators. Furthermore, human bodies can interfere with the line of sight between emitter to receiver.

*WIFI ARCHITECTURE* – The scan involves two methods: Active and Passive. It uses Scan, Authentication and Association procedures (Abbott-Jard et al. 2013). The scan procedure is used for finding MAC addresses in the area whether it may be in Active or Passive mode. During an active scan, the client radio transmits a probe request and listens for a probe response from an AP. During passive scans, the radio listens on each channel for beacons sent periodically by an AP. Once the device has found the AP, it operates the authentication phase followed by the connection. This allows the device to communicate with stations in other BSS's, to which the tracking device can then detect the signal by the tracking device. When a WiFi enabled device is actively seeking to connect to a known network, it can result to two different outcomes. (1) Involves scanning for 'Beacon Frames'. These are packets broadcasted by WiFi routers used in order to broadcast their presence and attempt to initiate a connection with a network that the device has previously connected to. (2) Involves broadcasting packets called 'Probe Requests'. This technique captures data by probing for network by circling through the access points within the area. This can periodically capture the

Service Set Identifier's (SSID) as it determines the closest AP and unique MAC address of the device.

*BLUETOOTH ARCHITECTURE* – Bluetooth detection has two states - standby and connection. In standby state, the device has no interaction with other devices. In connection state, data can be transferred between devices. Inquiry and inquiry scan are the main parts of the device discovery protocol. A discoverable device runs the Inquiry or 'Master' and Inquiry Scan is run by a device that is willing to be discovered or 'slave'. When the Master receives a packet from the slave, it sends a connect request to the master. Once the master receives the connect request, the devices are connected and can exchange data packets.

With the increasing popularity of smartphones, laptops and portable devices being configured with wireless communication, capturing the emitting WiFi and Bluetooth signals from devices is noticed as an effective crowd data collection and monitoring system (Liebig and Wagoum 2012, Stange et al. 2011). As these wireless communicators are attached to a unique MAC scanners, it can help estimate staff utilization spent time and frequency during different periods throughout the day using a low setup and processing cost. A study evaluated the impact of using MAC address data with WiFi and Bluetooth scanning technology as an effective tool for tracking and analysing human movement in terms of shared space utilization in a staff lounge of an office environment (Abedi 2014). It observed the proportion of staff utilization frequency over the duration of three weeks. The results demonstrate the functionality and significance of MAC data for human behaviour analysis. The results of the study extracted human movement features that are difficult and expensive through other methods such as video surveillance. Video surveillance can be expensive due to the amount of angles needed to track the trajectories of people moving through different frames of the footage (Rassia et al. 2009). In addition to this, illumination changes, limited viewing angles, density and brightness of crowd can hinder the accuracy of the results in office place environments.

## 4. Implementation

The tracking device consists of (1) two Raspberry Pi 2: Model B devices (RPI), a low cost, credit card-sized computer. It will run Raspbian Wheezy, an operating system optimized for the Raspberry Pi hardware. The RPI requires an (2) SD card for storing the data collected and, (3) a WiFi and Bluetooth USB adapter to capture the signals emitted from WiFi and Bluetooth enabled devices. One RPI is dedicated to capture WiFi signals and the second RPI with Bluetooth signals. It is possible to combine the scanners using

one RPI, however, is not currently capable of scanning WiFi and Bluetooth simultaneously. Therefore, for the purpose of this experiment, the scanners will be separated. Three WiFi adapters, TP-Link TL-WN727N, TL-WN722N and TL-WN821N, were evaluated during the experiment. The results indicated that whilst these USB adapters are compatible to connect WiFi to the local network, the TL-WN727N and the TL-WN821N were incapable of supporting monitor mode. Switching to this mode is required to sniff WiFi signals emitted from WiFi enabled devices without associating and connecting to the device. The study was conducted using the TL-WN722N. For Bluetooth, a Cambridge Silicon Radio (CSR) 4.0 USB adapter was used.

To maximize the amount of information collected about the detected devices, additional sniffing software was installed. Aircrack-ng was used to sniff WiFi signals, and Bluelog was used to sniff Bluetooth signals. Aircrack-ng is a network suite used to detect, sniff and manipulate WiFi networks. As clients send out directed and broadcast probe requests searching for AP they have connected to previously, Aircrack-ng has the ability to capture their unique addresses which can be displayed through two of its tools - airmon-ng to display probe requests and airodump-ng to record the data into a readable csv file. Bluelog, the second sniffing software, is a free Bluetooth scanner that is designed to capture and analyse the traffic of discoverable Bluetooth devices there are within a given area as quickly as possible. Intended to be used as a site survey tool, it prioritizes detecting the number of discoverable devices than device specifics. However, given the ability to identify MAC addresses of discoverable devices, this information can be used to assess the traffic of people in an area.

## 5. Experiment

This section presents real-world experiments to test whether it is *possible* to use commodity hardware as a technology to track the presence of humans in an indoor environment with sufficient veracity. The experiments are divided into four tests. The data and information collected as a result of each test is analysed and evaluated.

EXPERIMENT 1: TRACKING USING ONLY HARDWARE. The initial experiment was done to primarily evaluate the effectiveness of the device as a tracking tool prior to the installation of any sniffing software. The experiment was conducted for ten minutes with each RPI device needing to only detect one smartphone and one laptop device in a small, four by four meter room. The results for Bluetooth were simple. The RPI was able to de-

tect the Bluetooth enabled smartphone and laptop within 5 seconds of running. It was able to gather basic data about the device - MAC address and ‘friendly’ device name. Whilst the results for Bluetooth successfully capture the presence of different types of devices, however, it does not track the outgoing traffic from the area. Therefore, the data assumes that the human is in the area from the time the signal is detected until the termination of the test. Furthermore, as it detects two devices with two different MAC addresses, it also assumes that there are two people in the area. This can cause an inaccurate collection of results when evaluating the presence of humans in a more populated indoor environment. WiFi is able to actively detect access point connections using ‘iwlist scan’; unfortunately, there is no equivalent command that passively scans for devices. Therefore, the test could not be completed without the use of software. A second test was run, again for 10 minutes. The laptop was positioned in-between the RPI and the smartphone. The signals emitted from the phone were unable to be detected due to electronic interference throughout the duration of the experiment. In order to limit and reduce the chances for signal propagation loss, it is imperative that the RPI is positioned in an open area away from physical objects that can interfere and impact the results of the data collection.

EXPERIMENT 2: TRACKING WITH SOFTWARE. This involved running a test with each RPI with the sniffing software in the kitchen area of the architectural office. The test is conducted for one hour; during the lunch period. A video camera is strategically placed in the corner of the kitchen to ensure each person that enters of the area is captured in the frame to evaluate the accuracy and viability of the experiment. Bluelog and Aircrack-ng are initiated simultaneously. Airodump-ng allows filtering information, only collecting information that is relevant for the experiment. This experiment is configured to detect MAC addresses, signal strength and timestamps of the detected device, which is logged to a txt file as they are observed. Bluelog is also capable of filtering sniffing commands to collect required data for the experiment and logs the information into a csv file. This experiment is configured to detect the MAC address, device class and friendly name of the device, timestamp. Bluelog is run in amnesia mode to force it to detect all present devices each time step. This allows us to measure the approximate length of their presence in the kitchen by assuming that a device that is present for contiguous 4-second blocks hasn't left the area. The results revealed that both Bluelog and Aircrack-ng was unable to detect the presence of every person incoming and out of the kitchen area. An overall total of 55 people were detected in the video frame throughout the duration of the experiment. Only 33 WiFi devices were detected, approximating to 60%. However, as

four people are shown to have a laptop and phone each, the data assumes that there are a total of eight people when there are only four in the video. Results also revealed that the data gathering process for Bluetooth was delayed in comparison to Experiment 1 due to the amount of information it was configured to collect for a higher volume of people. This can hinder the evaluation of results when trying to collect real-time detection and approximated length of an individual's presence in the kitchen. Further, it also concludes that the popularity and signal availability of WiFi enabled devices is higher in comparison to Bluetooth. Although, the WiFi detection rate was not accurate, there is a 43% difference of data detection between both wireless signals.

EXPERIMENT 3: SPEEDING UP THE PROCESS TO COLLECT REAL-TIME DATA. This will be a repeat experiment followed by Experiment 2. Due to the slow detection rate when attempting to collect real-time data, the amount of information that will be collected from Bluetooth detected devices will be less. The class code of the device, the type of device and signal strength information is removed. The MAC address of the device and the timestamp will be the only information collected during this experiment. The results were slightly more efficient. Removing the type of device and signal strength increased the detection rate of Bluetooth devices. However, the results were not significant as it continued to present a low number of results in comparison to the presence shown in the video.

EXPERIMENT 4: SPIKE OF PRESENCE. This experiment was conducted during a surge of human presence. On Thursday afternoons, at exactly 4pm, the majority of the office gathers in the kitchen to collect sweets. Prior to this experiment, it was assumed that people will either not have their devices on them as this is a very short burst period or the tracking device will not detect the wireless signals in time. The results during the spike of presence indicated that there was an insufficient amount of data collected. The graph in Figure () indicates that at 4.01pm, only 42% of people with WiFi enabled devices were detected. This could be caused by two factors – signal propagation loss due to the high volume of people interfering emitting signals or people not carrying a device as they enter the surveyed area. Both factors have significantly affected the data, to which can conclude that using a low-cost tracker through WiFi and Bluetooth enabled devices is not efficient to monitor high volumes of human presence in a quick amount of time. Detecting Bluetooth signals throughout the duration of the experiment also displayed a significant amount of inaccuracy. At each 5-minute interval of the graph, it is evident that no more than 2 Bluetooth devices are detected at

a time. However, we can conclude the popularity of using such wireless devices with people choosing to enable their WiFi device over Bluetooth.

## 6. Conclusion and future directions

The main objective of this project was to determine whether a low-cost tracking device using commodity hardware was able to accurately automate and record presence in space with sufficient veracity. This conclusion presents an evaluation of the correlation between the collected data and reality using the video footage. It also presents the limitations and drawbacks that were encountered throughout the process that impacted the data gathering experiment. A low-cost tracker using commodity hardware *can* be used as a tool to monitor human movement to evaluate space utilisation behaviour. The assessment of compatible and effective hardware and software tools was required to gain an understanding to build a low-cost tracking tool that efficiently and appropriately scanned WiFi and Bluetooth enabled devices using inexpensive products. Evaluation of Bluetooth and WiFi popularity revealed that WiFi signals are more numerous than Bluetooth. This suggests that we can be more confident in data collected from WiFi signals than Bluetooth.

To point out limitations and drawbacks, it can be concluded that the integration of WiFi and Bluetooth in devices can be used as a human movement-tracking tool. It was able to detect nearby devices, however still presented significant challenges in indoor environments when attempting to detect real-time and accurate data.

*Not Carrying a Device* – The absence of an individual's device/s as they enter the surveyed area hindered the counting analytics of the data. The comparison of the video footage from Experiment 2 indicated that during short and quick moments of an individual walking through the kitchen, a device was not detected. The results concluded that out of the 55 people that were captured in the frame throughout the duration of the video, only 29 WiFi enabled devices were detected, approximating to 52%. A total number of 9 Bluetooth devices at the conclusion of the hour were captured, approximating to 16%. The significant number of inaccuracies can propose that the development of the low-tracking device is unable to accurately measure and identify the amount of human presence in an area that is prone to constant and quick incoming and outgoing traffic.

*Multiple Devices* – An individual that may carry a laptop, phone and a tablet at the same time as they enter the area can significantly hinder the analytics of the data. During experiment two, the tracking device was able to pick up 4 individuals with each interacting with a phone and laptop in the

kitchen. The data assumes that there are a total of eight people in the area when in fact there were only four.

Observing and evaluating the utilisation of space can be beneficial to businesses. Understanding the occupancy of spaces throughout an office place can help inform designers and businesses to improve existing design interventions in order to increase productivity, social interaction and business progression. It can also help analyse the density of flow and circulation throughout a space and evaluate the use and need of spaces in workplaces. By identifying the significance and peak periods of the utilisation, it can inform designers to find methods to optimise the performance of productivity. This kind of knowledge from human behaviour can facilitate them for the implementation of future plans with minimal risks involved. In another aspect, the results can be useful for human resources, helping those to understand the social interaction between people. This can help guide them to set up plans for the enhancement of social activities when organising events.

In order to progress forward from tracking human presence, one can start to localise the position of an individual through the process of triangulation. Triangulation has the ability to locate the position of the user by converting the Received Signal Strength (RSS) to a distance measurement between AP's and the user with the device. Three or more tracking devices are required to determine an accurate position of the user. This triangulation method will start by calculating the distance from the each closest base station to the user, which is then used as the radius from the station. As a result, the location is then assumed by pinpointing the area of the overlapping circuit and translates the user device to X and Y coordinates in space.

With only one Bluetooth, and one WiFi tracking device deployed at an architectural office, only basic information that can help detect the amount of devices could be collected. Installing various devices throughout the office can allow for advanced analytics with localisation and positioning strategies. Localisation analytics can help understand the behaviour of individuals in workplaces. As Space Syntax studies rely on manual data to track the patterns of human movement, using an automated metric data system can help speed up the process using inexpensive technology when comparing the expense to beacons, fitness bands and sensors.

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# A STUDY OF MEDIA FAÇADE SERVICE DESIGN FOR PROMOTION OF LOCAL COMMUNITY

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**Abstract.** This research was progressed as a media façade service design research for the development of a residential U-city experiencing zone in the Sejong City.

**Keywords.** Media façade; community; service design; U-City; Sejong City.

## 1. Introduction

By the recent development of digital media's technology, a new visual language is being formed with various types of communication methods increasing between people, people and objects and environment through a wireless internet and media with IOT features. Media-facade uses the city landscape's public design factors to cultivate resident awareness to city citizens and is expanding and generalizing its role in the community. However, even though installation examples of media-facade are increasing, the content from the media is quite en bloc and simple, which still lacks its qualitative improvements. As a media that can be used as a communication tool for city citizens and with the role to vitalize its region, media-facade needs to develop sensible contents that can bring out the psychological satisfaction of its users and research is also needed in a service design point of view to induce new experiences in a sensible way.

This research has been created as a design research to develop the Sejong City's residential U-city experience zone. With public organizations moving into Sejong City, commuting families are increasing, creating the needs of improvement in the cohesion of families and having a sense to be "settled"

after their residential movement. This research uses media-facade as a public design factor for the U-City and has been realized as a community factor that cultivates city citizen's residential awareness. Through a citizen interacting service, the problems within the region will be improved and media-facade service designs will be proposed as a public design community factor.

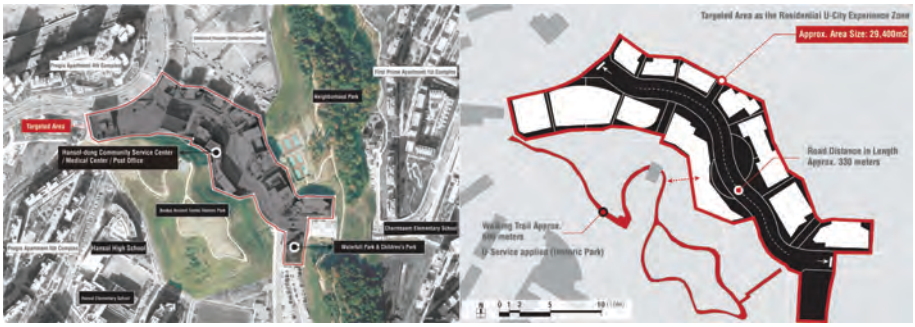



*Figure 1. Present conditions of the targeted area.*

## 2. Research method

This research will analyse previous researches that were processed in residential areas that regard the needs and characteristics of behavioural patterns to come up with a residential U-city experiencing zone persona model. With the analysed results, the media-facade services within the residential u-city experiencing zone will have its concept map and flow chart visualized with a service prototype suggested. Through the service scenario, a service that can actually be applied to an area will be proposed to promote the revitalization of the region's community.

This research's spatial scale will include Sejong City's Noeul 3-Ro, which is a road that has the first constructed residential area in Sejong City called the Hansol-dong "First Village", whereas several amenities are located such as cultural facilities, community institutions, community service centres, health centres and so forth. The detailed area of the targeted research area will be from the three-way intersection located at the "First Village" Prugio's 4th Apt. Complex to the three-way intersection that is located by the supermarket and fountain. This will be a 296-meter distance which also passes the community institution, community centre, medical centre and cultural facilities.

## 3. Analysing behavioural characteristics & needs of users

Surveys with users as targets were investigated with questions focused on the detailed needs and spaces that were necessary for experiencing activities within a residential area. This has been surveyed with the “experience zone’s” characteristics being considered.

Table 1. Outline of Survey for Users.

| | |
|---|---|
| Outline of Survey | Period: April 2, 2015 ~ April 5, 2015 (4 Days)<br>Target: Visitors at Sejong City's Noeul 3 Road<br>Research Method: Surveyed by hand<br>Participants: 100 people |
| Contents of Survey | General information of respondent<br>Awareness of U-city prior to survey<br>Evaluation of applied areas through a demonstration from the experience marketing investigation items (24 questions)<br>28 questions for digital lifestyles |

The surveys processed with users were investigated by a quota sampling method from Sejong City’s population proportion with various age groups suggesting ideas and thoughts. With actual users who visited the demonstrated and applied area as the respondents, it can be judged that the evaluated answers have high credibility. In the big picture, results were mainly drawn from a facility condition, contents and user aspects. The results from the survey are explained in Table 2.

Table 2. Summary of Survey Results.

| | |
|---|---|
| Facility Condition Aspect | Considering visiting frequency is high to community centers & commercial facilities, exploiting these areas in a multilateral and complex manner is needed.<br>As for the current area that has been applied as a demonstration, most users had a positive image of it but was analyzed that a service that triggers new experiences or detailed activities would be needed. Services and designs that induce the experiences of users would be necessary. |

| | |
|---|---|
| Contents Aspect | Crime prevention, education, transportation and culture were chosen as the most needed U-City services<br>To use the U-City services, images regarding its homepage, portals and etc., were positive while more than half of the respondents had plans to use it in the future. Services that had the users' interests were related priority to public data readings that could be related with civil affairs or civil services. In other words, users had more interests in services where they can actively use the information than services that were unilaterally "provided." |
| User Aspect | When considering that citizen voluntary participation was the highest response in a needed item to develop a U-City, an area where citizens can voluntarily and continuously participate is needed.<br>To maintain a relationship with other people, digital items can be used but exchanges between one's families showed low results. Services that are family-friendly will be needed.<br>When seeing that many users have interests in a family-focused life, it can be confirmed that if a spatial program is made that can induce this thought, the use of it will be high. |

## 4. Drawing a conclusion of the persona & scenario

With the results from the analysis of current conditions and theoretical consideration of user needs and behavioural characteristics that were complied beforehand of this research, a total of 4 personas of people have been concluded (Table 3). Persona is a circular model where various purposes and observed behaviour patterns from potential users and purchasers in a consuming market are condensed so that the users can be analysed in a closer fashion and defined as “users that have similar experiencing characteristics” to describe their using manner, motivation, needs, attitudes and etc. The defined persona can be used when making major decisions for UX design work and when processing detailed design work as well.

Table 3. Persona Characteristics and Needs.

| Persona | Characteristics | Needs |
|---|---|---|
| Housewife<br>Mrs. A | Entire family moves to Sejong-City due to her husband's work-place relocation. | Concerns of children education as a school parent<br>Adapting in a new residential environment and communication with residents<br>Healthy, safety and convenient livelihood with her family |

| Persona | Characteristics | Needs |
|---|---|---|
| High School Student Mr. B | First student to enroll in Sejong City's smart school | Smart education environment outside of school<br>Convenience and being safe when going to school.<br>Communication with friends<br>Adapting in a new school |
| Kindergarten Student Ms. C | Kindergarten student scheduled to enter elementary school | Communicating with friends<br>Enjoying sensible & experiential activities |
| Office Worker Mr. D | Single male who just moved to Sejong City due to the relocation of his institution | Convenient transportation when going & coming back from work<br>Since living alone, interests in health |

Through brainstorming, key-words and needs for experiential activities in residential areas have been secured. Through this type of research, a total of 4 personas have been shown as an example in which they are a housewife, high school student, kindergarten student and an office worker. The scenarios by its category are as below.

## 5. Proposing an interactive media-facade service

By various activities, digital graphics and media-facade that is being exposed to induce communication and participation, citizens can be provided with advertisements, commercials and etc. that are related with the city without any limits in time or place (Figure 2). Also, the main groups that manage the city will be able to use easy and efficient methods to provide the needed information. Information that is provided through LED panels can go through interactive services so that citizens can directly participate and share while it can have a role to be a space whereas the city and the citizen or a citizen and a citizen can communicate with one another. It also can especially have a role as not just an information transferor but as entertainment as well to provide new ways citizens can play and enjoy.

Unit services that are being provided from media-facade can be environment informational artefact services, digital graffiti services, interactive canvas services and etc. Explanations of these services are as Table 4.

By expanding information interfaces by media-facade, communication between citizens can become possible, it can secure the locations in areas and improve the landscapes and can provide bidirectional services compared to the existing LED media-facade which can create a road space into an experiencing space.

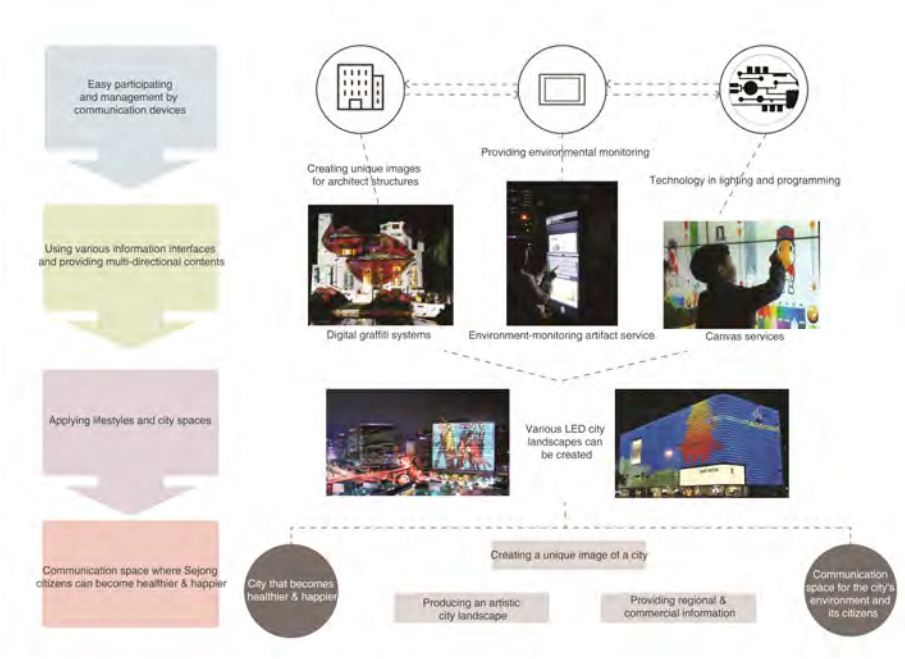



*Figure 2. Idea Map of Media-Facade Service.*

Table 4. Definition of Media-Facade Detailed Services.

| Detailed Service | Definition of Service |
|---|---|
| Environment informational artifact services (One-way) | Fine & yellow dust, the o-zone and other atmosphere conditions and amount of carbon emission is monitored at real-time conditions installed in horizontal spaces as a video information service provider at media-facade or media polls. |
| Digital graffiti services (One-way with realization of conditions) | Mainly an LED panel installed on lower parts of a building that is a service that exposes regional information, commercials and public services |
| Interactive canvas services (Both-ways) | Through a touchscreen kiosk, the user can use his or her hand to make an image or word come up on the monitor and with a sensor that can recognize a person's face, various panorama imaging filters can be used for revision. Usually an interactive service that is an LED electronic display installed on a facility's wall and exposed with real-time conditions. |

## 6. Planning space with interactive services as its basis

A standard design to actually create a space that has the base of a service concept would be like as below. System plans for environment informational artefact services, digital graffiti services and digital canvas services have been planned with its focus on technology and infra that is related with sensing, networks, interfaces, processing and security (Figure 3). A proposal of installing a media-facade within Sejong City's Noeul 3 Road is as follows. An image and a basic design plan that can be applied as a facade for a shopping district within Figure 1's targeted area is as below (Figure 4).

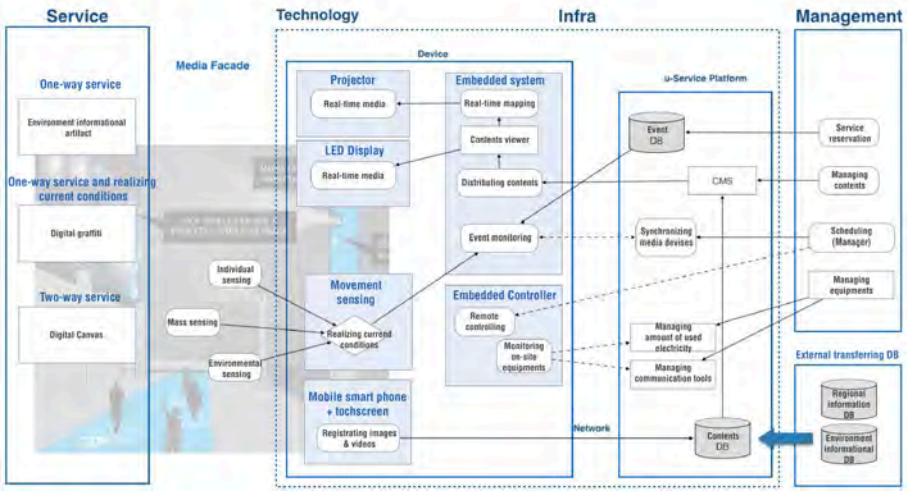



*Figure 3. Media-Facade Service System Plan.*

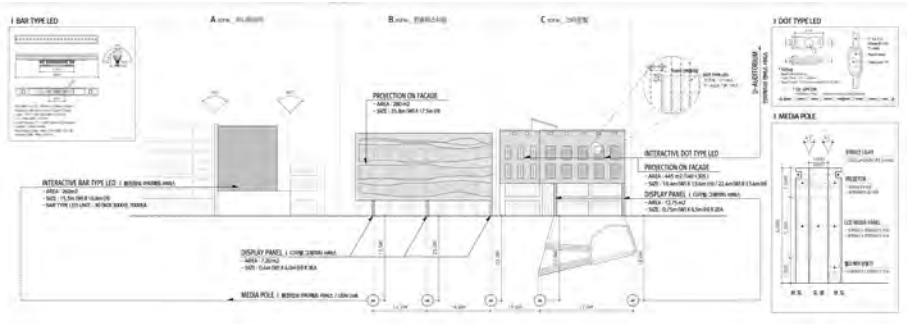


*Figure 4. Basic Blue Print of a Media Façade.*

## 7. Conclusion

This research has proposed a service design to revitalize a region by activating a media-facade that is recently becoming more interesting as a marketing and communication tool. Using the results of a survey from users with their personas models as the basis, a service scenario has been drawn upon. A media-facade that induces the participation of citizen communication and participation have been proposed by 3 types of unit services while their concepts and system plans have been drawn out as well. Also, it has been suggested that a simulated facade located at the targeted area's shopping district can be possibly applied. Through media-facade, information interfaces in city spaces can be expanded so that communications between citizens are possible while spatial locations and improvement of city landscapes can be secured and by using mobile smart devices and wearable devices, an individual's demand in wanting to socially and creatively produce and communicate anywhere can be fulfilled in the city spaces. Also, it is judged and expected that the existing LED media-facades that are currently being used as one-way information providers, showing off means for personal buildings can be replaced with services that provide two-way services and create an experiencing area from a street area with other kinds of various effects.

This research is significant to propose the method of service design using interactive media façade as the communication tool between citizens. The most important purpose of this research is the service scenario that can be used for applying systems of media façade.

## Acknowledgements

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# INDIGENOUS PARAMETRICISM – MATERIAL COMPUTATION

*The implementation of a collaborative indigenous domain based research lab*

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**Abstract.** The use of computational formats and digital tools including machine fabrication by indigenous people worldwide to augment traditional practices and material culture is becoming more and more commonplace. However within the practice of architecture while there are indigenous architectural practitioners utilizing digital tools, it is unclear as to whether there is motivation to implement traditional indigenous knowledge in conjunction with these computational instruments and methodologies. This paper explores how the tools might be used to investigate the potential for indigenous development, cultural empowerment and innovation. It also describes a general methodology whereby capacity can be shared between academia and indigenous groups to foster new knowledge through a recently implemented indigenous focused design research entity, SITUA. The importance and significant research potential of what we term 'domain based research' is reinforced through the exploration of emergent materials and building systems located within specific tribal domains. A recent project employing 3D clay extrusion printing is used to illustrate this approach.

**Keywords.** Indigenous domain based research: Maori; materials; digital fabrication.

## 1. Introduction

This paper consists of three distinct but closely inter-related aspects of localized production. Firstly it provides a general analysis and argument for a cul-

turally focused research collaboration between an academic institution, The School of Architecture, Victoria University of Wellington, and a Maori Tribal Group (Iwi) in New Zealand. Secondly, it outlines the implementation of a newly formed 'domain based' research laboratory - SITUA, as a model for a decentred 'micro institution', an intersecting space for broad indigenous research and material production. Thirdly, it argues the value of hybrid computational workflows and processes as a key part of design project delivery. Integral to this approach is how this site specific or domain based model could represent a new collaborative research 'frontier'. As a model it challenges centrally dependent design and production networks (university design studios), inert and demotivated local government and industry - making way for provincial and regional (tribal) localization and commerce, further providing a framework for inter-cultural interaction and interdisciplinary research collaboration. The framework described here was tested by a Master of Architecture Design Thesis that employs domain based knowledge and materials, parametric design and rapid prototyping production workflows employing additive manufacturing technology.

## 2. Research context

Over the last 25 years the economic landscape has changed dramatically for many Maori tribal groups due to a comprehensive land settlements process. This has entailed the return of historically significant land assets and in some cases substantial economic compensation. With an estimated worth to the New Zealand economy of around 37 billion dollars annually the ‘Maori Economy’ as it has recently been termed, is seen as a vital, innovative, people-centric and future focused yet commercial space (MBIE 2011) A space characterized by Iwi themselves in asserting the right to set the terms and direction of their own development. This has been achieved through a combination of both external commercial investment portfolios and crucial internal investment in the development and restoration of tribal domains. Focusing resources toward providing care for tribal elders, improving failing housing stock, employment opportunities and the revitalization of cultural infrastructure, including culturally significant buildings and landscapes. Consequently, change is also occurring in academic and private research institutions in the acknowledgement of the uniqueness and global esteem of Maori traditional knowledge (Matauranga Maori). Seen as a potent new knowledge 'frontier' Matauranga Maori encompasses a new and untapped cultural resource, with associated technologies and processes that can potentially effect change to inform mainstream New Zealand culture and industry.

## 2.1. NGAI TAMANUHIRI

Our research partner Ngai Tamanuhiri has a population of less than 2000 members. Their main geographic location or papakainga is rurally based, 30kms south of the Gisborne Township on the east coast of New Zealand. They have a diverse yet compact landholdings consisting of coastal areas, agricultural farm land and forested hill country. Being one of the smaller sized iwi has not been a disadvantage to their developmental ambitions fostering strong research relationships with external partners around biodiversity projects, forest holdings and new buildings since settlements were made 3 years ago. Like many Iwi, they have a growing interest in collaborative research that is innovative and has significant and real impact on the advancement of their Iwi, the wider community and the preservation and enhancement of their cultural and material domain.

## 2.2. SITUA

The authors, through prior involvement with Ngai Tamanuhiri on various small scale building design projects recognized the need to move away from the traditional ‘western’ client/architect working relationship in order to exploit the potential of closer collaborative exchange, in acknowledging that both partners bring their own specialist knowledge base to the research table. It was agreed as to the importance of operating in a more design research orientated mode, and in a way not too dissimilar to a cross-disciplinary design research lab format. Further prioritizing design research as a speculative and openly collaborative activity, with less emphasis on having an industry focus. As architectural academics with a special interest in machine based fabrication technologies, it also meant that we could potentially focus on the design of systems, workflows - the apparatus of delivery itself (machine fabrication and associated technologies). Through this close working association SITUA (Site of Indigenous Technologies Understanding Alliance), was established in 2014.

Essentially SITUA is a domain based, partnered research lab and although there are many other international examples of off-site remote research labs, two of the more prominent being the Architectural Association's Hooke Park and Guan Lee's Grymsdike Farm in the United Kingdom associated with the University of Westminster, The Bartlett (UCL) and the Royal College of Art. SITUA differs in that it deals with the convergence between emergent digital technologies in conjunction with traditional indigenous knowledge. Sited within an indigenous cultural domain it draws upon cultural knowledge in its active collaboration with local people/ and end users, uti-

lizing materials specific to the domain either in the design process or as a resource for fabrication and testing.

Although in its early stages, SITUA provides a potential framework for Ngai Tamanuhiri to move towards their goals of self-sufficiency within their built environment. Offering a model for developing research projects and systems that support and align to climate, vernacular, or cultural identity.

## 2.3. THE PROJECT

SITUA's main facilities are based in a disused woolshed and shearers' quarters close to the Ngai Tamanuhiri village of Muriwai. The spaces are setup for a range of 'dirty' and 'clean' activities. Both having spaces for teaching small to medium sized groups.

The current project being undertaken by SITUA tests and investigates the notion of working within indigenous cultural and material domains. With the title "Clay Crafting" it is the result of inquiry into general clay types found within the Ngai Tamanuhiri cultural domain. It is abundant as well as diverse and appears in a map of geological testing for clays and soils carried out on the region in 1962 by Pullar, who mapped and recorded the diversity and richness of some endemic varieties of clay found only on this region (Pullar, 1962). Ngai Tamanuhiri have a tradition in the use of various clays for medicinal purposes, arts and in the open fire cooking of particular foods.

As clay was identified as a key resource early in the research through gaining access to geological maps indicating a widespread and diverse set of clay types, samples were taken from a range of locations over the 2000sqm property. Suitable extraction points were selected across a range of elevations from hillside sites down to flats and gullies. Exposed areas that were subject to erosion, riverbank setbacks, open field and bush sites. This was enabled through a local Ngai Tamanuhiri guide who indicated well known areas for clay diversity helped with extraction and transport of materials across to the processing site. Much of the extraction was through a thick ash topsoil layer in some cases to depths of 1.5m in other areas surface exposed.

The means of assessment of clay types consisted of a simple potters hand test through the rolling of a small amount in the palm of the hand to test for bonding, and around the finger for elasticity. The raw clay had to undergo a process firstly of air drying and then maceration to separate the material in order to manually filter for foreign objects and lump deposits. Any inconsistent hard clay bits or vegetation were removed as they would affect the consistency of the end product. After the cleaning process the material was then further crushed and sieved through a fine grade sieve to be reduced to a fine powder with the consistency of millet. This powder was then added to

water and left overnight to settle. The settlement process allows the clay body to condense at the bottom of the container. The water on top is drained off with the remaining clay poured onto a suspended muslin cloth until it becomes the consistency of workable clay. The end product is comparable to commercially available potters' clay (Figure 1).



*Figure 1. Most of the clays extracted while categorically diverse and different when dried, appeared the same in coloration when fired.*

## 2.4. SMART BRICKS

One of the first design investigations was into masonry 'smart' brick modules. This was explored through an iterative geometry of recursive shapes to make stacked filigree structures or walls. Other versions and iterations appeared to be more like a traditional masonry brick employing the positioning of spigots for fixing and to reduce the need for mortar, allowing the potential for untrained assembly and multi-variate configurations. A final series of explorations consisted of a part post-tensioned assembly. This was assessed in terms of how the process allowed for collaborative production. It was discussed within SITUA that if the process of fabrication was entirely subtractive then it would potentially lengthen the process as casts would need to be produced and an extensive casting process would be required. As the paradigm of file to factory was something that we all wanted to commit to earlier on, subtractive processes at this stage in relation to the production of small

scale modules seemed to run against our desire to keep the workflow continuous.

The structural range of the brick assembly was obviously limited to compression as a masonry product. The spigot system for spacing, separation of each module and assembly however remained a positive potential in terms of providing a non-specialist construction assembly system with a variable range of possible configurations (Figure 2).



*Figure 2. Early stage design analogue studies for smart brick.*

## 2.5. 3D FLUID CEMENT-TYPE PRINTING

Additive manufacturing in the form of 3D printing in particular Fused Deposition Modelling (FDM) was investigated and adapted as the basis for a fluid cement-type material extruder in the customization of a small *Delta Style-3* arm printer. Further development of the printer to allow large scale models or modules to be printed resulted. The incorporation of off-grid solar power features and collapsibility for ease of transportation over difficult sites were part of the new customization. Further adaptations and design changes included 3D printed hinges, support bracketry, electronic console and motor housings, XYZ moving gear fixed to linear bearings and three vertical rod arms. The custom component designs were modelled in *Rhinoceros* and printed using ABS plastic in an *UP BOX 3D Printer* by *3D Printing Systems Ltd.* A repurposed 24volt wheelchair hoist motor and worm-screw jack were redeployed to extrude the clay from the 150mm PVC pipe drum to the 5mm or 10mm brass print head (Figure 3).



*Figure 3. From left to right, V1 compressed air driven. V2 low pressure air driven - modified base tower resized print limits, electronics stepped up. V3 extensive modification custom parts, mechanical ram, increased print bed size.*

## 3. Design Research

Early stage preliminary design research into scale-able tiles for the design of a small scale pavilion was tested through the use of an *UP Mini* and an *Up Box* 3D printers using ABS plastic. The process was used to streamline the 3D model and the configurations of the overall tile families that would make up the pavilion skin. The team assumed a transferability in scale via the small scale printer workflow to the newly built clay printer would be straight forward. Apart from obvious material difference and challenges of scale, the structure of process remained the same. The ease of iterative model testing at the smaller scale allowed rapid feedback during the early stage design process taking into consideration Maori formal design generators and patterned configurations at a scale that general issues of formal language and element arrangement could be resolved as a simulation of the larger scale sited pavilion.

As a design project, a pavilion structure was selected due to the limited timeframe for the research to be undertaken. The design of the pavilion was proposed as a tiled or scaled structure explored through a series of analogue massing models and the use of *Rhino* and *Grasshopper*. The scale module was dispersed over a base quad mesh giving rise to five primary modules showing varying degrees of blending and morphological change.

The shape of the module that configures the surface of the pavilion was based upon the 'whai' a stingray fish species, a living icon that occurs throughout Ngai Tamanuhiri history and cultural identity. Place names, carved and woven patterns found in carved meeting houses pay tribute to the stingray as epitomizing resilience, strength and tenacity.

The subsequent 3D clay printing and firing of iterations and test prints however, were not directly taken from 1:50 scale ABS printing to a 1:1 scale clay printing, but instead were stepped up only to 1:10. Again this was done in order to become more familiar with the material and its degrees of viscosity, volatility, shrinkage and drying overall as a means to gain better control over the workflow processes. These 1:10 scale modules were air dried over a period of 48 hours to ensure a 'chalk dry' consistency - to reduce the potential of damage before pre heating failure through fire shock. The modules were then subsequently pit fired.

Pit firing consisted of loosely arranged layers of combustible material on a brick base at the bottom of the pit. The pit used to fire the first modules was dug to a depth 450mm by 1m square. On top of the brick base a layer of driftwood and mixed wood chips to help oxidize and aerate the clay toward the bottom of the pit with the remainder of the pit having a combination of 'magic dust' consisting of mixed oxides to add surface texture, coloration and

'crazing.' Magic dust can include anything from salts, metal grinds, banana peels, grass clippings or flax fibre, with a heaped bonfire to cap off the pit. A key aspect of ensuring firing success is having the pit temperature up to around 1000 degrees, enabling the clay to vitrify. A process by which a clay-body transforms into a ceramic material. At an elementary level it changes the material/chemical structures to the extent they cannot be reversed or reduced back to a useable powder or pliable clay form.

### 3.1. STRUCTURE

The pavilion structure throughout the early stage design iterations explored the possibility of a self-supporting and integrated structural system that exploited the module shape, its lapped joint and the evident hardness of the ceramic once fired. A reciprocal triangulated configuration was also considered earlier and tested at the 1:50 ABS printed scale but was assessed to be reductively generic in its aesthetic expression, especially in light of cultural articulation of the surface and modulation (Figure 5).

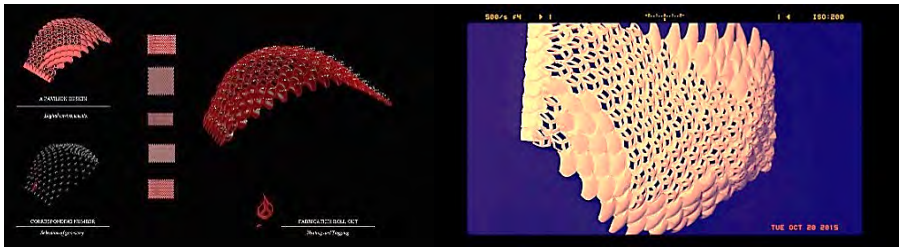


*Figure 5. Early stage pavilion design and surface texture based on the 'whai' or stingray.*

A post-tensioned wire and light steel sub structure due to the timeframe and the stringent health and safety requirements was finally developed to support the external module/tile cladding. This was one of the non-negotiable aspects of the pavilion that ran against the ethos of the agenda put in place initially. Seen as an externally derived structure - even though with better time and resources it took the pavilion from an internally (domain negotiated) driven project to an ancillary regulated conventional type. Moving it out of the hands of its fabricators and assemblers to an externally implemented engineered frame.

## 4. Conclusion

The pavilion and 3D clay printer is in its final stages of completion at 1:1 scale. Our third version of our clay 3D printer has the capacity to extrude

highly viscous cement based material obtaining fine resolution outputs with minimal effort.

3D FDM printing in general as an additive process of manufacture exceeded the design scope for the project in comparison to available subtractive manufacturing methods, in that it would also allow a wider field of formal exploration and design innovation. Digital model variations allowed our scope to extend to a geometric design matching indigenous design expressions.

While much time has been spent discussing the project in good detail and its technology we believe that focus should really lie with the efficacy and inherent potential of the domain based research model and its associated workflow within dispersed rural communities. As a potent yet somewhat rudimentary form of 'file to factory' these technologies may be seen as getting closer in alignment and calibration to the real capacities of communities to serve their own internal - and in this case indigenous and tribal domains.

Digital technologies deserve more credit however, for opening up the potential for a new articulation and understanding of traditional technologies and ontological frameworks, arguably only found in these communities. With regards to this deep collaborative exploration of the 'domain', a leading question for SITUA has been how we might begin to map, reinterpret and decode its internal subsystems for the very people they belong? What are the implications of what is essentially an intervention? How can we best understand the effects? What is lost and what is potentially gained that is of use to the diverse livelihood needs of Iwi, including lifestyle and commerce?

SITUA will surely develop, and potentially subdivide into more specialized, interdisciplinary compartmental research areas. We envisage a lively influx of interest as has already begun, with a view to greater collaboration across other research institutions. With transferability as a model to other Iwi groups and wider indigenous communities. We are also excited by the prospect of engaging with interoperable research fields such as traditional and new materials, natural and artificial energy, heritage/restoration, environmental monitoring, indigenous parametric and computation, education, pattern, ecology, form exploration and housing.

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# DEFINITION OF A DOMAIN-SPECIFIC LANGUAGE TO REPRESENT KOREA BUILDING ACT SENTENCES AS AN EXPLICIT COMPUTABLE FORM

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**Abstract.** This paper aims to define the syntax of KBimCode Language as a domain-specific computer language to represent Korea Building Act sentences. KBimCode Language represents building permit requirements in Korea Building Act as explicit computable rules. KBimCode aims to accomplish the neutral and standardized way of rule-making in an easy-to-use syntax. This paper introduces the approach of language design and definition. The main concerns handled in the paper are: 1) features of building permit-related regulations in Korea Building Act are reflected in the strategy for the lexical and syntactic design of KBimCode Language; 2) specification of KBimCode based on the context-free EBNF notation is introduced; and evaluation of the language definition is performed. KBimCode is an ongoing project. Together with newly developed rule checking applications, KBimCode will establish automated design quality assessment system in Korea.

**Keywords.** Automated building permit system; automated design assessment; rule checking; rule-making; domain-specific language.

## 1. Introduction

Building Information Modelling (BIM) is increasingly used in the various fields of architecture, engineering, construction and facility management (AEC-FM) industry. As one of promising direction of BIM application, automated assessment of building design become available (Lee et al, 2012; Eastman, 2009). Conventionally, design assessment was done by manual and it was tedious, iterative, time-consuming, and error-prone process (Ding et al, 2006). BIM-enabled design assessment is expected to streamline this pro-

cess and increase efficiency and precision (Han et al, 1997; Eastman et al, 2009).

The design requirements are written in human language (natural language) and consequently embraces ambiguity and vagueness (Nawari, 2012). Therefore, the natural language rules need to be formalized into a set of explicit and computational rules (Malsane et al, 2015) to perform automated code compliance checking. It is a process of transforming design knowledge into a computable format and maximizing computer-executable semantics. As one of the rule-making solutions, this paper introduces domain-specific language called KBimCode. KBimCode is developed to translate building permit regulations in Korea Building Act into computable rules with ease of use and high fidelity. Among various issues regarding KBimCode, this paper mainly focuses on language design and definition. The following sections introduce 1) overview of KBimCode, 2) strategy for language design, 3) specification of KBimCode based on the context-free EBNF notation, and 4) language evaluation.

## 2. What is KBimCode?

The distinguishing feature of KBimCode is that it is a software-independent and standardized approach to the rule-making process. Some previous projects embedded design knowledge in rule checking tools. In such case, the rule-making process was integrated with the development of rule checking software. The resulting rules are inevitably dependent on specific proprietary software and closed BIM environment. On the other hands, KBimCode is an intermediate script language that is independent of rule checking tools. As Figure 1 illustrates, KBimCode is processed into open text files such as JSON (ECMA, 2015), XML (W3C, 2015), etc. Therefore, it can be used in various BIM assessment tools. The theoretical approach for generating KBimCode is described in (Lee, 2015).




*Figure 1. The scope of KBimCode within the entire rule checking process. Building Act sentences are translated into KBimCode and then processed into open text files to be imported to rule checking tools for evaluating building permit requirements.*

Based on such background, KBimCode can be summarized as follows:

1) KBimCode can be classified as a domain-specific language, a programming language, and a rule language.
2) Its main functionality is to convert natural language rules into computable rules for automated code compliance checking.
3) Its target field is basically AEC industry, especially focusing on building permit issues in Korea.
4) KBimCode Language attempts to deal with building act in an intuitive way in order to define user-friendly computable rules.

The main target of KBimCode is Korea Building Act, especially building permit regulations. The entire regulations were analysed to capture general syntactic and lexical elements of language design. For example, Korea Building Act-specific building objects and their properties were clarified to be used as a lexicon of the KBimCode. Various expressions such as high-level methods or dot notation approach were devised in advance to describe specific conditions in the building act.

## 3. KBimCode language design

### 3.1. LEXICAL DESIGN

This section describes a lexical design strategy for basic tokens and idioms used in KBimCode Language. The fundamental strategy can be as follows:

1) A Building act can be split into atomic sentences (ASs), a type of declarative sentence that is either true or false. The AS is processed into translated atomic sentence (TAS) that can be expressed in a single S (subject) + V (verb) + O (object) structure.
2) KBimCode assumes that S is Korea Building Act-specific building objects and properties. They are specified into a dictionary and will be used as the fundamental lexicon.
3) To represent properties of KBimCode objects: dot-notation.
4) Predefined object names will be starting with upper case, while properties and user-defined names will start with lower case.
5) V + O structure can be pre-defined as basic methods, for example, getObect(), isExist(), getObjectDistance(), etc. The details of the predefined methods are described in (Park et al, 2015).

### 3.2. SYNTACTIC DESIGN

This section briefly previews a syntactic design style for KBimCode Language. A basic syntactic form of KBimCode can be represented as follows:

```
check(arg) {
```

```
    Statement;
    …
}
```

– Where `check` is a pre-defined method that declares the checking of a certain building act sentence.
– Where `arg` and `Statement` are non-terminal tokens.

The non-terminal token `arg` is pointing a building act sentence to be checked. The `Statement` is a rule defined in the building act sentences. The statement types can be categorized as follows:

- Arithmetic Logic Units (ALUs)
- Conditional Statement
- KBimCode Object Model (KOM)

Originally, ALU is a digital electronic circuit that performs arithmetic and bitwise logical operations (Wikipedia, 2015). In this paper, ALU stands for a declarative clause that performs the atomic unit for rule checking. Structure of the ALU is detailed in the next section. As for Korea Building Act, content of a single sentence consists of two parts: a checking condition and a checking content. They are joined using IF-THEN-ELSEIF-ELSE logic to form conditional statement. KBimCode Object Model (KOM) is one of the key features of KBimCode Language. It is a human-cantered abstraction of building objects specified in the building act. By using KOM, user can define virtual objects with desired rules as constraints. The defined KOM can be applied to the various locations within KBimCode.

A set of statements can be grouped and used as an object. The syntactic form of the statements group is as follows:

```
var {
    Statement;
    …
}
```

– Where `var` and `Statement` are non-terminal tokens.

The statements group is declared outside of the basic syntactic form and its name is used as a variable in the form. By using the statements group, KBimCode can be written in a clear and simplified way.

## 4. KBimCode language definition

### 4.1. OVERVIEW

This chapter defines the syntax of KBimCode language grammar. The formal definition described in this chapter is EBNF-based ANTLR rule (Parr,

2008). ANTLR is a language parser generator. Non-terminals starting with lower case are syntactic rules and non-terminals starting with upper-case are lexical definition. As mentioned in the previous section, KBimCode Language basically has three key components as follows:

- Check declaration
- Statements Group declaration
- KBimCode statement

The Check declaration and the Statement Group declaration consist the syntactic form of KBimCode, while KBimCode Statement is subordinate to the other two components. These three components are defined as: [1] kCheckDef, [2] kStatGruopDef, and [3] kStatDef. Most of all, a non-terminal syntactic rule kKBimCodeProgram is the starting point of KBimCode Language definition. A lower case ‘k’ means KBimCode and the rest of alphabets are simplified token to represent each syntactic components.

```
kKBimCodeProgram
    :      kCheckDef? kStatGroupDef?
    ;
```

[1] Definition: kCheckDef

```
kCheckDef
    :      CHECK ‘(‘ kCheckParamDef ‘)’
           ‘{‘ kStatDef ‘}’
    ;
```

[2]Definition: kStatGroupDef

```
kStatGroupDef
    :      kStatGroup ‘{‘ kStatDef ’}’
    ;
```

In these syntactic rules, the lexical rule `CHECK` stands for the pre-defined method “check” that instantiates checking of a target building act sentence. The `kCheckParamDef` defines identifier tokens for the target sentence. The `kStatGroup` defines a user-defined variable name of the Statement Group.

## 4.2. KBIMCODE STATEMENT

The KBimCode statement has three types of statements and each type is defined as [3-1] kALUsStat, [3-2] kIfThenElseStat, and [3-3] kKOMDef. The definition of KBimCode statement is as follows:

[3] Definition: kStatDef

```
kStatDef
```

```
    :      kStatLines
    ;
kStatLines
    :      kStatLine+
    ;
kStatLine
    :      (kALUsStat | kIfThenElseStat | kKOMDef)
    ;
```

*4.2.1. Arithmetic Logic Units (ALUs)*

Arithmetic Logic Unit is an atomic rule for checking. It returns true or false result by comparing left operand and right operand with an operator. Left operand describes a specific condition while the right one states an explicit value. With AND, OR conjunctions, multiple ALUs can be joined in expressive way. The definition of ALUs is as follows:

- [3-1] ALUs definition: kALUsStat

```
kALUsStat
    :      kALUStat ((AND | OR) kALUStat)*
    ;
kALUStat
    :      kLOperand kALUOperator kROperand
    ;
```

The `kALUsStat` defines multiple ALUs joined with conjunctions and the `kALUStat` defines a single ALU. The `kLOperand` and the `kROperand` can be predefined methods, dot notation access to building objects and properties, or explicit values such as truth or falsity, string, or numeric values. Operators are data type-specific. Operators defined by the `kALUOperator` can be as follows:

- Operators for string: =, !=, ==
- Operators for numeric: >, >=, =, <, <=, !=

Some examples of the valid KBimCode segments within the rule `kALUsStat` are as follows:

```
1) getSpaceDistance(LivingRoom, Stairs, MRP) <= 30;
2) Rail.Space.type = Balcony AND Rail.Floor.number >= 2;
3) getResult(BA.49.1) = TURE;
```

*4.2.2. Conditional Statement*

[3-2] Conditional Statement definition: kIfThenElseStat

```
kIfThenElseStat
    :      kIfStat kThenStat kElseIfStat* kElseStat*
    ;
```

The conditional statement inheres IF-THEN-ELSEIF-ELSE logic. The ELSEIF and ELSE are optional. Following are example snippets.

```
1) IF(BuildingStoriesCount()>=6) THEN isExist(Elevator)=TRUE
2) IF (CS) THEN KS
```

Logically, 1) and 2) are same. The inherent ALUs can be replaced with variable name of the Statements Group (in this example, CS and KS).

### *4.2.3. KBimCode Object Model*

Korea Building Act has its own semantics of building objects and their properties which are different from that of IFC or proprietary BIM platform. KBimCode Object model (KOM) is a human-centred abstraction of building objects based on the semantics of the Korea Building Act. It is borrowed concept from (Lee, 2011). By using KOM, users can derive the objects of interest. KOM is dynamically instantiable with user-defined condition rules.

The basic syntactic form of defining KOM is as follows:

```
ObjectType var {
    Statement;
    …
}
```

– Where `ObjectType`, `name`, `Statement` are non-terminal tokens.

The non-terminal token `objectType` are class level objects defined in the KOM lexicon. The `var` is a user-defined variable name that can be replaced with the dynamically instantiable KOM. The `Statement` is KBimCode statements that specifies constraints of the KOM.

The definition of KOM is as follows:

[3-3] KOM definition: kKOMDef

```
kKOMDef
    :      kKOMDefStatDec
           '{' kStatDef '}'
    ;
kKOMDefStatDec
    :      bWrapObjType BID
    ;
```

The `bWrapObjType` defines type of building objects. The lexical rule `BID` can be instantiated by any of the variable names. The examples of KOM definition and application are described in the following evaluation section.

## 5. Evaluation

This section shows snippets of KBimCode. Enforcement Decree of Building Act (EDBA), Article 35, Clause 1 (NSDCK, 2015) was selected as an example. It regulates the installation of direct stairs. Table 1 shows the building act sentences and the corresponding KBimCode.

Table 1. Example of KBimCode based on actual Korea Building Act: "Enforcement Decree of Building Act Article 35, Clause 1".

| **Korea Building Act : Enforcement Decree of Building Act (EDBA), Article 35, Clause 1** |
|---|
| **[EDBA.35.1]** Direct stairs installed on the fifth or upper floor or the second or lower underground floor shall be installed as fire escape stairs or special escape stairs: Provided, That the same shall not apply to cases where main structural parts are made of a fireproof structure or noncombustible materials and falls under any of the following subparagraphs: |
| **KBimCode** |
| `check(EDBA.35.1) {`<br>`  IF !(CS1 AND CS2) THEN KS`<br>`}`<br>`CS1 {  isFireResistantStructure(MainStructure) = TRUE`<br>`  OR getObjectMaterialType(MainStructure) = Non-combustible;`<br>`}`<br>`CS2 {  getResult(EDBA.35.1.1) = TRUE`<br>`  OR getResult(EDBA.35.1.2) = TRUE;`<br>`}`<br>`KS {  Floor myFloor {`<br>`  myFloor.number >= 5`<br>`  OR myFloor.number <= -2;`<br>`  }`<br>`  Stair myStair {`<br>`  myStair = getObject(DirectStair);`<br>`  getObjectProperty(myStair) = EscapeStair`<br>`  OR getObjectProperty(myStair) = SpecialEscapeStair);`<br>`  }`<br>`  hasElement(myFloor , myStair) = TRUE;`<br>`}` |

Evaluation of KBimCode Language is performed using parsing tree which is auto-generated by a parser. Figure 2 shows part of the evaluation results: KBimCodeProgram, Check declaration, and KOM definition. KBimCode segments in the Table 1, the EDBA 35.1 was used as the sample KBimCode for the evaluation.

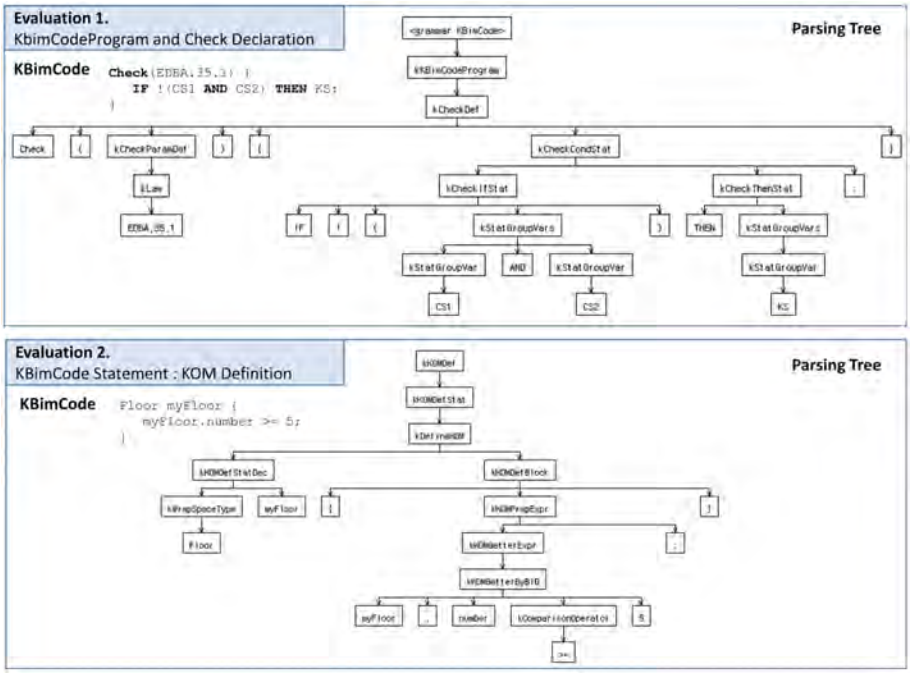



*Figure 2. Snapshots of the evaluation results of KBimCode Language with parsing tree.*

## 6. Summary

This paper introduced the approach to language design and definition of KBimCode. The lexical and syntactic form of KBimCode Language reflects features of building permit regulations in Korea Building Act and can be categorized as; 1) Check declaration, 2) Statement Group, and 3) KBimCode statements. The Check declaration specifies a target building act sentence to be checked and contains a set of statements that express conditions of checking. Types of statements are ALUs, conditional statement, and KOM. Especially, KOM is one of the key features of KBimCode. The set of statements can be grouped into the Statement group and used as a reusable object.

KBimCode development is an ongoing project. Further development of KBimCode Language will reflect extended syntax as KBimCode aims to extend its target to various requirements such as design guideline, request for proposal, etc.

## Acknowledgements

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# DIGITAL GENERATION OF CHINESE ICE-RAY LATTICE DESIGNS

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**Abstract.** Being a rich source of geometric forms, Chinese lattice designs have interested some scholars. With shape grammar and algorithmic approaches, the generation of Chinese lattice designs has been achieved except for that of irregular interdependently structured ice-ray designs. This paper introduced an algorithmic approach to solve the problem. The algorithm includes crack-track presetting, crack-track cutting, crack correcting, and bad shape disposing, realized by programming with Grasshopper VB script component.

**Keywords.** Ice-ray; algorithm; designs; generation.

## 1. Introduction

In his book *A Grammar of Chinese Lattice*, Daniel Sheets Dye collected over 1200 Chinese lattice designs and catalogued them into 26 types. Most of the designs have a clearly regular structure except the "rustic ice-ray" designs, which look sophisticated and mysteriously diversified. The creation of ice-ray designs has been depending on the skill and aesthetic sensibility of the craftsman. "Its development shows a high degree of artistic progress. It is the most careful of lattice design, a genus that is distinct and distinctive." (Dye, 1949)

Being a rich source of geometric forms, Chinese lattice designs have interested some scholars. Early in the 1970s, George Stiny introduced shape grammar to generate traditional Chinese lattice designs. Stiny's grammar (Stiny, 1977; 2016) is effective in generating regular patterns. Recently, Lee and Tiong (2013) presented an algorithmic approach of generating Chinese lattice designs by simple procedures, not including ice-ray designs.

To generate irregular ice-ray designs, Stiny (1977) defined parametric shape grammar. With a few of rules, his grammar can create a serious of

beautiful ice-ray patterns, as Figure1 shows. Stiny's ice-ray grammar was expanded by Liew Haldane and Mark Tapia. Haldane further categorized shape grammar rules for ice-ray designs into 4 types: 1) simple parametric grid shape grammar rules; 2) parametric shape grammar rules; 3) constrained parametric shape grammar rules; and 4) unknown shape grammar rules (Shape Grammars of Ice-ray Chinese Lattice Designs, 2005). He also developed an AutoLISP program as an implementation of his ice-ray grammar. Tapia (1992) followed the design intention that Stiny used to describe ice-ray designs, while defined new shape rules for the ease of computer implementation.

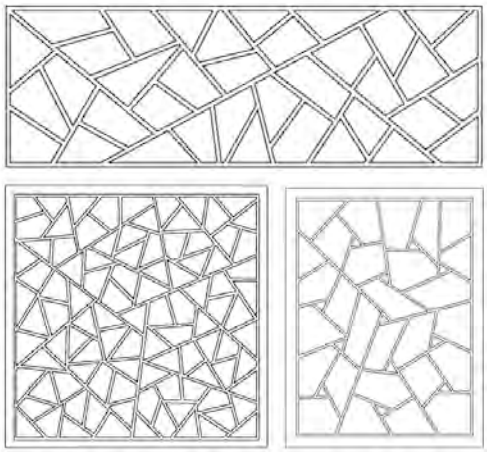


*Figure 1. Ice-ray designs generated by shape grammar (taken from Stiny, 2006, pp. 336, 339, 340).*

The above ice-ray grammars can generate regular ice-ray designs and some irregular ice-ray designs, but not all kind of ice-ray designs. Due to the iteration of shape grammar, the generated irregular ice-ray patterns, as Figure1 shows, all have certain hierarchical structure. In reality, we can see that most of ice-ray designs don't have a hierarchical structure, wholly or partly (Figure 2). Their bars are usually interdependent. Such designs belong to Haldane's "unknown shape grammar rules" and "seem to defy any known rule".



*Figure 2. Interdependently structured ice-ray lattices.*

Dye (1949, p. 21) described the technique of ice-ray lattice construction as: "… he divides the whole area into large and equal light spots, and then subdivides until he reaches the size desires." This is followed by Stiny and similar studies. This way obviously doesn't work for interdependently structured ice-ray designs. Yuan et al (2011) noticed the shape at the bar joints, which they called "human shape" and thought as Chinese cultural intention embodied in ice-ray designs because the shape is similar to a Chinese character "人" which means human, as the key of ice-ray designs. They developed a grammar to generate interdependently structured ice-ray designs, starting from a central hexagon (or other polygon) and repeatedly adding a bar on existing ones with "T" shaped joints (Figure 3). This method is similar to the drafting process of the carpenters, as briefly introduced in the book *Decoration of Chinese Traditional Building* (Guo and Chen, 2005, 97-98). Lack of shape control means, this method may only work when the ice-ray pattern is not very complicated and composed by not many lines.

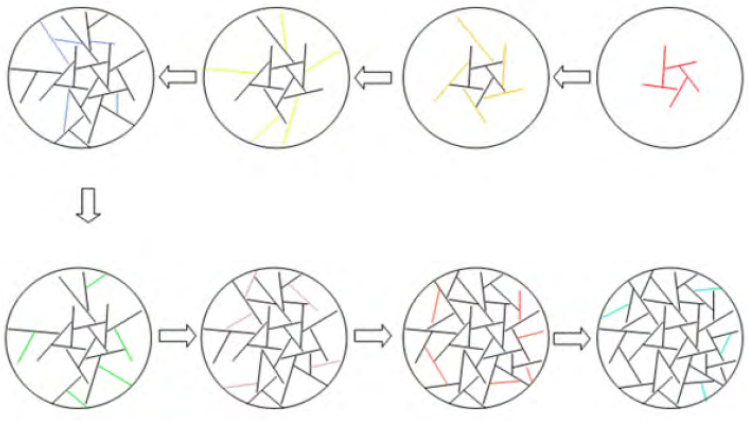


*Figure 3. Generating process of interdependently structured ice-ray by Yuan et al (2011).*

For interdependently structured ice-ray designs, it seems not easy to generate with the departure from one or several simple shapes. An approach on generating overall layout seems necessary. This paper will introduce an algorithmic approach based on this idea, by which such designs can be achieved.

## 2. From synchronous cracks to "T"-shape joint patterns

It is easy to find out that an ice-ray design is essentially composed of a set of lines which are "T"-shape connected. Literally, the Chinese name of ice-ray means "ice crack". Inspired by this, the generation of such a "T"-shape joint pattern can be achieved with the following idea. Each line in the pattern is considered a crack, which breaks from a point and extends along a straight or curve line. When it meets another crack, the extension will stop at the meeting point. When every crack stops extending, a "T"-shape joint patterns is resulted. This process can be transformed to the following algorithm:

Step 1: The pre-setting of crack tracks. This step sets the break points of a certain amount of cracks as well as the crack tracks. The tracks may be a set of straight of curve lines, and the break point of each crack may be at a certain position of the line, for instance the midpoint (Figure 4(a)). The outer or inner borders of the pattern can be treated as existing cracks, which will not extend but will obstruct the extension of other cracks.

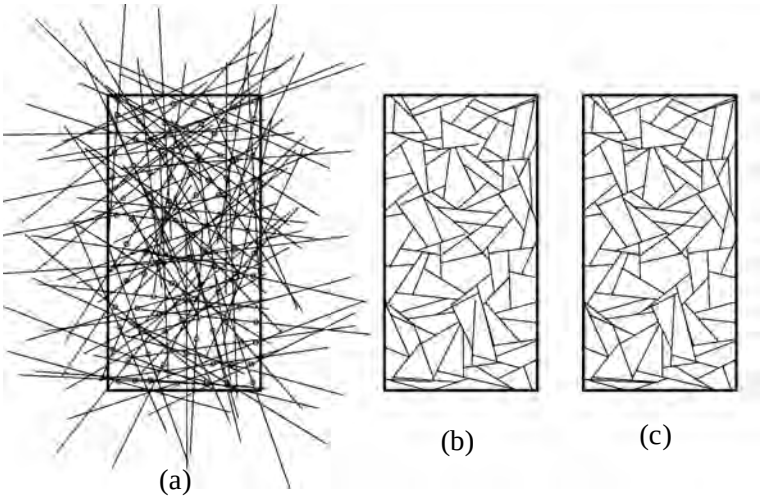



*Figure 4. Process of generating "T"-shape joint patterns.*

Step 2: The blocking-up of crack extensions. Every crack will stop it extension when it meet an early arrived crack or existing crack. This is equivalent to cutting out the segment of the crack tracks beyond the intersection

point. For every crack track, we first calculate and record its intersection points with the existing cracks. Then we calculate the intersection point with other crack tracks. When the distance from the intersection to the break point of the crack track is larger than that from the intersection to the other crack track's break point, the intersection point is recorded. Here we assume that the cracks are synchronous, namely they break at the same time and their extending speeds are equal, so that the crack with shorter distance will extend to the intersection point earlier and block the extension of the crack with longer distance. (If asynchronous cracks are considered, we need to calculate the time instead of the distance.)

After calculating and recording all the intersection points, each crack track is trimmed, keeping the section between the nearest intersection points on the two sides from its break point. Thus, a "T"-shape joint pattern is preliminarily obtained, as Figure 4(b) shows.

Step 3: The correction of miscut lines. In Figure 4(b), we can see some of the crack endpoints are not on any other crack. The reason is that in the above step, some blocking cracks have been already blocked by other cracks before they extend to the intersection points, so that their effects of blocking don't actually occur. To correct this, we can treat the cracks of which both endpoints are on other cracks as existing cracks and repeat the above step, until all the joints are "T"-shaped. In most cases, the miscut crack tracks will not block each other, so that we simply extend the miscut cracks to the nearest crack. The result of this step is shown in Figure 4(c).

## 3. Shape control

Due to the randomness of ice-ray designs, it is somehow inevitable to produce small or narrow polygon shapes in the "T"-shape joint pattern out of the above process. Such shapes are not suitable for a beautiful ice-ray design which normally consists of well-proportioned polygons. To avoid this, we may try to re-preset the crack tracks or let computer deal with this problem. Anyway, the judgment of ill-shaped polygon is needed. Theoretically, it is easy to distinguish such ill-shaped polygons by checking the angles of each polygon if we can extract all the polygons in the "T"-shape joint pattern. This needs an extra algorithm which is usually complicated. In this study we use a simpler algorithm to distinguish ill-shaped polygon by checking the relation of each couple of crack lines.

1) Find the start point to end point vectors of two cracks, and then calculate the angle between them. Reverse one of the vectors if the angle is larger than 90 degrees, and then get the bisector vector of the two vectors.

2) For each crack, construct two planes through the start point and the end point and perpendicular to the bisector vector, and find the intersection points of the two planes with the other crack. If the intersection exists, calculate the distances from the start/end points to the intersection points respectively. The intersection situations differentiate the relations between two cracks as follows:

If the two planes of any crack both intersect the other crack, then the relation between the two cracks will be one of the situations shown in Figure 5(a) or Figure 5(b). In this case the two intersection points are recorded. If both cracks have one plane intersecting the other crack, then the relation is among those shown in Figure 5(c), 5(d), and 5(e). It is easy to differentiate them, and the two intersection points are recorded. If the overall number of intersection points is zero, then the situation is that shown in Figure 5(f).

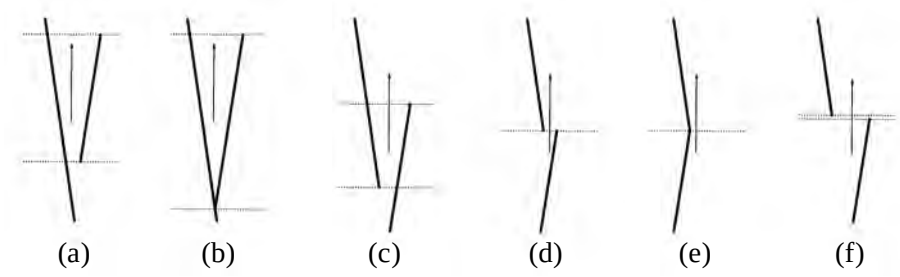



*Figure 5. Differentiating relations between two cracks based on plans perpendicular to bisector vector.*

3) In the situations shown in Figure 5(a), 5(b) and 5(c), the two cracks will most likely be segments of a same polygon in the pattern and they may cause ill-shaped polygon. Two indicators are set to judge whether the polygon is ill-shaped. The first one, “d”, denotes the distance between the two intersection points for determining whether the area of the polygon is too small. The line connecting the two intersection points is divided into equal length segments, then a serious of planes though the points of division are set. Each plane has two intersection points with the two cracks. The distance between each two intersection points is found, and the average value of the distances dividing by the first indicator, the distance between the original two intersection points, is set as the second indicator “r” to judge whether the polygon is too narrow.

If one of the two indicators values is smaller than the threshold value set by the user, the track of the shorter crack will be deleted and the program will be restart, until all the relations between each two cracks satisfy the demand. Figure 6 shows the results of the pre-set same as in Figure 4, under

the control of the two indicators (6(a): d=0, r=0.2; 6(b): d=0, r=0.4; 6(c): d=a certain value, r=0.4).

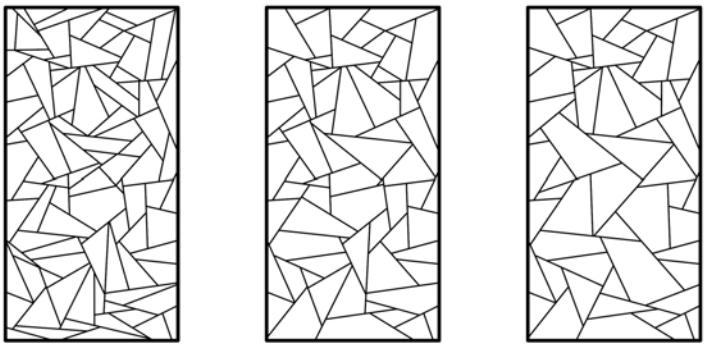



*Figure 6. Shape control results.*

## 4. From "T"-shape joint patterns to ice-ray designs

The algorithm except the pre-setting step is realized with VB scripting on Rhino Grasshopper, which can generate various "T"-shape joint patterns based on users' different presetting of crack breakpoints and tracks with control on polygon shapes.

Figure 7 shows some computational results based on randomly set crack tracks. Those "T"-shape joint patterns embody some attributes of traditional Chinese ice-ray designs, but they still look different in the aspect of self-similarity.

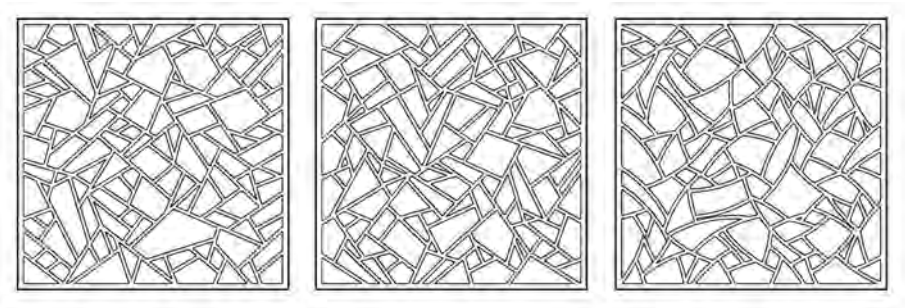


*Figure 7. Ice-ray designs based on randomly preset crack traces.*

The solution is in the presetting process. Observing various ice-ray designs, one may discover that each irregular ice-ray pattern has certain simi-

larity with certain regular ice-ray pattern. If the crack tracks are preset with a slightly transformed regular ice-ray pattern, then such similarity will be achieved. Figure 8 (left) shows one of the common regular grids of ice-ray designs. Based on it, the crack tracks is preset by randomly moving the lines with small distances, rotating with small angles (less than 15 degrees), and extending to a relatively long length. The crack break points are at the middle points of the original grid lines. The program can successfully generate a serious of designs similar to traditional ice-ray designs, one of which is shown in Figure 8 (right). Figure 9 shows another example out of a regular grid composed by hexagon.

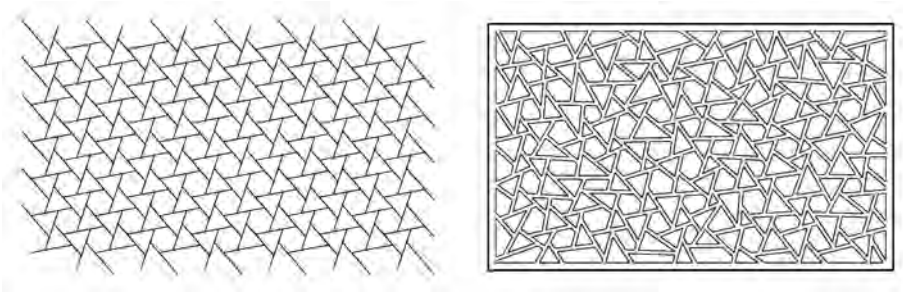


*Figure 8. Ice-ray designs based on a frequently-used regular ice-ray grid.*

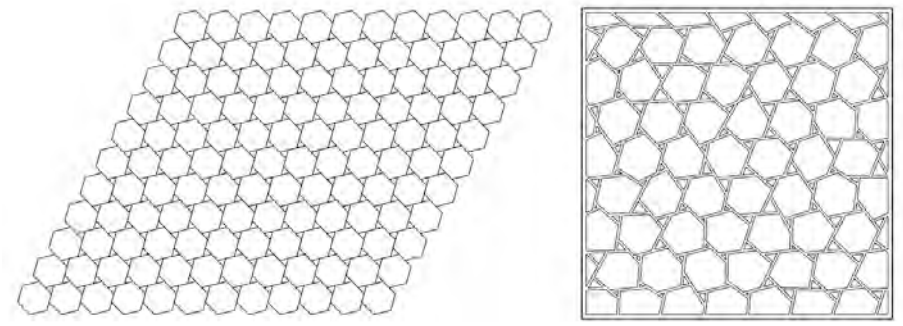


*Figure 9. Ice-ray designs based on a regular grid composed by hexagons.*

Regular ice-ray patterns can be generated by the program as well. Based on an array of regular polygon, by locating each crack point at one end of each polygon segment and extending the other side, the program generates a regular ice-ray design. Based on it, slightly randomized ice-ray designs can be further achieved. This forms a two-step-generating process, as Figure 10 and 11 shows.

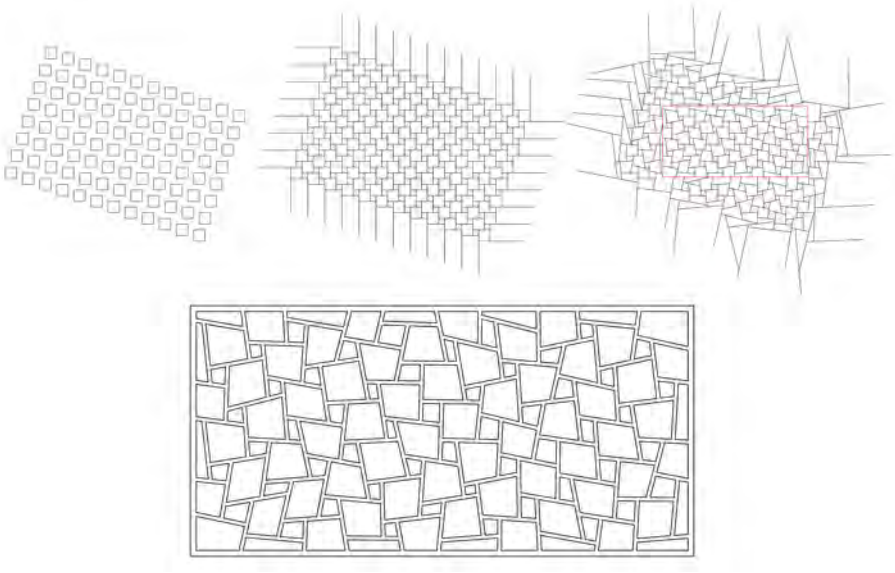


*Figure 10. Two-step generating of Ice-ray designs based on square array.*

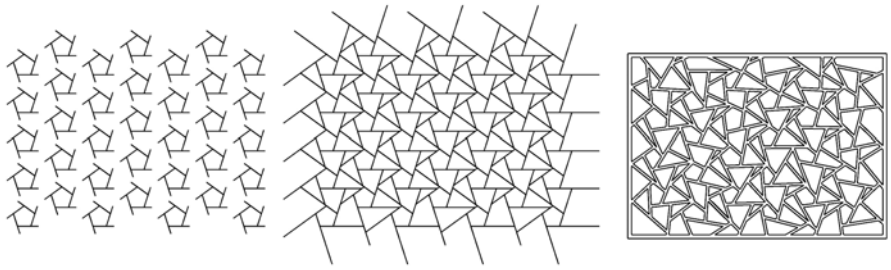


*Figure 11. Two-step generating of Ice-ray designs based on pentagon array.*

## 5. Conclusion

This paper presents an algorithm of "T"-shape joint patterns that consist of straight or curve lines, on plane of curve surface. The algorithm is based on the concept of cracks, as well as their occurrence and development. Based on regular ice-ray grids, it can generate irregular traditional Chinese ice-ray lattice designs with interdependent structure. With two-step generating process, such designs can also be got from array of regular polygons.

Since the purpose is to generate Chinese ice-ray lattice designs, the principle of crack invoked in this study is very conceptual, and the algorithm is much simplified. By carefully studying cracking phenomena, other crack

patterns as those on earths and glasses may be generated with the same idea. This will be an interesting topic for the further study.

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# COMPUTATIONAL ANALYSIS AND GENERATION OF TRADITIONAL CHINESE PRIVATE GARDENS THROUGH SPACE SYNTAX AND PARAMETRIC DESIGN

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**Abstract.** This research develops a methodological framework for computational analysis and generation of traditional Chinese private gardens, powered by two well-known algorithms in the field, with Space Syntax for analysis and parametric design for generation. Applying this framework, the paper commences with an analysis of two different categories of Chinese private gardens using selected Space Syntax techniques. Next, mathematical measurements derived from the analysis are used as the basis to capture essential spatial patterns in these two garden types. These quantitative results are then used to direct the development of a parametric design system to generate new design instances that share the same spatial patterns of the original traditional Chinese private gardens. The effectiveness of this computational approach is demonstrated through two case studies, Yuyuan Garden and Wangshiyuan Garden, both located in Southeast China and each representing a different category of traditional Chinese private gardens with a typical planning structure. The outcomes of the paper contribute to potential new insights about these important heritage sites, and demonstrate a formal approach to their computational analysis and generation.

**Keywords.** Computational design analysis; generative design; Space Syntax; parametric design; traditional Chinese private gardens.

## 1. Introduction

Traditional Chinese private gardens form an important part of the world's architectural and landscape heritage. These gardens have a long history in

China (with most existing examples initially built around the 16th and 17th centuries AD), and are famous for their intricate spatial planning and arrangement that associates with traditional Chinese cultural, philosophical and aesthetic values (Peng, 1986; Tong, 1997). Despite of a very few quantitative attempts (Chang, 2006; Lu, 2010), past design research on traditional Chinese private gardens is typically from various historical, qualitative perspectives focusing on historical records, individual experiences and interpretations. Through the existing research, the unique spatial properties of traditional Chinese private gardens have been emphasised and extensively debated by historians but have rarely been formally measured and generalised. Supported by computational algorithms, these spatial properties can now be mathematically analysed and more directly compared and clustered to provide potential new insights about such important heritage, complimenting the existing understandings. Further, these quantitative data can be utilised to direct computational generation (i.e. through parametric design) to more effectively facilitate the inheritance of such design heritage in contemporary culture and practice.

## 2. Background

Before presenting the methodological framework and the two case studies, this background section introduces three topics that are closely related to this research.

### 2.1. TRADITIONAL CHINESE PRIVATE GARDENS

By the 17th century AD, the arts of traditional Chinese private gardens had peaked and established themselves as a unique type of architectural and landscape design characterised by its intricate spatial planning and arrangement. Traditional Chinese private gardens have been researched extensively from a wide range of qualitative perspectives and a much smaller number of studies have also examined their spatial properties via quantitative means. For example, qualitatively, Keswick (1978), Zhou (1999) and many other researchers in-between or after them, explored the spatial characteristics of selected gardens from historical, social and cognitive perspectives. Quantitatively, multiple attempts have been made to understand the rich spatial planning and arrangement in the gardens, through the use of syntactical techniques (Chang, 2006) and by combined syntactical techniques with grammatical interpretations of formal composition (Lu, 2010). Despite of the above existing research, the spatial characteristics that make traditional Chinese private gardens unique have rarely been formally measured. Therefore this paper aims to develop and demonstrate a methodological framework that

can computationally generate new design instances of these gardens, using parametric design, which share the same spatial characteristics of the originals as measured by selected Space Syntax techniques.

## 2.2. SPACE SYNTAX

Developed and extensively applied over the last few decades, Space Syntax is a collection of techniques used for analysing the topological properties of space (i.e. permeability and intelligibility), through graph theories (Hillier and Hanson, 1984). Space Syntax techniques have been widely adopted in design including urban planning, landscaping and architectural design. One important capability of Space Syntax approach for design analysis is that it provides a formal way of critically understanding spatial configurations by translating their properties into topological graphs, which can then be mathematically analysed (Ostwald, 2011). Generally, Space Syntax abstracts spaces into graphs through three formal methods: convex, axial, and isovist mappings. Once the selected spaces are represented by a graph, then various mathematical properties of the graph may be derived from it (Hillier and Hanson, 1984; Ostwald, 2011). For example, the step depth of each node in the graph can be determined, then the total depth (TD), mean depth (MD) and integration (*i*) values can be calculated for each node. These values reflect the relative role of each space within the larger structure of the plan.

## 2.3. PARAMETRIC DESIGN

Parametric design is a computational design method characterised by the use of rule algorithm and the capability to generate multiple design solutions (Karle and Kelly, 2011). The term “parameters” is used to describe factors that determine a series of variations leading to a potentially infinite range of possibilities being generated (Kolarevic, 2003). Parametric design systems support the creation, organisation and management of complex computational design models (Woodbury, 2010). In architecture, parametric design tools are mainly used for complex form generation, multiple design solution optimisation, as well as multidisciplinary design, i.e. structure and sustainability control. There are several different types of parametric design and scripting tools currently available commercially. They include Design Script, Digital Project, Generative Components, Grasshopper, Rhino Script, Processing, and Python Script. In our case studies, Grasshopper is used to support the parametric design of traditional Chinese private gardens.

## 3. Methodological framework

The methodological framework is supported by two computational design algorithms, with Space Syntax for analysis and parametric design for generation. This framework for computational analysis and generation of traditional Chinese private gardens contains three main stages.

### 3.1. SPATIAL ANALYSIS

To conduct the connectivity analysis of a traditional Chinese private garden, a plan graph is first developed. Connectivity or permeability graphs are normally constructed to represent and study the relationships between visible zones (convex spaces). For the present research two methods of defining space are chosen – functionally-defined areas and size-defined areas. In the case studies, the analysis does not take into consideration of artificial ponds and mountains, each node is therefore a functional space or an area within specific size ranges in the garden that can be physically entered (accessed). The analysis commences by identifying different spatial types (as defined by the two above methods) in each selected garden then determining how they are linked. After linking the nodes the graph is generated. From this generated graph, the step depth of each node, then the total depth (TD), mean depth (MD) and integration (*i*) values can be calculated.

### 3.2. PARAMETRIC RULE DEVELOPMENT

In order to develop a parametric design system that can generate new garden designs sharing the spatial characteristics of the originals, firstly we develop parametric rules based on the derived planning guidelines. For instance, to develop parametric rules based on the results of connectivity analysis, the parametric rules will set constraints to specify that certain pavilion has only one connection, or certain areas are connected to other areas, etc. Next, the numbers of different spatial types, such as the numbers of functionally-defined areas and size-defined areas, are set as input parameters. Other input parameters can also include factors that are related to the site such as the predefined entrance(s), general site boundaries and main navigation path(s).

### 3.3. DESIGN GENERATION AND VERIFICATION

With parametric rules and input parameters defined, the parametric design system can be operated to generate new garden designs, each suggesting a possible spatial planning schema reflecting the characteristics of the original. Finally to verify the designs generated, the *i* values of each newly generated garden design are tested against the inequality genotype produced for the

original. The more similar values found between the two during the testing, the more closely the characteristics of the new garden design reflects those of the original. The final selection from multiple generated design is based on the comparison test against the *i* value.

## 4. Two case studies

The above methodological framework is demonstrated through two case studies, Yuyuan Garden and Wangshiyuan Garden, two of the renowned traditional Chinese private gardens situated in Southeast China. Yuyuan is categorised as large scale garden with the overall size at around 20,000 square meters, and Wangshiyuan is categorised as a small scale garden with the overall size at around 5,300 square meters. The two categories respectively represent two different planning structures of the typical traditional Chinese private gardens: one is organic, free form oriented (in large scale gardens) and the other is courtyard oriented (in small scale gardens).

### 4.1. YUYUAN GARDEN – A LARGE SCALE GARDEN

Yuyuan Garden was built in the 16th century AD. Parts of the garden were destroyed during World War II, although they have since been restored.

Figure 1 shows the plan of Yuyuan Garden. In order to graph the connectivity patterns of these gardens, six distinct spatial types have been identified: (1) large rooms, (2) small rooms, (3) pavilions, (4) yards/squares, (5) covered corridors and (6) pathways. Large and small rooms are physically and often visually defined in plan by extensive walls and landscaping elements.

Table 1 shows the connectivity analysis results for Yuyuan Garden. The pavilions have the highest MD value (MD = 4.73), which means that it is the most isolated spatial type. Having the highest integration value ($i$ = 12.04) suggests that the pathways are the most integrated space and these results also confirm the common expectation because in traditional Chinese private gardens the pathways provide the major connections to other spaces. The least integrated spatial type is the covered corridors ($i$ =0.67). The inequality genotype arising from the data is as follows: Pathways > Small rooms > Pavilions = Large rooms = Yards/Squares > Covered corridors.



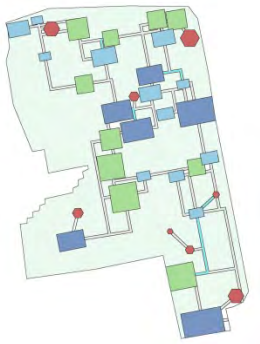

*Figure.1. Yuyuan Garden plan with six functionally-defined areas.*

TABLE 1. Connectivity analysis for Yuyuan Garden

| **Spatial types** | **Number of spaces** | **Total depth (TD)** | **Mean depth (MD)** | ***i* value** | ***Inequality genotype ranking*** |
|---|---|---|---|---|---|
| Large rooms | 10 | 39 | 4.33 | 1.20 | 3 |
| Small rooms | 18 | 79 | 4.65 | 2.19 | 2 |
| Pavilions | 12 | 52 | 4.73 | 1.34 | 3 |
| Yards/Squares | 7 | 22 | 3.67 | 0.94 | 3 |
| Covered corridors | 5 | 13 | 3.25 | 0.67 | 6 |
| Pathways | 63 | 219 | 3.53 | 12.04 | 1 |

Our parametric design system is implemented with Grasshopper and both the design generation and verification are conducted in this environment. The testing criteria can be flexibly adjusted to suit different selection needs. For example, in Table 2, the selected new design generated by the system pass the inequality genotype test as both have the same inequality genotype ranking as the one of the original Yuyuan Garden. However, the comparison between *i* values reveal further differences about these spatial types. This will require further studies to verify the complexity of the results.

TABLE 2. Comparison between Yuyuan Garden and a selected new design

| **Selected new plan** |  | **Spatial types** | ***i*** | ***I-g ranking*** |
|---|---|---|---|---|
| | | Large rooms | 0.94 | 3 |
| | | Small rooms | 2.04 | 2 |
| | | Pavilions | 1.31 | 3 |
| | | Yards/Squares | 1.80 | 3 |
| | | Covered corridors | 0.83 | 6 |
| | | Pathways | 10.54 | 1 |

## 4.2. WANGSHIYUAN GARDEN – A SMALL SCALE GARDEN

The origin of Wangshiyuan Garden may be traced to Song Dynasty (1127-1129), although its current form is the result of restorations from Qing Dynasty (around 1751). Water is the major feature of Wangshiyuan Garden, which is also famous for the many small courtyards that are distributed throughout the garden, with a main (central) courtyard located at the centre.

For this paper, three spatial types were initially identified (Table 3), courtyards (Type 6), corridors (Type 5) and rooms (Type 1 to 4). Since Wangshiyuan Garden is relative small, some functionally-defined areas are limited, therefore we further define the "room" by the size of the area. Type 1 to Type 4 are four types of room space divided according to the size of their areas.

TABLE 3. Spatial types and their size ranges in Wangshiyuan Garden

| **Spatial Types** | | |
|---|---|---|
| Type 1 - Rooms | Number of spaces | 11 |
| | Mean area ($m^2$) | 8.32 |
| | Std. Deviation | 1.92 |
| Type 2 - Rooms | Number of spaces | 10 |
| | Mean area ($m^2$) | 15.45 |
| | Std. Deviation | 1.93 |
| Type 3 - Rooms | Number of spaces | 15 |
| | Mean area ($m^2$) | 25.62 |
| | Std. Deviation | 3.05 |
| Type 4 - Rooms | Number of spaces | 14 |

| | | | |
|---|---|---|---|
| | Mean area ($m^2$) | | 84.24 |
| | Std. Deviation | | 62.99 |
| Type 5 - Corridors | Number of spaces | | 7 |
| | Mean area ($m^2$) | | 37.00 |
| | Std. Deviation | | 22.98 |
| Type 6 - Courtyards | Central | Area ($m^2$) | 614.38 |
| | Other court-yards except central | Number of spaces | 18 |
| | | Mean area ($m^2$) | 125.22 |
| | | Std. Deviation | 128.67 |

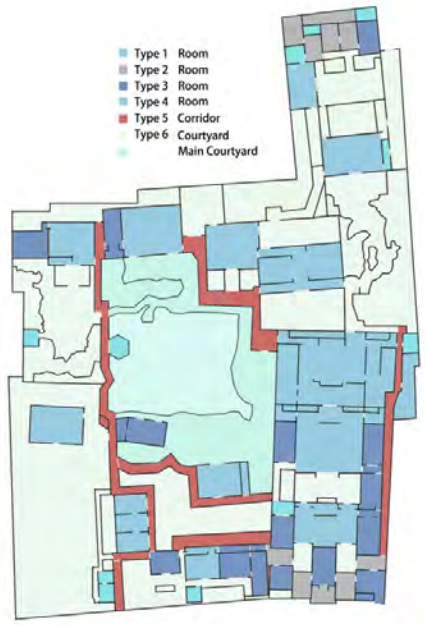



*Figure 2. Wangshiyuan Garden plan with six size-defined areas*

Table 4 shows the spatial analysis of Wangshiyuan Garden. From the table we can see that spatial Type 5, the corridor, has the highest integration value ($i$=1.179). Thus, this spatial type is central in both the social and cognitive structure of this garden type. Spatial Type 6, the courtyard, has the second highest integration value ($i$=1.079), which is not unexpected, given that these spaces make up a large proportion of the visually accessible spaces of the garden. The inequality genotype arising from the data is as follows: Corridors > Courtyards = Type 4s > Type 1s > Type 3s = Type 2s. Collectively, the data developed in this analysis capture the typical structural, social and cognitive properties of the plans of this garden type.

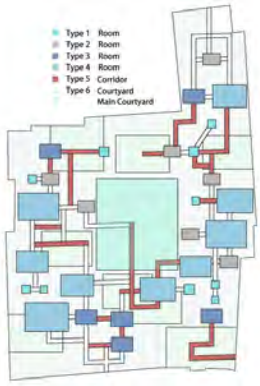
TABLE. 4. Connectivity analysis for Wangshiyuan Garden

| **Spatial types** | **Number of spaces** | **Total depth (TD)** | **Mean depth (MD)** | ***i* value** | ***Inequality genotype ranking*** |
|---|---|---|---|---|---|
| Type 1 | 10 | 435.091 | 5.801 | 0.825 | 3 |
| Type 2 | 7 | 452.100 | 6.028 | 0.773 | 4 |
| Type 3 | 6 | 384.400 | 5.125 | 0.945 | 4 |
| Type 4 | 9 | 341.214 | 4.550 | 1.077 | 2 |
| Type 5 | 30 | 325.143 | 4.335 | 1.179 | 1 |
| Type 6 | 11 | 344.421 | 4.592 | 1.079 | 2 |

Tables 5 shows a selected example of parametrically generated new instances of this garden type. This new plan complies with the inequality genotype test against the original Wangshiyuan Garden.

TABLE. 5. Comparison between Wangshiyuan Garden and a selected new design

**Selected new plan**




| **Spatial types** | ***i*** | ***I-g ranking*** |
|---|---|---|
| Type 1 | 0.837 | 3 |
| Type 2 | 0.7894 | 4 |
| Type 3 | 0.833 | 4 |
| Type 4 | 1.037 | 2 |
| Type 5 | 1.45 | 1 |
| Type 6 | 1.2857 | 2 |

## 5. Conclusion

This research develops a methodological framework for computational analysis and generation of traditional Chinese private gardens through Space Syntax and parametric design. The framework has been demonstrated via two case studies: Yuyuan Garden and Wangshiyuan Garden. The case studies show that for the two different categories of traditional Chinese private gardens, that key properties of spatial planning and design in these garden types can be formally measured, compared and clustered to reveal and gen-

eralise common patterns. Further, these quantitative data can be directed to develop a parametric design system (through Grasshopper in the case studies) for generating new design instances that share the same characteristics of the originals.

Although the case study has limited its focus to one spatial quality of these gardens and demonstrated through connectivity only and on 2D plans, the ultimate goal of the research is to consider a wide range of spatio-social qualities of traditional Chinese private gardens. Our current direction is to enrich and diversify the analysis to computationally explore other spatial properties in traditional Chinese private gardens, for example, those associated with "transparency" and "mystery". To critically understand and mathematically examine "transparency" and "mystery" in these gardens, the visual and permeable properties can be explored using an extensive set of Space Syntax techniques supported with comprehensive measures including Intelligibility, Control, Isovist Occlusivity, Isovist Jaggedness, Drift Magnitude, etc.

The future study will also be planned to further validate this approach and strengthen the findings with a larger sample size for both types of the selected gardens and with a more thorough verification mechanism.

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# GENERATION OF WEAVING STRUCTURE ON FREE-FORM SURFACE USING A REMESHING ALGORITHM

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**Abstract.** Inspired by the study on traditional weaving handicrafts, this paper focuses on a new weaving structure system that could be used in construction of different organic geometries. A new and viable remeshing algorithm is proposed that a free-form surface could be converted into a certain mesh grid, in which the edges represent the weaving elements, and the vertices represent their joints. The research essentially seeks to integrate the intangible cultural heritage into the construction technique, as well as to narrow the gap between the complex geometry with digital fabrication.

**Keywords.** Weaving structure; free-form surface; remeshing; complex topology.

## 1. Introduction

Weaving with plant fabrics is a long-existing and widely used folk technique in Asian countries, and the traditional weaving handicrafts made by bamboo sticks, rattan or reed are still playing a versatile role in people's daily life. In addition to containers such as baskets, the technique is also used in rain coats, sun hats, mats (tatami), and even as enclosure structure for houses. Since they are made of elastic materials, when woven together, the prestress force inside these bended elements increases the stiffness of the whole structure, making it more efficient and adaptive. At the same time, the technique also creates patterns that enhance the aesthetics of the handicrafts, which also become an important sort of traditional patterns in Asia (Lu, 2014). The advantages suggest great potential in its application in architecture.

Traditional hand-made weaving items are usually of simple forms such as flat plate, cylinder or cone. They largely tend to be of such continuous plump shapes because of the pre-stressed force in the sticks. Nowadays, the characteristic reveals that the weaving structure also has the potential for construction of some organic forms that are designed or generated in the realm of contemporary digital architecture. Then in this paper, the aim is to develop a weaving structure system that can be used in not only the ones with simple forms, but also those with complex topology.

The weaving structure is composed of intersecting sticks that flow along curved surfaces. This geometrical form can be conveniently represented by a mesh model in which the edges represent the sticks and the vertices for the joints. Hence the related remeshing algorithms are also be studied in addition to the traditional weaving handicrafts, and then based on the mesh model the weaving structures can be generated and optimized.

The proposed workflow for generating a weaving structure starts from a designed organic surface. The first step is to convert the surface into a certain mesh geometry in view of material properties of the structure. Then structural simulation and optimization are carried out. After that, the joint detail and construction sequence are considered, and finally digital construction technique is employed in its construction. This paper mainly focuses on the generation of the mesh geometry for the weaving structure using a new and viable remeshing algorithm.

## 2. Related work

There has been considerable related work on remeshing surface as well as employing mesh-related algorithms in the realm of digital construction. Generally, the related work can be grouped into several categories.

The first group can be named as *mesh optimisation* in the view of computer graphics. The position and connectivity of vertices are treated as variables to optimize some global functions while preserving the original shape. For example, Hoppe et al (1993) defined this global function as an Energy Function. The resulted mesh grid may be irregular, and a following operation of mesh relaxation is needed (Ohtakey et al, 2001).

When it comes to the realm of digital fabrication and construction, some remeshing algorithms are developed for panelization, which try to subdivide a surface into standard panels that could be prefabricated to save cost (Eigensatz et al, 2010). Instead of one, several types of panels can even be combined together (Zimmer et al, 2013). In the view of computer graphics, this issue is relevant to equalizing the edge length or Area-Equalising Remeshing (Botsch et al, 2004). These methods are designed exclusively for

the optimization of panels, so they are not suitable to directly convert the mesh edges they generate into the members of a weaving structure.

Besides the methods mentioned above that divide the surface into similar panels, the *geodesic line* was used to cut the surface into parallel strips (Pottmann et al, 2010), which is closely related to our work. Furthermore, Flöry et al (2012) introduced a concept of conoidal ruled surfaces and ruled strips are founded from the boundaries. Similarly, Sechelmann et al (2013) proposed a quasi-isothermic mesh lay-out based on curvature directions. These methods gave us some inspirations but they generally don't take the original boundary of the surface into consideration. These methods become even more unsuitable when dealing with more complex surfaces.

To sum up, most of the related works are focused on either panelization of free-form surfaces or geometrically dividing them into parallel strips. These works are different from this paper that focuses on the remeshing algorithm for converting free-form surfaces into constructable weaving structures, based on the inspiration from the traditional weaving handicrafts.

## 3. A study on the traditional weaving handicrafts

Traditional handicrafts can give us a lot of inspiration in weaving structure topology. After the study of existing woven items, it can be found that handicraft workers and artisans have employed one important strategy as follows.




*Figure 1. A study on traditional weaving handicrafts*

Figure 1 shows a traditional woven container, and its construction procedure can be perceived as this way. Firstly, circular sticks that are parallel to the upper boundary create the framework that defines the geometry (Figure 1, Middle). When weaving by hand, it is rather convenient for artisans to quickly locate and set the rattan sticks because of this parallel relation. Secondly, sticks along the other direction are arranged to bend inwards and outwards to bind the circular sticks together.

The description of the process is simple and it can be potentially applied to any orientable manifold surface: if the shape has one or several boundaries, then the boundaries are offset until they fill all the surface area, like the latitude lines of the globe; then in the other direction, the longitude

lines bind them together. In fact, the *offset* step is more complex and vital so the essay will lay more emphasis on it.

## 4. Offset - the latitudinal polyline family

Compared to Pottman's (2010) methods, our algorithm does not divide the surface into segments and on the contrary keep the boundary intact.

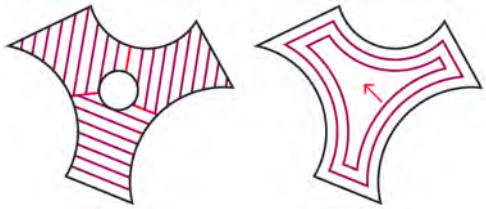


*Figure 2. Comparison of the method (Pottman et al, 2010, left) and our proposal (right)*

If the boundary is simple such as a circle (Figure 3, Left), the offset is out of question. However, if one part of the boundary is close to the other part of it (Figure 3, Middle), the line after the offset will have *self-intersection*. If two boundaries are very close (Figure 3, Right), a *mutual intersection* will occur. The two type of exceptions should be instantly caught and handled otherwise the following result would be unexpected. If the problem happened on a *surface*, it would be hard to detect and not realistic to solve (Chiang, 1991). Luckily this time the geometry being operated is mesh, which is defined by vertices and faces instead of an equation. Thus an effective approach is found to locate the intersections as well as cope with them.

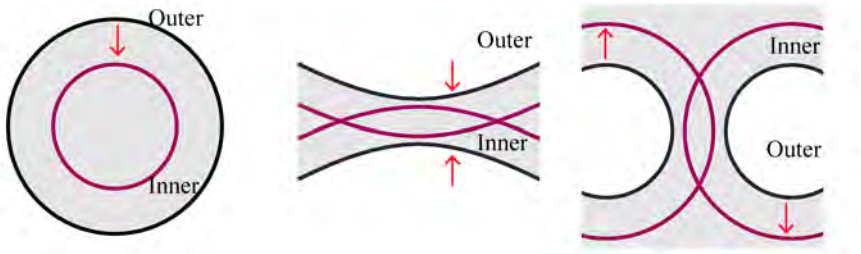



*Figure 3. Three kinds of results after offsetting*

### 4.1. FLIP INDEX ORDERS OF THE BOUNDARY VERTICES

A mesh usually has at least one boundary, except the closed mesh. But in that case it can be divided into two parts, then each of them has a boundary. Thus the following method will work on all orientable manifold mesh.

It is obvious that every boundary is a closed polyline. The order of vertex indexes in conjunction with the normal of the mesh can be used to determine the direction of the offset using the *right-hand rule*. If the ascending order is $\vec{c}$, the mesh normal is $\vec{n}$ and then the offset direction can be calculated to be $\vec{c}\times\vec{n}$ (Figure 4). Furthermore, to ensure the correct offset direction, to unify the index orders ($\vec{c}$) is needed for the mesh with two or more boundaries.

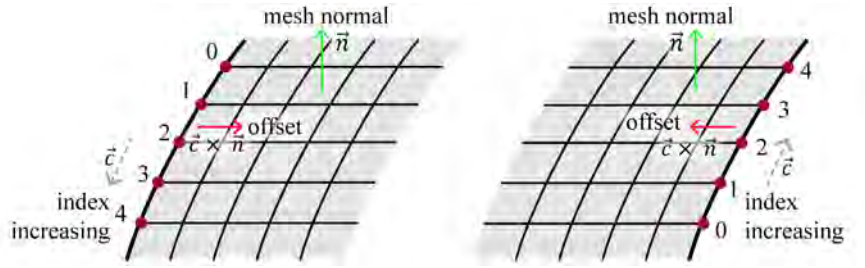



*Figure 4. Unify the index orders to calculate the offset direction*

## 4.2. OFFSET THE VERTICES ON THE POLYLINES

To make it clear, the polyline on the mesh $M_0$ is named as $S$ (can be an original boundary or offset result). The polyline $S$ that is going to be offset is named as the *parent* and the next offset result is its *child*. Additionally, every polyline $S$ is composed of a series of vertices $A_0A_1A_2 \ldots A_{n-1}$.

As mentioned above the child polyline may have self-intersections, which will be analysed in 4.3. Then 4.4 will discuss mutual intersections. After the operations in 4.3&4.4, the child polyline will be regrouped into several polylines which no longer has intersections despite that some of them should be deleted while others will be reserved continuing to be offset (as in 4.5).



*Figure 5. Steps of handling an intersection*

## 4.3. DISENTANGLE THE SELF-INTERSECTIONS

Though the intersections are addressed as *intersections*, they do not really intersect in 3D space with the polyline data structure. To detect whether two polyline intersect on the curved mesh, a projection trick is applied, reducing

the judgement to a standard 2D plane problem. As in Figure 6 (left), the four relevant vertices, i.e. $A_i, A_{i+1}, A_j, A_{j+1}$ are projected onto a reference plane. Then if there do be a self-intersection between segments $A_iA_{i+1}$ and $A_jA_{j+1}$, the sum of four projected angles $\langle A_iA_{i+1}, A_iA_{j+1}\rangle + \langle A_{i+1}A_i, A_{i+1}A_j\rangle + \langle A_jA_{i+1}, A_jA_{j+1}\rangle + \langle A_{j+1}A_j, A_{j+1}A_i\rangle$ should be $2\pi$ (Figure 6, Middle). By contrast, if there is no intersection it should be less than $2\pi$. Thus the sum is used as a criterion of intersection. An intersection will be removed after detected by re-connecting $A_i$ to $A_{j+1}$ and $A_j$ to $A_{i+1}$ respectively, which results in two polyline side by side, correcting the intersection.

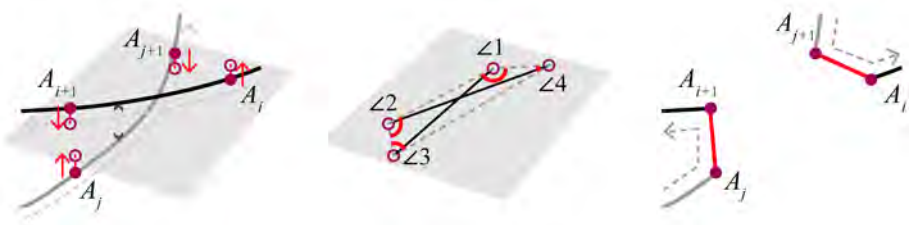



*Figure 6. Detect an intersection and regroup the polyline*

## 4.4. DISENTANGLE THE MUTUAL INTERSECTIONS

If the polyline $S$ intersects with another polyline $S'$, specifically, $A_iA_{i+1}$ in $S$ intersects with $A'_jA'_{j+1}$ in $S'$, similarly the solution is to break them and connect $A_iA'_{j+1}$, $A'_jA_{i+1}$. Then these two polylines will be joined into a new one, which may still possess self-intersections (Figure 7, Middle). There seems to be a dead loop, however, it is actually not, since the overall result is that intersections are removed one by one in each step until vanish in the end.

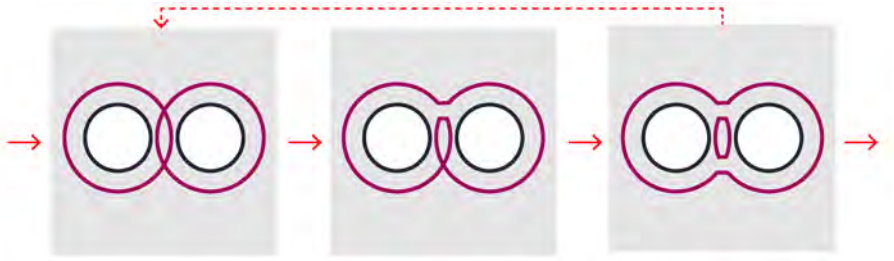


*Figure 7. Reduce intersections one by one*

## 4.5. FILTER THE CHILD POLYLINES TO CONITINUE THE OFFSET

The combination of 4.3 and 4.4 results in several child polylines that are free from intersections as shown in Figure 8 (left). Apparently some should be removed while the others should continue to move forward. To judge if a child polyline should be deleted, it is offset one more time to get *grandchild* polylines. Their intersection with parent polylines (if it happens, Figure 8, Right) will indicate that the corresponding polylines have filled all possible vacuum space nearby, beginning to go back to encounter their ancestors.

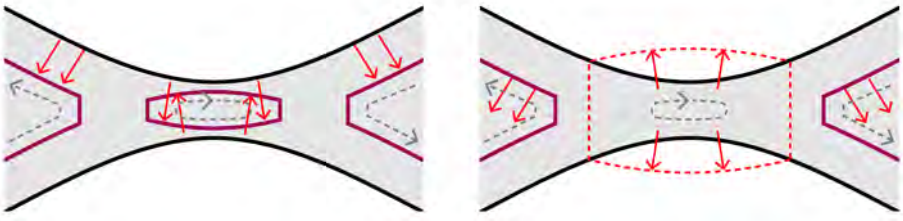


*Figure 8. Detect if the child polyline should be deleted*

## 4.6. TEST WITH COMPLEX MODELS

Repeat the procedures in 4.3~4.5, and the surface will be totally covered with the closed polylines named as the *latitudinal polyline family*. This part has been implemented in Grasshopper using C# and tested on complex shapes, such as surfaces with narrow neck (solving *self-intersections*, Figure 9, Top Left), a 6-way-joint (solving *mutual intersections*, Figure 9, Bottom Left) and a trimmed minimal surface (Figure 9, Right), which is even hard to understand by naked eyes but our module tells that there's only two borders and 80 polylines are used to cover this mesh. From here, we can see the algorithm performs excellently even for complex shapes.

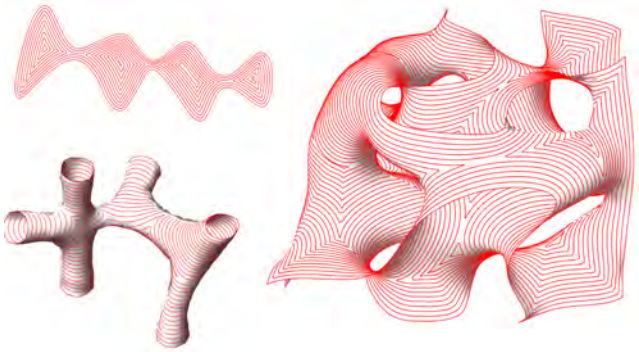


*Figure 9. Test models and results*

## 5. Division and Connection – the longitudinal polyline family

Given the *latitudinal polyline family*, apparently more than half of weaving elements have already been finished now. The remaining work is comparatively easy – another one or two directions of weaving elements can be used to bind them together, freely designed such as hexagonal, triangular etc. at least using algorithms summarized in EvoluteTools Primer (Hammerberg, 2012) (Figure 10, Left), since the latitudinal elements have essentially ensured its shape.

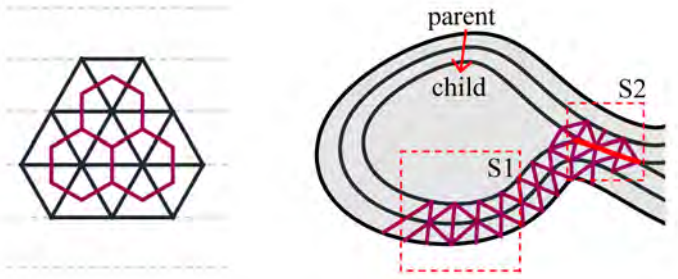



*Figure 10. Generation of the longitudinal polyline family*

Specifically, we take the triangular grid as an example and it is also an experimental model in the next section since it can endow the structure with the maximum stability. Given the latitudinal polyline family, they can be generally divided by almost equal length despite in some special zones.

Then, the generation of *longitudinal polylines* can be divide into two steps. In the first step all child latitudinal polylines are connected to their parents via longitudinal polylines. (The offset part of this algorithm has previously stored the parent-child information in the polyline data structure). The first step will cover most area but however with some exceptions. The second step is to handle these exceptions by detecting non-co-plane polygons enclosed by indivisible areas and then dividing them into several triangles. For example as in Figure 10 (right), a child polyline may connect to the other part of itself. Similar situation may happen frequently in the case where two parallel polylines meet and result in a sharp corner. This might be the special part of the weaving structure and additional elements can be used to strengthen it. Due to the page limit, here we do not give more details.

## 6. Construction experiment

The weaving structure makes use of the prestress force inside the bended elements, thus the material with high strength and stiffness should be given priority. From bamboo strips to plastic sticks, eventually the glass fibre

reinforced plastics (FRP) are chosen. Using nylon cable ties as joints, we first made a small model, about 60cm long and wide (Figure 11, Left).

In the experiment, we discovered the joints can be almost immovable due to the strong friction. As a result, the structure would deform little after the construction. To confirm the validity of this structural system, we then built another complex model, which is 2.4m wide, 1.6m high (Figure 11, Right).

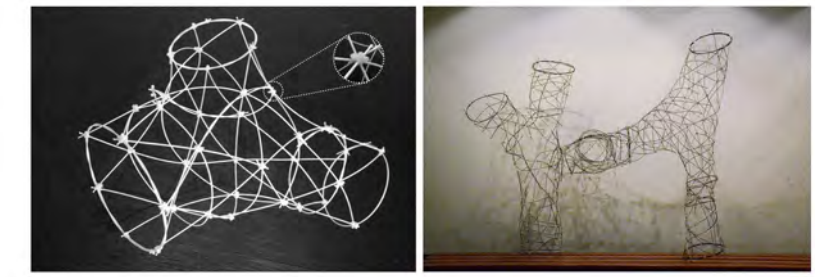


*Figure 11. Experimental models for the weaving structure*

## 7. Conclusion

In the present research, based on a detailed study on a variety of traditional handicrafts such as bamboo hats, rattan basket, etc., a remeshing algorithm is developed in order to create the lattice of a weaving structure system that could be used in construction of free-form surface geometries.

In this algorithm, latitudinal edges are created by offsetting the naked border(s) on the original surface, and certain methods are invented to deal with the *self-intersections* and *mutual intersections* of the offset boundaries, creating an evenly distributed, well organized lattice system.

Compared to the geodesic line methods, our method ensure that the original borders remain intact and the whole surface is treated as a whole. Compared to the panelization or mesh optimization methods, this method takes in to consideration the weaving logic and material properties of the woven sticks. In addition, faces of the mesh are almost of similar size and similar edge length.

To sum up, this method results in a type of weaving structure that has two distinct types of members, the longitudinal and the latitudinal, which are suitable for the weaving technique.

## Endnotes

1. All pictures in the article are drawn or taken by the authors.

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# THE COMPUTATION OF DESCRIPTION GRAMMARS

*Two case studies*

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**Abstract.** We revisit two case studies that adopt a shape grammar to relate different architectural styles. Both adopt a description scheme, augmenting the shape grammar, as the main vehicle for relating different styles, however, they both present the description rules only conceptually. Following a description grammar interpreter and its notation for descriptions and description rules, we explore a valid explication of both description schemes. This exploration serves three purposes: firstly, as a demonstration of the notation adopted; secondly, as an evaluation of the applicability of the description grammar interpreter and its notation to these case studies; and, thirdly, as a demonstration of the explication of description grammars from concept to computation.

**Keywords.** Shape grammars; description grammars; architectural styles; description.

## 1. Introduction

A shape grammar is a formal device for producing a language of shapes, e.g., corresponding to an architectural style. In this paper, we consider two case studies that adopt a shape grammar to relate, possibly, different architectural styles. Al-Kazzaz (2011; also, Al-Kazzaz et al, 2010) considers a shape grammar for hybrid design reflecting on a heterogeneous corpus of antecedents, specifically, traditional minaret designs. Ahmad (2009; also, Ahmad and Chase, 2006) considers the transformation of a shape grammar encoding an existing style in response to a change in design style requirements, applied to Greek temple façades and mobile phone designs. Both Al-Kazzaz and Ahmad use description grammars, augmenting the shape grammar, as

the main vehicle for relating different styles. In both cases, the description schemes are conceptually developed and only partially explicated; quite a few of the details remain uncovered.

In this paper, we revisit both case studies and suggest an explication of the description schemes. Specifically, we explore the embedding of the detailed computational processes of Ahmad's style mapping and of Al-Kazzaz's user guide and evaluation metrics within the notation adopted for descriptions and description rules by a description grammar interpreter (Stouffs, 2015). This exploration serves three purposes: firstly, as a demonstration of the notation for descriptions and description rules; secondly, as an evaluation of the generality of the notation and applicability of the description grammar interpreter to these case studies; and, thirdly, as a demonstration of the explication of description grammars from concept to computation.

## 2. Ahmad's style mapping

Ahmad (2009) proposes a style description scheme based on the concept of semantic differential to map the style characteristics of shape rules. These characteristics are specified as numeric values quantifying opposing adjectival pairs for each shape rule. The values are collected through rule application and analysed to characterize the style or styles of the design and of the language of designs as generated by the grammar. The mapping of the style range of the grammar may serve as a guide for grammar transformation. Ahmad presents two exemplar grammars, one for Greek temple façades and one for mobile phone designs; we limit our study to the first example.

The Greek temple façade grammar specifies 5 rule sets. Composition rule sets B and C consider style descriptor ranks reflecting on spatial relations between primitive shape elements: *Symmetric—Asymmetric*, *Monolithic—Fragmentary*, and *Stable—Directional*. Specification rule sets D, E and F consider style descriptor ranks reflecting on the primitive shape elements themselves: *Rectilinear—Curvilinear*, *Symmetric—Asymmetric*, and *Simple—Detailed*. Each rule in these sets specifies a shape transformation, a rank for each relevant style descriptor, and a weight. The style descriptor rank is specified both as a numeric, either 1 or −1, and an alphanumeric value. For example, in the case of style descriptor *Symmetric—Asymmetric*, the rank is either 1, "Symmetric", or −1, "Asymmetric". Derived designs collect style descriptor ranks for each rule applied, also considering the weight of the rule. Based on this collection of style descriptor ranks, the final design is ranked according to the style descriptors *Unity—Diversity*, *Balanced—Unbalanced*, *Simple—Complex*, and *Dominance*.

Ahmad presents a number of style analysis examples of student designs. Design 15 (Figure 1) applies composition rules B4, C3, and specification D15, E7, F18 and F1. The rules have different weights, either 1, 2 (D15) or 3 (E7). The rules define style descriptor ranks that can easily be collected as positive and negative values, separately. Ahmad (2009, pp. 174–175 (Tables 49–53)) separately presents the conditions for the definitions of the style descriptors for derived designs, i.e., *Unity—Diversity*, *Balanced—Unbalanced*, *Simple—Complex*, and *Dominance*, as well as a *similarity* concept. Each style descriptor takes one of three values, for example, the style descriptor *Unity—Diversity* takes the values "Unity" (if all the descriptors are "Similar" according to the *similarity* concept), "Diversity" (if all the descriptors are "Dissimilar" according to the *similarity* concept), and "Partly unified and partly diversified" (otherwise). The condition for design elements (or their spatial relations) to be "Similar" is that "three-fourths or more design elements in a derivation have either positive or negative values for a style descriptor" (Ahmad, 2009, p. 174 (Table 49)). Otherwise they are considered "Dissimilar". We refer to Ahmad (2009, p. 175 (Tables 51–53)) for the conditions for the other style descriptors.

| | Rule | Frequency | Weight | Total Weight | Descriptor | Value | Descriptor | Value | Descriptor | Value |
|---|---|---|---|---|---|---|---|---|---|---|
| **Design 15 (Student Q)** | **Column spacing rules** | | | | | | | | | |
| | A1.1 | 1 | | | | | | | | |
| | A1.2 | 2 | | | | | | | | |
| | A1.3 | 2 | | | | | | | | |
| | **Composition rules** | | | | | | | | | |
| | B4 | 1 | 1 | 1 | Symmetric | -1 | Fragmentary | 1 | Stable | -1 |
| | C3 | 1 | 1 | 1 | Symmetric | -1 | Fragmentary | 1 | Stable | -1 |
| | Total weight of positives | | | | | 0 | | 2 | | 0 |
| | Total weight of negatives | | | | | 2 | | 0 | | 2 |
| | Similarity | | | | Similar | | Similar | | Similar | |
| | **Specification rules** | | | | | | | | | |
| | D15 | 3 | 2 | 6 | Curvilinear | 1 | Symmetric | -1 | Detailed | 1 |
| | E7 | 2 | 3 | 6 | Rectilinear | -1 | Symmetric | -1 | Detailed | 1 |
| | F18 | 2 | 1 | 2 | Curvilinear | 1 | Asymmetric | 1 | Detailed | 1 |
| | F1 | 4 | 1 | 4 | Rectilinear | -1 | Symmetric | -1 | Simple | -1 |
| | Total weight of positives | | | | | 8 | | 2 | | 14 |
| | Total weight of negatives | | | | | 10 | | 16 | | 4 |
| | Similarity | | | | Dissimilar | | Similar | | Similar | |
| | **Design style description** | | | | | | | | | |
| | **Partly rectilinear and partly curvilinear** | | | | | | | | | |
| | **High degree of balance** | | | | | | | | | |
| | **High degree of complexity** | | | | | | | | | |

*Figure 1. Design 15 (taken with permission from Ahmad, 2009, p. 182).*

Table 1 presents description rules that explicate this description scheme. Only the rules that are necessary for the derivation (Table 2) of design 15 are included in Table 1. Four descriptions are considered: `spatial_relations`, `primitives`, `design_style`, and `similarity`.

Table 1. Description grammar rules used for design 15.

| | design_style + primitives + similarity + spatial_relations |
|---|---|
| B4 | Place three base markers symmetrically below the exterior columns<br>spatial_relations: { `<sym, asy> <mon, fra> <sta, dir>` } →<br>{ `<sym - 1, asy> <mon, fra + 1> <sta - 1, dir>` } |
| C3 | Place two pediment markers on top of the exterior columns<br>spatial_relations: { `<sym, asy> <mon, fra> <sta, dir>` } →<br>{ `<sym - 1, asy> <mon, fra + 1> <sta - 1, dir>` } |
| D15 | Apply base design 15<br>primitives: { `<rec, cur> <sym, asy> <sim, det>` } →<br>{ `<rec, cur + 2> <sym - 2, asy> <sim, det + 2>` } |
| E7 | Apply pediment design 7<br>primitives: { `<rec, cur> <sym, asy> <sim, det>` } →<br>{ `<rec - 3, cur> <sym - 3, asy> <sim, det + 3>` } |
| F1 | Apply column design 1<br>primitives: { `<rec, cur> <sym, asy> <sim, det>` } →<br>{ `<rec - 1, cur> <sym - 1, asy> <sim - 1, det>` } |
| F18 | Apply column design 18<br>primitives: { `<rec, cur> <sym, asy> <sim, det>` } →<br>{ `<rec, cur + 1> <sym, asy + 1> <sim, det + 1>` } |
| G1a | Mark the design elements as Similar for the spatial relations descriptor Symmetric-Asymmetric<br>similarity: { `<s1, s2, s3> prims` } → { `<“Similar”, s2, s3> prims` }<br>spatial_relations: { `<sym, asy?<=(sym / -3)> <mon, fra> <sta, dir>` } →<br>{ `<sym, asy> <mon, fra> <sta, dir>` } |
| G2b | Mark the design elements as Similar for the spatial relations descriptor Monolithic-Fragmentary<br>similarity: { `<s1, s2, s3> prims` } → { `<s1, “Similar”, s3> prims` }<br>spatial_relations: { `<sym, asy> <mon, fra?>=(mon * -3)> <sta, dir>` } →<br>{ `<sym, asy> <mon, fra> <sta, dir>` } |
| G3a | Mark the design elements as Similar for the spatial relations descriptor Symmetric-Asymmetric<br>similarity: { `<s1, s2, s3> prims` } → { `<s1, s2, “Similar”> prims` }<br>spatial_relations: { `<sym, asy?<=(sym / -3)> <mon, fra> <sta, dir>` } →<br>{ `<sym, asy> <mon, fra> <sta, dir>` } |
| G5a | Mark the design elements as Similar for the primitives descriptor Symmetric-Asymmetric<br>primitives: { `<rec, cur> <sym, asy?<=(sym / -3)> <sim, det>` } →<br>{ `<rec, cur> <sym, asy> <sim, det>` }<br>similarity: { `rels <s1, s2, s3>` } → { `rels <s1, “Similar”, s3>` } |
| G6b | Mark the design elements as Similar for the primitives descriptor Simple-Detailed<br>primitives: { `<rec, cur> <sym, asy> <sim, det?>=(sym * -3)>` } →<br>{ `<rec, cur> <sym, asy> <sim, det>` }<br>similarity: { `rels <s1, s2, s3>` } → { `rels <s1, s2, “Similar”>` } |
| G9 | Specify a high degree of balance<br>design_style: { `unidiv balunb simcom domina` } →<br>{ `unidiv “High degree of balance” simcom domina` }<br>spatial_relations: { `<sym?<0, asy?=0> <mon, fra> <sta, dir>` } →<br>{ `<sym, asy> <mon, fra> <sta, dir>` } |
| G12 | Specify a high degree of complexity<br>design_style: { `unidiv balunb simcom domina` } →<br>{ `unidiv balunb “High degree of complexity” domina` }<br>similarity: { `<rec, cur> <sym, asy> <sim, det?>(sim * -3)>` } →<br>{ `<rec, cur> <sym, asy> <sim, det>` } |

Table 2. Derivation of the descriptions for design 15.

| | |
|---|---|
| | design_style: { `“Partly unified and partly diversified” “Partly balanced and partly unbalanced” “Partly simple and partly complex” “Partly rectilinear and partly curvilinear”` }<br>primitives: { `<0, 0> <0, 0> <0, 0>` }<br>similarity: { `<“Dissimilar”, “Dissimilar”, “Dissimilar”> <“Dissimilar”, “Dissimilar”, “Dissimilar”>` }<br>spatial_relations: { `<0, 0> <0, 0> <0, 0>` } |
| B4, C3, D15, D15, D15, E7, E7, F18, F18, F1, F1, F1, F1 | design_style: { `“Partly unified and partly diversified” “Partly balanced and partly unbalanced” “Partly simple and partly complex” “Partly rectilinear and partly curvilinear”` }<br>primitives: { `<-10, 8> <-16, 2> <-4, 14>` }<br>similarity: { `<“Dissimilar”, “Dissimilar”, “Dissimilar”> <“Dissimilar”, “Dissimilar”, “Dissimilar”>` }<br>spatial_relations: { `<-2, 0> <0, 2> <-2, 0>` } |
| G1a, G2b, G3a, G5a, G6b, G9, G12 | design_style: { `“Partly unified and partly diversified” “High degree of balance” “High degree of complexity” “Partly rectilinear and partly curvilinear”` }<br>primitives: { `<-10, 8> <-16, 2> <-4, 14>` }<br>similarity: { `<“Similar”, “Similar”, “Similar”> <“Dissimilar”, “Similar”, “Similar”>` }<br>spatial_relations: { `<-2, 0> <0, 2> <-2, 0>` } |

The description `spatial_relations` collects style descriptor values reflecting on the spatial relations between primitive shape elements: *Symmetric—Asymmetric*, *Monolithic—Fragmentary*, and *Stable—Directional*, in this order. The descriptor values are grouped in pairs, each enclosed with angle brackets. Similarly, the description `primitives` includes three pairs of style descriptor values reflecting on the primitive shape elements themselves: *Rectilinear—Curvilinear*, *Symmetric—Asymmetric*, and *Simple—Detailed*, in this order. The weight of each rule is encoded in the computation of the rule: the weight value is added or subtracted from the relevant descriptor values (e.g., rules D15 and E7).

The description `design_style` ranks the final design according to the style descriptors *Unity—Diversity*, *Balanced—Unbalanced*, *Simple—Complex*, and *Dominance*, in this order. Rules G7 through G14, in pairs, encode the respective conditions and identify the appropriate design style descriptions, as alphanumeric values. For example, rule G7 checks whether there is a high degree of unity and rule G8 whether there is a high degree of diversity. If neither applies, then the default description “Partly unified and partly diversified” is retained. Rules G11 and G12 rely upon the final description `similarity`, ranking the design as similar or dissimilar for each of the three spatial relations’ descriptor ranks and primitives’ descriptor ranks. Therefore, this description is composed of two triples—each triple enclosed with angle brackets—of the terms “Similar” and “Dissimilar” apply-

ing to the descriptor ranks in the order as specified within the descriptions `spatial_relations` and `primitives`, respectively. Rules G1 through G6 encode the similarity conditions and identify the appropriate term for each descriptor rank. Each rule has two variants, one for positive values and one for negative values. If neither variant applies, then the default term "Dissimilar" is assumed.

## 3. Al-Kazzaz's user guide grammar and evaluation metrics

Al-Kazzaz (2011) considers descriptions in shape grammars for hybrid design, where the descriptions provide feedback on rule application based on comparisons between the generated design and the antecedents in the corpus. One description scheme acts as a user guide for hybrid design and is specified as a set of antecedent labels. In order to ensure that subsequent shape rule applications are taken from different antecedents, each shape rule requires the label of its antecedent to be part of the user guide and subsequently removes the same label from the user guide.

Al-Kazzaz considers two more description schemes specifying evaluation metrics for rules and derivations, respectively. These provide feedback on the degree of innovation in hybrid design, specifically, whether the resulting design combines features from different antecedents and whether the design is sufficiently different from the antecedents in the corpus (Al-Kazzaz, 2011, p. 73). The evaluation metrics provide feedback both on the rule under application and on the design currently being derived. At the rule level, Al-Kazzaz distinguishes a rule prevalence value, a rule geometrical difference value, and a rule sequential difference value. The rule prevalence value depends on the number of antecedents the rule is derived from and, thus, the number of antecedent labels of the rule (divided by the total number of antecedents in the corpus). The other two values depend on the number of antecedents defining rules that share the same left-hand-side as the current rule while sharing the same geometry or sequence (Al-Kazzaz, 2011, p. 73–75).

At the derivation level, Al-Kazzaz distinguishes the following metrics:

- Design diversity is the number of antecedents that the generated design is derived from, divided by the total number of antecedents in the corpus;
- Design abundance is the cumulative sum of the number of antecedents in each of the applied rules, divided by the number of applied rules;
- The matching degree equals the highest number of applied rules derived from a same antecedent, divided by the number of applied rules;
- The design geometrical difference is the sum of rule geometrical difference values of the applied rules, divided by the number of applied rules;

- The design sequential difference is the sum of rule sequential difference values of the applied rules, divided by the number of applied rules

Al-Kazzaz's hybrid minaret design grammar considers a corpus of 12 antecedents, identified as d1 through d12. Each rule in the minaret design grammar identifies the antecedents this rule is derived from. For example, rule OR7a applies to the design of antecedent d12 (only) and, therefore, has the antecedent label "d12". In order to ensure hybrid minaret designs, Al-Kazzaz stipulates that a rule only applies if at least one antecedent label is present in the user guide, and that all antecedent labels of the rule are removed from the user guide upon application of the rule. In the case of rule OR7a, a description rule `{ `"d12"` } → { }` may be considered that ensures the presence of the label "d12" in the user guide, and subsequently removes it from the user guide. Unfortunately, this type of rule does not apply for more than one antecedent if some, but not all, antecedent labels are already absent from the user guide. Instead, we consider a description `a_user_guide` containing a list of numbers of applied rules, one for each antecedent d1 through d12. Thus, a rule applies if the number for applied rules is 0 for at least one antecedent, and the number of applied rules is increased by one for each antecedent of the rule. Expressing this condition requires a rule variant for each antecedent of the rule.

Table 3 explicates description rules for the first four rules of an example presented by Al-Kazzaz (2011, pp. 131–137) for a hybrid design derived using seven (original) rules. For the last rule, only one variant is presented. Table 4 presents the resulting derivation. A separate description is considered for each metric at the derivation level: `diversity`, `abundance`, `matching_degree`, `geometrical`, and `sequential`. They receive their values from other descriptions. The value of `diversity` is computed from an `antecedents` description that maintains a list of (unique) antecedents from which rules have been applied. The values of `abundance`, `geometrical` and `sequential` are computed from a `design_values` description, which contains a list of three values: the cumulative sum of the number of antecedents in each of the applied rules, the sum of rule geometrical difference values of the applied rules, and the sum of rule sequential difference values of the applied rules. The value of `matching_degree` is computed from `a_user_guide`, it is its maximum value divided by the number of applied rules. A description `rules` maintains the number of applied rules and a description `rule_values` contains the evaluation metrics at rule level.

We refer to Stouffs (2015) for any details on the notation used but would like to point out the following:

- Tuples are enclosed with angle brackets.

- `length`, `unique`, and `max` are functions operating on tuples, where `length` returns the number of elements in the tuple, `unique` returns a new tuple with duplicates removed, and `max` returns the maximum numeric value in a tuple.
- The append operator on a tuple is implicit, e.g., in `(da “d12”)`, the alphanumeric value `“d12”` is appended to the tuple `da`.
- The literal ‘`e`’ defines an ‘empty’ entity, that is, zero, an empty string, or an empty tuple.
- A reference to the value of another description takes the form `<description>.value` for the value before rule application and `rhs.<description>.value` for the value after rule application. In the latter case, the description name should precede the current description name alphanumerically, to account for the order in which they are processed.
- A reference to a parameter of another description rule takes the form `<description>.<parameter>`.

Table 3. Four description grammar rules for a hybrid minaret using 7 original rules.

| | |
|---|---|
| `a_user_guide + abundance + antecedents + corpus + design_values + diversity + geometrical + matching_degree + sequential + rule_values + rules` | |
| OR7a | Add a circular minaret base |
| `a_user_guide: { `<d1, d2, d3, d4, d5, d6, d7, d8, d9, d10, d11, 0>` } → { `<d1, d2, d3, d4, d5, d6, d7, d8, d9, d10, d11, 1>` }`<br>`abundance: { `da` } → { `(design_values.sda + 1) / (rules.n + 1)` }`<br>`antecedents: { `da` } → { `unique(da “d12”)` }`<br>`design_values: { `sda, tgdv, tsdv` } → { `sda + 1, tgdv + 1 - 1 / corpus.value, tsdv + 1 - 6 / corpus.value` }`<br>`diversity: { `dd` } → { `length(rhs.antecedents.value) / corpus.value` }`<br>`geometrical: { `gd` } → { `rhs.design_values.tgdv / (rules.n + 1)` }`<br>`matching_degree: { `md` } → { `max(rhs.a_user_guide.value) / (rules.n + 1)` }`<br>`sequential: { `sd` } → { ` rhs.design_values.tsdv / (rules.n + 1)` }`<br>`rule_values: { `rpv, rgdv, rsdv` } → { `1 / corpus.value, 1 - 1 / corpus.value, 1 - 6 / corpus.value` }`<br>`rules: { `n` } → { `n + 1` }` | |
| OR4b | Add an octagonal minaret body above the base |
| `a_user_guide: { `<d1, d2, 0, d4, d5, d6, d7, d8, d9, d10, d11, d12>` } → { `<d1, d2, 1, d4, d5, d6, d7, d8, d9, d10, d11, d12>` }`<br>`abundance: { `da` } → { `(design_values.sda + 1) / (rules.n + 1)` }`<br>`antecedents: { `da` } → { `unique(da “d3”)` }`<br>`design_values: { `sda, tgdv, tsdv` } → { `sda + 1, tgdv + 1 - 1 / corpus.value, tsdv + 1 - 6 / corpus.value` }`<br>`diversity: { `dd` } → { `length(rhs.antecedents.value) / corpus.value` }`<br>`geometrical: { `gd` } → { `rhs.design_values.tgdv / (rules.n + 1)` }`<br>`matching_degree: { `md` } → { `max(rhs.a_user_guide.value) / (rules.n + 1)` }`<br>`sequential: { `sd` } → { ` rhs.design_values.tsdv / (rules.n + 1)` }`<br>`rule_values: { `rpv, rgdv, rsdv` } → { `1 / corpus.value, 1 - 1 / corpus.value, 1 - 6 / corpus.value` }`<br>`rules: { `n` } → { `n + 1` }` | |
| OR12b | Add an octagonal second minaret body above the first body |

| |
|---|
| a_user_guide: { `<d1, d2, d3, d4, d5, d6, d7, d8, 0, d10, d11, d12>` } →<br>{ `<d1, d2, d3, d4, d5, d6, d7, d8, 1, d10, d11, d12>` }<br>abundance: { `da` } → { `(design_values.sda + 1) / (rules.n + 1)` }<br>antecedents: { `da` } → { `unique(da “d9”)` }<br>design_values: { `sda, tgdv, tsdv` } →<br>{ `sda + 1, tgdv + 1 - 5 / corpus.value, tsdv + 1 - 1 / corpus.value` }<br>diversity: { `dd` } → { `length(rhs.antecedents.value) / corpus.value` }<br>geometrical: { `gd` } → { `rhs.design_values.tgdv / (rules.n + 1)` }<br>matching_degree: { `md` } → { `max(rhs.a_user_guide.value) / (rules.n + 1)` }<br>sequential: { `sd` } → { ` rhs.design_values.tsdv / (rules.n + 1)` }<br>rule_values: { `rpv, rgdv, rsdv` } →<br>{ `1 / corpus.value, 1 - 5 / corpus.value, 1 - 1 / corpus.value` }<br>rules: { `n` } → { `n + 1` } |
| OR4d_2 \| Add a circular balcony above the second body |
| a_user_guide: { `<d1, d2, d3, d4, d5, 0, d7, d8, d9, d10, d11, d12>` } →<br>{ `<d1, d2, d3 + 1, d4, d5, 1, d7 + 1, d8 + 1, d9, d10, d11, d12>` }<br>abundance: { `da` } → { `(design_values.sda + 4) / (rules.n + 1)` }<br>antecedents: { `da` } → { `unique(da “d3” “d6” “d7” “d8”)` }<br>design_values: { `sda, tgdv, tsdv` } →<br>{ `sda + 4, tgdv + 1 - 5 / corpus.value, tsdv + 1 - 6 / corpus.value` }<br>diversity: { `dd` } → { `length(rhs.antecedents.value) / corpus.value` }<br>geometrical: { `gd` } → { `rhs.design_values.tgdv / (rules.n + 1)` }<br>matching_degree: { `md` } → { `max(rhs.a_user_guide.value) / (rules.n + 1)` }<br>sequential: { `sd` } → { ` rhs.design_values.tsdv / (rules.n + 1)` }<br>rule_values: { `rpv, rgdv, rsdv` } →<br>{ `4 / corpus.value, 1 - 5 / corpus.value, 1 - 6 / corpus.value` }<br>rules: { `n` } → { `n + 1` } |

Table 4. Partial derivation of the descriptions for a hybrid minaret using 7 original rules.

| | |
|---|---|
| | a_user_guide: { `<0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0>` }<br>abundance: { `e` } antecedents: { `e` }<br>corpus: { 12 } design_values: { `0, 0, 0` }<br>diversity: { `e` } geometrical: { `e` }<br>matching_degree: { `e` } sequential: { `e` }<br>rule_values: { `e, e, e` } rules: { `0` } |
| OR7a | a_user_guide: { `<0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1>` }<br>abundance: { `1.0` } antecedents: { `“d12”` }<br>corpus: { 12 } design_values: { `1, 0.917, 0.5` }<br>diversity: { `0.083` } matching_degree: { `1` }<br>geometrical: { `0.917` } sequential: { `0.5` }<br>rule_values: { `0.083, 0.917, 0.5` } rules: { `1` } |
| OR4b, OR12b, OR4d_2 | a_user_guide: { `<0, 1, 2, 1, 0, 1, 1, 2, 1, 0, 1, 1>` }<br>abundance: { `1.75` }<br>antecedents: { `“d12” “d3” “d9” “d6” “d7” “d8” “d4” “d11” “d2”` }<br>corpus: { 12 } design_values: { `7, 3.0, 2.417` }<br>diversity: { `0.5` } geometrical: { `0.75` }<br>matching_degree: { `0.5` } sequential: { `0.604` }<br>rule_values: { `0.333, 0.583, 0.5` } rules: { `4` } |

## 4. Discussion

Both case studies only present one possible explication. For example, in the case of Ahmad's style mapping, we chose to include only the numeric values for the style descriptor ranks and collect these ranks into a `spatial_relations` and a `primitives` descriptor. Instead we could have opted to include the alphanumeric values for the style descriptor ranks alongside the numeric values and maintain a separate description for each style descriptor rank. The latter may better reflect on the way Ahmad chooses to present the results (Figure 1) but is far more verbose. In the case of Al-Kazzaz's user guide grammar and evaluation metrics, we adopted a number of auxiliary descriptions in order to calculate and derive the different metrics. There is certainly some flexibility in the way these auxiliary descriptions are defined and specified.

## 5. Conclusion

We have demonstrated for two case studies that the description grammar interpreter (Stouffs, 2015) and its notation for descriptions and description rules are able to support the development and explication of description grammars from concept to computation. Certainly, the given examples present only one manner of explication; others may exist that are as valid. Also, each present only a single derivation; other derivations may require additional rules that are not mere variants of the rules presented. Nevertheless, the case studies do point to the generality of the notation and the description grammar interpreter. We do hope these examples may inspire authors of description schemes to extend their development beyond the conceptual level.

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# DESIGN WITH BAMBOO BEND

*Bridging natural material and computational design*

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**Abstract.** Bamboo is a high potential alternative solution for substituting industrial material with its natural characteristics, economical and environmental aspects. However, one of the biggest challenges for natural materials to be used in computational designed is the controllability due to its unevenness nature. The other gap is the lack of material parameters that might be bridged by analysing data acquired from conventional tests. This research studied the raw bamboo strip and its natural forming from bending, by using sampling points and curvature reconstruction. The parametric models of bamboo strips were then constructed to represent its material behaviours for form prediction, material selection, and simulation in parametric design. It also serves as an assistive method for material selection when crafting with bamboo bend.

**Keywords.** Bamboo; bending; material computation; digital crafting.

## 1. Introduction

### 1.1. CONTEXT

The advantages of using bamboo in construction are low cost, environmental friendly and low technical requirements. Among all the basic construction elements of bamboo (Minke 2012), strip is not only one of the most bendable materials but also has high strength-to-weight ratio useful for structural applications (Janssen 2000), which is favourable for building sophisticated curvy surfaces. Compare to the high technical requirements, budget, and energy consumption in manufacturing and fabricating industrial materials, bamboo is a highly potential alternative with its characteristics, economical and environmental aspects.

However, one of the biggest challenges of natural materials to be used in digital crafting process is its unevenness and controllability. Common solution for material induced problems is by manual correction (Hoang and Bunge 2008). Designers tend to go through varieties of material and construction studies, learned from trial-and-error manually. However the result can hardly be used in digital design process directly without a proper model to describe the material behaviour.

In winter 2014, a parametrically designed bamboo pavilion was constructed in Emei, Hsinchu County, Taiwan, by a group of voluntary students. Due to its irregular geometry and lack of computational model, the team suffered from difficulties in planning and selection of the bamboo for construction. The team had to stumble through the trial-and-error process without a clear picture of connecting material behaviour and tectonics. The experience motivated this research (Figure 1).

To bridge the gap, the performance and behaviour of bamboo needs to be further studied and analysed. The hypothesis is that if we can find the model, or pattern, of how the bamboo strips perform in certain condition, we may effectively know how to choose a proper bamboo strip to fit to a specific curve and then to construct a surface. This is merely a process of reverse-engineering and physical form-finding for crafting with bamboo (Oxman and Rosenberg, 2007).

Hence, the research problems can be elaborated as the followings:

- How to take the heterogeneous nature of bamboo into account when looking for a general model of its behaviour?
- How to map the material behaviour to a parametric model that is reusable?
- How to design a form based on the parametric model of a bamboo strip?



*Figure 1. The project.*

## 1.2. BAMBOO

No two bamboos are the same. Bamboo is a heterogeneous and anisotropic material. The shape is tapered toward tip as the outer diameter and wall thickness decreases. The internodes length increases toward the middle part of the bamboo. At around 50~70% of the culm, the internodes length tends

to be constant with minor differences. Then the length decreases as it near the tip (Figure 2). Along the culm, the density of nodes increases from lower to upper part. Transversally, the fibre is denser at the outer third of the culm (Yu, 2007); therefore the outer surface has higher tension than the inner wall when bending. Individual bamboo plant may differ from one another by site, age and species, however the anatomical features are not much different between species (Weinstock, 2006). Material selection in this research was based on these properties.

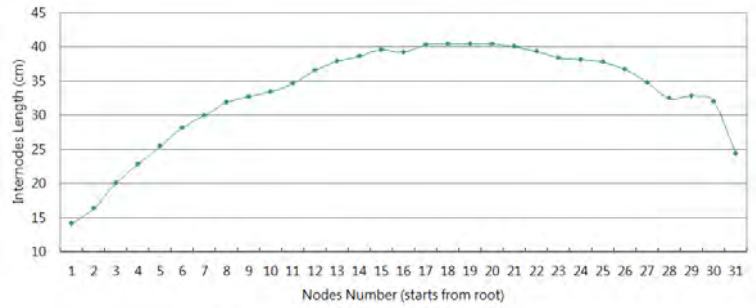



*Figure 2. Variations of internode lengths.*

## 1.3. OBJECTIVE & RESEARCH STEPS

This research studied raw bamboo strips, its physical properties and natural forming by bending caused by pushing the strip ends inward and proposed an approach to combine natural material and computational design. The objective is to increase controllability of natural material by integrating the results of material study and parametric model into digital system. The first part is material parameterization. Different types of bamboo strip were studies and documented by photos and charts, then data were analysed to construct a parametric model. The second part is to rationalize a parametric design, e.g. a curvy surface, by utilizing the model. The model not only provides a foundation for spatial, structural and construction preview and prediction, but also provide suggestions for bamboo strip selection, including: width and thickness of the bamboo strip, distribution of bamboo nodes, and internodes lengths (Figure 3).

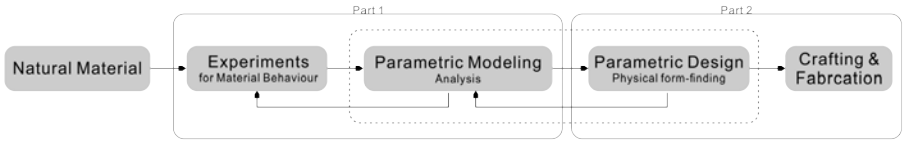



*Figure 3. Research process.*

## 2. Experiments and parametric model

Considering the availability and feasibility, a species that is commonly seen and used in Taiwan, Phyllostachys Makinoi, was chosen to study how the distribution of bamboo nodes influences the bending tendency. The research focused on bamboo strips in its raw state without stripping the nodes to keep its initial physical performance and material behaviour.

The lengths of internode vary from the root side to the tip (Figure 2). To better control the material behaviour, we used the bamboo strips taken from the middle part of the bamboo culm, approximately between 50% and 75% measured from the root side, to maintain the evenness of the internodes. For the selected bamboo strips, the width and thickness are constants, and the lengths of internodes range from 37 to 45cm.

### 2.1. EXPERIMENTS

The purpose of this experiment was to investigate bending behaviour of a group of strips. The bamboo nodes play a crucial part in natural forming when bended. The distribution of nodes within a strip influences its direction and tendency of tilting. Hence the bamboo strips were categorized into five basic types based on the relationship of nodes and internodes (Figure 4).

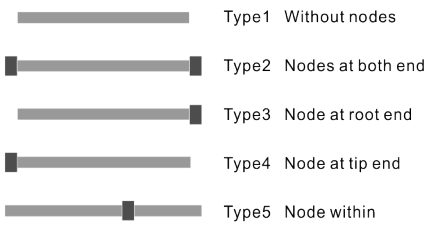



*Figure 4. Basic types of nodes location.*

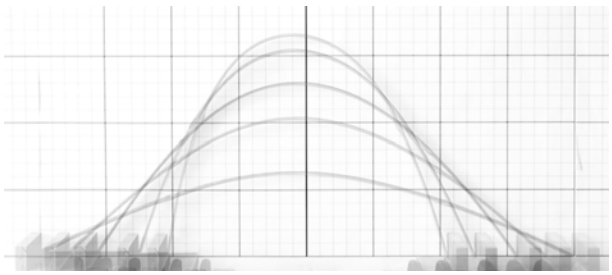


*Figure 5. A series of bending.*

A set of measuring tools was designed for the experiment, which allows adjusting the span width by moving both ends. A series of strips with different span widths were tested starts from 95% of total length, at decremental step of 5% (Figure 5).

## 2.2. PARAMETRIC MODELLING

Bamboo is an anisotropic material (Chaowana, 2013) and it does not bend symmetrically all the time. Bending tendency (Figure 6) can be easily compared when overlapping two charts. On the bamboo strip, 10 sampling points were evenly positioned (Figure 7) where $P_0$ is toward the tip and $P_{10}$ is toward the root. When the span width of the bamboo strip changes from 100% toward 0%, sampling points on the strip were recorded and yield a set of traces (Figure 7). By analysing the X-Y coordinates of the sampling points the bending behaviour of the strip was able to visualized and compared.

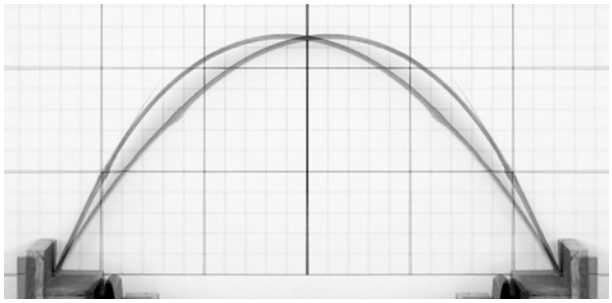


*Figure 6. Bending tendency.*

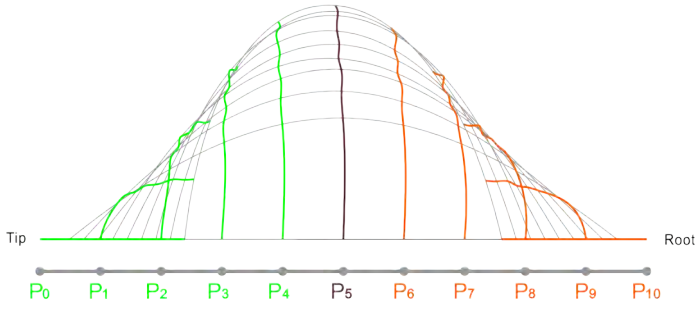



*Figure 7. Position on a material length and its traces.*

Rhinoceros and Grasshopper were used to construct the parametric model. Each bending curve was reconstructed in Rhino as a NURBS object (Figure 8). Then the curves were analysed and synthesized in Grasshopper. We

were able to use curvature analysis and visualization tools in Rhino and Grasshopper to help finding out the key properties of the bending behaviours.

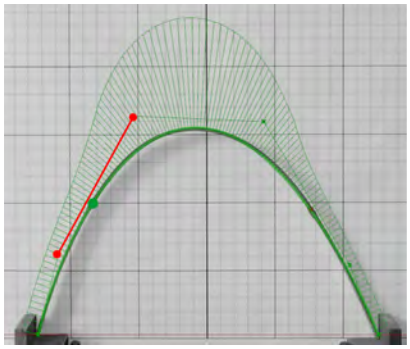


*Figure 8. Reconstruction of bamboo strip curve by NURBS representation.*

Both X-Y coordinates and span width were normalized according to the strip length so that bamboo strips with similar lengths could compare to each other. By keeping the charts of X-Y coordinates, the tendency of how the strip bends and the relationships between parameters were captured and ready to be reused in parametric design.

The horizontal axis of the chart shows the percentage of span width to strip length. For “100%”, it denotes that the span width is equal to the strip length, which means no bending is occurred. The vertical axis indicates offset of the sampling points (Figure 9). P0-P5 and P5-P10 are symmetric groups with respect to P5, the mid-point on the strip. Moving paths of both groups are in different colours. When overlapping the moving paths of two groups, we are able to associate the bending tendency and tilting to the differences in sampling points and the nodes (Figure 10).

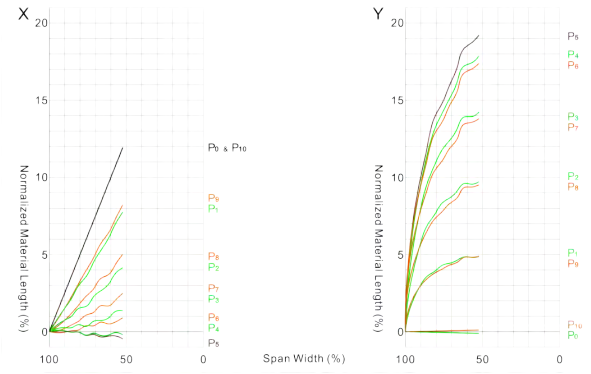



*Figure 9. Paths of sampling points.*

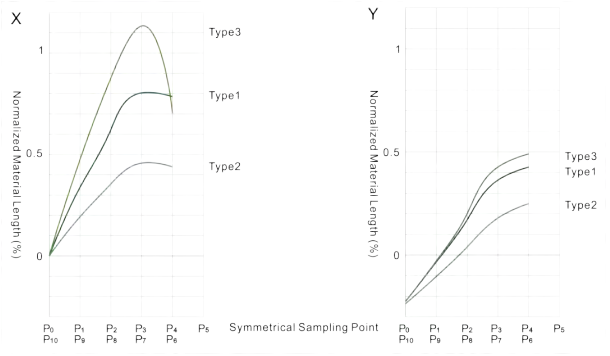



*Figure 10. Delta values of X-Y coordinates.*

Comparing delta values of X and Y in symmetrical positions for different types of node location, we found that type 2 has smallest bend tendency (Figure 10). Another symmetrical node location type, type 1 with no nodes, has bigger bend tendency than type 2. Type 3 the asymmetrical type with one node at one end, has largest difference among the three.

## 3. Parametric design and tests

By combining data of a group of bamboo strips with similar properties, we could get the general parametric model of their material behaviour. As long as we have the parametric model, we are able to reverse the process and generate curves from it that can be fitted by its associated bamboo strip. Thus when the span width is determined, a bended curve can be reconstructed from the chart (Figure 11).

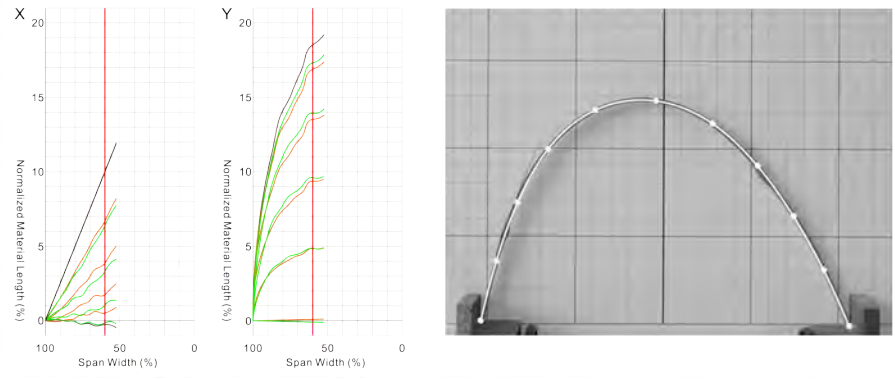



*Figure 11. Reconstruct curve from chart.*

The model associates properties of the bamboo strip, such as bend curvature, bend tendencies, strip length and node locations, where the span width is the key variable to find the form. Therefore, due to its computability, the model then can be utilized in the computational design process.

Once bending curve and material behaviour are associated, simulation and form prediction are possible. We may generate in-between curves by interpolation between physically bending curves. With this outcome, a suggestion can be made on bamboo strips with certain properties that matched the analysis of the target surface for physical form-finding. The result will be a series of suggested values of bamboo strip types, distribution of nodes, and span width (Figure 12). Sections of the target surface serve as the reference paths of bamboo strip and also the guiding paths for construction (Figure 13).

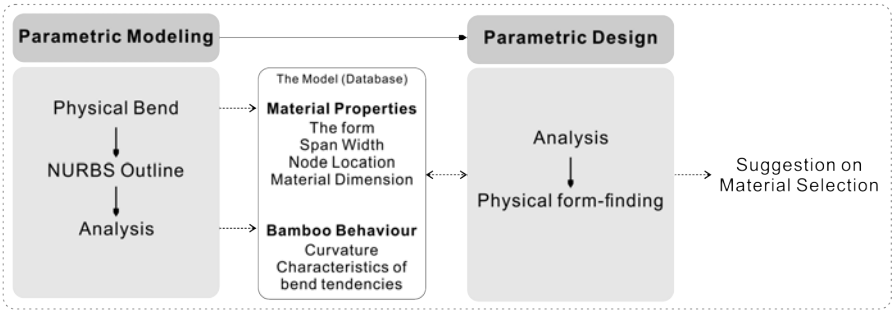



*Figure 12. Parametric modelling.*




*Figure 13. Form generated from span width.*

## 4. Conclusion

Motivated by the prior experience of digital crafting with bamboo and the intention of bridging material behaviour and computational design, this paper introduces a process that:

- Brings natural material into digital design process.
- Experiments with bamboo strips to acquire key factors and relationships that influence the material behaviour.
- Constructs parametric models to capture the knowledge of the material.
- Exercises parametric design by utilizing the model to rationalize the target form.

The implications of this research to design profession are:

- By fusing computational design and natural material, we may pursue innovative digital crafting with significant potentials. However, more fundamental researches in material properties and design science is required to build the ecosystem for material computation.
- Controllability of natural material would increase, because spatial arrangements, structural analysis, and fabrication process could be easily evaluated.
- Predictability of a unique design form could be achieved by looking at the parametric model, aside from simulation and visualization. And it would be also supported by data and models from other researches like this.

The potential future studies involve improvements and challenges are:

- Better instruments or tools are needed for measuring and experiments.
- To automate the process and increase the reliability for general usage in computational design.
- Different modelling approaches for workflow optimization.

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# FINDING RELATIONSHIPS BETWEEN MOVEMENT AND TREE PATTERNS IN THEME PARKS

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**Abstract.** Tree planting in design practice is considered simply as void fillers or view blockers. However, for a sustainable design, creating places using trees need to be reconsidered. Going beyond traditional tree plantings in urban environments, an application of computational methods in landscape architecture for the management of the complex system is needed. While computational methods have been extensively applied to buildings, less has been applied to trees. The goal of this paper is to investigate how the presence of trees affects human movement and find out if computational methods can be used for recommending tree planting patterns. We analysed the tree planting patterns in renowned theme parks as an initial research categorizing tree planting patterns, using an agent-based analysis for simulation, and comparing the results of the average agent counts in theme park plans without trees and those with trees. We noticed there was a clear distinction between tree planting pattern types and the change in agent counts supporting the qualitative theory in landscape architecture. The result of this research can guide theme park designers as well as urban park designers when deciding which tree planting patterns to implement for the purpose of controlling pedestrian movements.

**Keywords.** Tree planting pattern; agent-based analysis; theme parks; pedestrian movement.

## 1. Introduction

The way trees are planted in cities mean nothing to people because they are not planted to form places; instead, they are planted along roads or in parking lots instrumentally not interactive with people. However, according to a Norwegian architectural theorist, Christian Norberg-Schulz, a landscape is one of the components that make up an existential space. Existential space

lies between the perceptual space and the cognitive space in a list of five space concepts (in the order of growing abstraction: physical space, perceptual space, existential space, cognitive space, and geometrical space). The existential space indicates a complex space where human interact with the environment experiencing the immediate perception and schemata or an image that the environment creates. In this sense, landscapes—as masses and spaces—determine, and perceptually and schematically influence the paths taken by the people (Norberg-Schulz, 1971).

Keeping in mind that landscape is one of the components of existential space and that people interact especially through their movements, the current situation of landscape architecture in practice should be examined. Trees are planted along the roads linearly or planted around the buildings as buffers. However, tree planting patterns should be utilized for the control of movements in a complex space. Control of the movement means areas, where people need to gather, should gather, and that areas, where people need to walk on, should walk on. However, to apply the tree planting patterns for the control of movements, we need information on how different kinds of tree arrangement patterns influence the movements in a complex system.

In this research, we investigated how the presence and the arrangement patterns affect agent movements by comparing the simulation results from plans without trees and the results from plans with trees. To do so, we first categorized different types of tree planting patterns from literatures and used an agent-based analysis from a space syntax theory to compare the analysis results from the plans with trees and without trees. After the agent-based analysis, the sub-regions in plans were categorized according to the tree arrangements to see whether if there is a pattern between tree planting patterns and average agent counts. For this paper, theme parks are chosen as research sites because, unlike the cities, theme parks are designed to create a spatial identity and to persuade people to walk around. In other words, the tree planting patterns in theme parks are supposedly designed to control the movements in a complex space (Clavé, 2007).

## 2. Research background

### 2.1. TREES AS STRUCTURE

According to Christopher Alexander et al (1977), trees have a crucial meaning to humans often representing dreams, power, and perseverance. The trees that people love create special social places: places to be in, pass through, and dream about or draw. And these trees are arranged in different patterns:

an umbrella (a single, low-sprawling tree), a pair (two trees forming a gateway), a grove (several trees cluster together), a square (an enclosed open space), and an avenue (a double row of trees lining a path).

Alexander further adds trees should be planted to form an enclosure, avenue, square, or an umbrella since trees and people have a complex interactive symbiotic relationship where people need trees and trees need care from the people, and thus trees need to form places where people occupy, pass through, and rest to be taken a good care of (Alexander et al, 1977).

Further supporting Alexander's work, Gang Chen (2011) has published a book that lists a number of spatial arrangements that affect human movements (Figure 1).

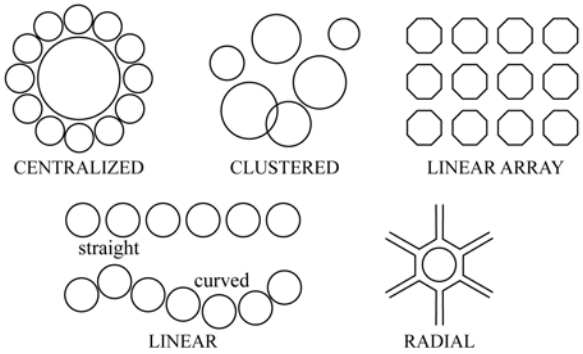



*Figure 1. Basic spatial arrangements (redrawn from Chen, 2011).*

Chen (2011) lists centralized, clustered, linear array, curved and straight, and radial spatial arrangements. Each of these spatial relationships create a distinct sense of place for the people. For example, in the centralized organization, the tree in the centre plays a role of a dominant space acting as a focal point. In another case, in the linear organization, people are encouraged to move along a straight line and have access to a powerful perspective view (Chen, 2011).

Theoretically, from Alexander et al (1977) and Chen (2011), it is clear that trees create spaces with enclosure and identity depending on what kind of pattern they are planted as. However, it is unclear how these tree patterns influence human movements in a holistic bounded system.

## 2.2. COMPUTATIONAL RESEARCH AIDING LANDSCAPE DESIGNS

Application of computational methods in architecture has been ongoing for a long time simulating human movements inside buildings and proving how spaces influence people's movements. In contrast, the application of compu-

tational methods in landscape architecture field has been slow because trees do not have definite and solid characteristics like walls in buildings, and because, in practice, landscape architecture requires more heuristic knowledge when designing. However, researches exploring ways to design landscape quantitatively are recently on a rise and are becoming more diverse.

For example, in urban greening research field, there is a research that identified locations that are spatially available for potential tree planting based on satellite images (Wu et al, 2008) as well as a research that prototyped decision support system for sustainable urban tree planting programs for micro-management of the urban forest canopy (Kirnbauer et al, 2009). In addition, there are researches where a graph theory is used to investigate the connectivity of patches of green fields to recommend the location of urban greens for a higher habitat connectivity value (Galpern et al, 2011; Hepcan, 2013). However, these researches only deal with the tree and green patch placements in relation to other environments, not examining the existential relationship between human and trees.

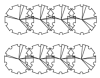
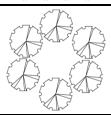
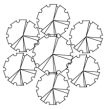
There recently was a research on the usage of space syntax theory for planting design in urban parks. In Mahmoud and Omar's research, the authors investigate how space syntax techniques can be incorporated for predicting the social structure of the proposed space and assess design alternatives at a pedestrian movement level (Mahmoud and Omar, 2015). The authors use the visibility graph analysis to assess the design alternatives of tree planting and computationally illustrate which alternative is better. Our research used a similar method used by Mahmoud and Omar (2015), but with a different purpose where the goal is to see whether if there is a noticeable relationship between tree planting patterns and human movements.

## 3. Methodology

### 3.1. TREE PLANTING PATTERN CLASSIFICATION

While Alexander et al (1977) and Chen (2011) both classified tree planting patterns, the terms used are different. For instance, Alexander called a tree pattern where one tree stands as an 'umbrella', while Chen called it a 'point'. The terms are organized in Table 1 along with the corresponding diagrams. As illustrated, a 'pair' planting pattern is considered similar to a linear planting pattern, so it included in the linear/avenue category, and similarity a 'centralized' pattern, where a large tree stands in the middle with small trees around, is categorized as a pattern that encloses a space—circular and square. In this paper, the most planting patterns shown in the first column of Table 1 are used.

Table 1. Tree planting patterns.

| Pattern Names Used | Diagrams | Chen (2011) | Alexander et al (1977) | Description |
|---|---|---|---|---|
| Point/Umbrella |  | Point | Umbrella | A single tree |
| Linear/Avenue |  | | Pair | Two trees forming a gateway |
| |  | Linear | Avenue | A double row of trees lining a path |
| Centralized/Square/ Circular |  | Circular | Square | An enclosed open space |
| |  | Centralized | | |
| Cluster/Grove |  | Cluster | Grove | Several |

## 3.2. DATA COLLECTION

The purpose of this research is to computationally find out how the presence of trees and the tree pattern types influence the way human move through space as Alexander et al (1977) and Chen (2011) have mentioned. In this particular research, the four representative theme parks of Walt Disney (Tokyo Disneyland, Disneyland Paris, the Magic Kingdom at Walt Disney World, and Disneyland California) were investigated because theme parks are designed to create social space and induce movements (Clavé, 2007).

The trees in the middle of the streets—the trees located near the buildings that do not directly interact with the pedestrians are not considered in this research—were plotted onto CAD maps of the theme parks marked using a small square as Mahmoud and Omar (2015) have done (Figure 2).



*Figure 2. Plotting the trees into CAD map (linear/avenue type).*

After plotting the trees, the tree clusters were categorized into different tree planting patterns according to the categories: cluster/grove type, linear/avenue type, point/umbrella type, centralized/square/circular type.

### 3.3. AGENT-BASED ANALYSIS

For the analysis, we used an agent-based analysis tool in DepthmapX 0.30 which is based on a visibility graph from a space syntax theory. DepthmapX 3.0 is developed by Tasos Varoudis based on the theories suggested by Alasdair Turner and Bill Hillier. The agent-based analysis was first proposed by Turner and Penn (2002) with a visibility graph as its foundation. For our research, 1000 agents were randomly placed throughout the CAD maps. We first confirmed whether if tree plantings in theme parks have a structural role in terms of their influence on agent movements by comparing the results of agent-based analysis between a plan with and without the trees. When the difference was confirmed, we investigated whether if there is a relationship between planting pattern types and the change in the average number of agents at a spatial node identified by the tree planting structures (Figure 3). Lastly, we determined which patterns increase the average number of agents and which decrease it.

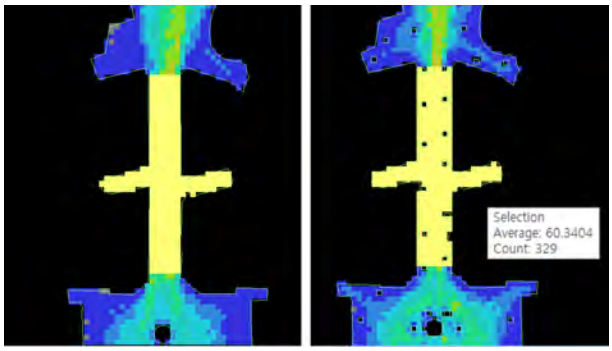



*Figure 3. Counting the average number of agents.*

## 4. Results

When the agent-based analyses were implemented on four theme park plans without the trees and plans with trees, it showed a clear difference in terms of the average agent count. Overall, the plans with trees showed more distribution of agents than those without. We were able to conclude that trees play a significant structural role on how space is occupied. After this confirmation, we categorized each occurrence of tree planting patterns into those that

increased in the number of agents going from a plan without the trees to a plan with the trees and those that decreased.

The main planting pattern types that decreased the number of agents were the cluster/grove and the linear/avenue types (Figure 4a and 4b) where the area of warm colours decreased from when there are no trees planted to trees planted. From the agent-based analysis, we can suspect that the reason why cluster/grove type and linear/avenue type decreases the number of agents is because the cluster/grove type blocks the views of the agents and the linear/avenue type narrows a path thereby decreasing the visibility, and thus the number of agents passing by. Meanwhile, the planting patterns that increase the number of agents are the point/umbrella and the centralized/square/circular types (Figure 4c and 4d) meaning that they gather agents.

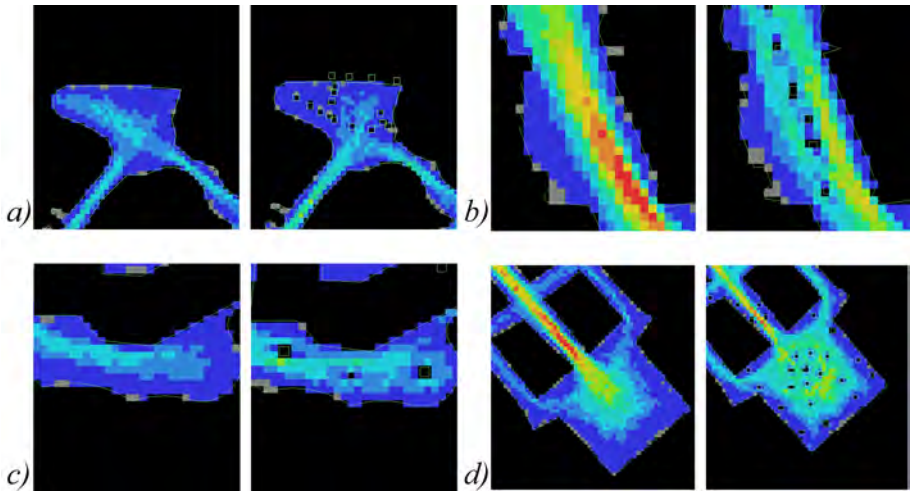



*Figure 4. a) Cluster/grove type, b) Linear/avenue type, c) Point/umbrella type, d) Centralized/square/circular type.*

For the graphical visualization (Figure 5), the percentage differences are averaged for each planting types and represented as bar graphs. We can see that the cluster/grove planting pattern type influenced the number of agents the most negatively, then the linear/avenue type; meanwhile, the point/umbrella planting pattern had the least influence. The reason might be because the agent-based analysis is based on the visibility graph so the point/umbrella planting patterns have a minimal impact on the sightlines.

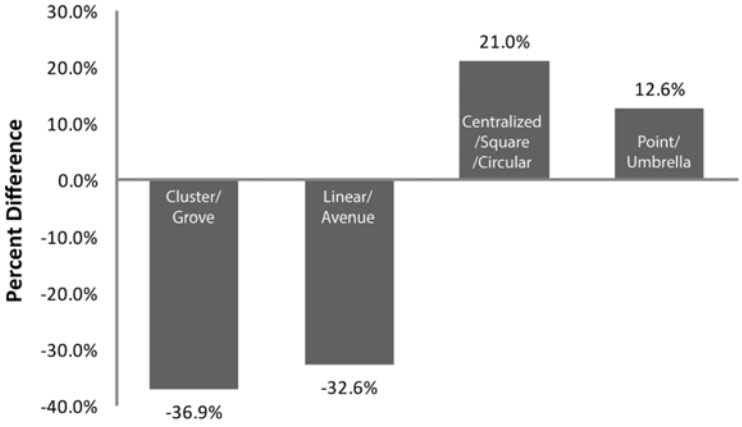



*Figure 5. The average percentage differences for each tree planting patterns.*

## 5. Conclusion and contribution

The goal of this paper was to investigate how the presence of and the arrangement patterns of the trees affect agent movements. In this particular research, we analysed renowned theme parks as an initial approach to answering this question because theme parks are designed to create a spatial identity and to persuade people to walk around controlling the movements. For our research, we categorized different types of tree planting patterns identified in the literatures and used an agent-based analysis. When we compared the results of the agent-based analysis on theme park plans without trees and those with trees, we noticed that trees had the tendency to distribute the agents more. This result was as expected, since agent-based analysis is based on a visibility graph, and with more obstacles (trees), it means that there are more diversity in the lengths of sightlines. When the areas with tree patterns identified previously were listed in the order of percent difference, we were able to see that cluster/grove and linear/avenue types influenced the agent count the most where the point/umbrella type influenced the agent count the least. This is also possible because point/umbrella type is minimal on its impact on sight lights of the agents.

A surprising finding was that there was a clear distinction between tree planting pattern types where two types (cluster/grove & linear/avenue) decreased the agent counts while other two types (centralized/square/circular & point/umbrella) increased the agent counts. In the theory of landscape architecture, cluster/grove planting patterns are used to block views while linear/avenue planting patterns are used to make people move linearly. Furthermore, centralized/square/circular patterns and point/umbrella planting

patterns are to gather people. The results from this research where it was only dependent on the agents and the algorithm created by Turner and Penn (2007), it clearly reflects how the theories in landscape architecture can also be replicated computationally. While, it is understandable for the cluster/grove and linear/avenue patterns that they decreased the number of agents, because they do interrupt the sight lines of the agents, this research result should be reinvestigated on how point/umbrella and centralized/square/circular types actually had increased agent counts because for these patterns, people gather not due to sight lines but psychological reasons. One possible reason might be because cluster/grove and linear/avenue types distribute agents that other places must have increased in the number of agents. Still, using agent-based analysis for tree planting design is shown to be effective from the results.

The result of this research not only can guide theme park designers when making design decisions regarding the tree planting pattern to control pedestrian movements, but it is also applicable for places where inducing human movement in an open space plays a big part. A main reason is because, although we used the arrangements from tree planting patterns, from the agent analysis point of view, the trees are simply considered as obstacles where it can be anything from a bench to a trashcan. For example, the finding from this research can be used when designing shopping malls or even traditional markets in city centres; for areas where many people are expected to pass through, a linear/avenue or a cluster/grove obstacle arrangements should be implemented, for areas where people are expected to not pass through often, a centralized/square or a point/umbrella obstacle arrangements should be implemented. Nevertheless, choosing the trees as obstacles is appropriate since there are no other ‘obstacles’ that can be placed in the manner how trees are placed. Our research demonstrates that trees can be used to create space as well.

## 6. Limitations and future works

One of the limitations of this research was that it was limited to an agent-based analysis in two-dimension and neither tree shapes nor the psychological effects of trees were taken under considerations. The trees were simply represented as a square. Space syntax is based on the visibility analysis developed by Bill Hillier; it is extensively used for buildings where a wall is usually straight. However, applying space syntax in an urban park with trees, we expect there will be differences. Next step in this research is to investigate the nature of space syntax theory around trees adjusting space syntax to be used in exterior space. How different tree shapes (crown shape and

height) influence our sight lines should be taken under considerations, because currently, in this research, the trees are simply represented as a pole indicating that the research result may not have anything to do with the psychological benefits of trees. Giving weight to the places with certain tree patterns would definitely provide more meaning and depth to the agent-based analysis.

Furthermore, it would have been really supportive if we were able to compare our simulated results to real observations but to verify the analysis results, we would have to observe a site for a long time where a site begins as a site without the trees to a site with trees.

## Acknowledgements

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# PORTABLE GENERATIVE DESIGN FOR BUILDING INFORMATION MODELLING

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**Abstract.** Generative Design (GD) is a valuable asset for architecture because it provides opportunities for innovation and improvement in the design process. Despite its availability for Computer-Aided Design (CAD), there are few applications of GD within the Building Information Modelling (BIM) paradigm, and those that exist suffer from portability issues. A portable program is one that will not only work in the application it was originally written for, but also in others with equivalent results. This paper proposes a solution that explores portable GD in the context of BIM. We also propose a set of guidelines for a programming methodology for GD, adapted to the BIM paradigm. In the end, we evaluate our solution using a practical example.

**Keywords.** Building information modelling; generative design; portability; programming.

## 1. Introduction

Despite the fact that CAD tools support efficient working processes in architectural design, the creation of complex geometries can still be a challenge. This can be simplified with the use of GD, an algorithmic-based approach to design (Garber, 2014). GD also enables the automation of repetitive, time-consuming tasks, relieving architects from tedious and error-prone work.

To take advantage of GD, several tools, such as Grasshopper, Visual LISP and RhinoScript, emerged, allowing architects with basic programming skills to develop programs that generate models in CAD applications.

Recently, BIM tools have been replacing former CAD applications and, given the advantages of GD, it is tempting to extend it to BIM, introducing an algorithmic-based approach to Building Information Modelling.

The CAD and BIM paradigms are very different, and using the latter involves some significant shifts in design methodologies. For example, while CAD tools mostly deal with geometry, BIM tools produce digital representations of building components, containing both geometrical information and data attributes, such as material composition and cost (Eastman et al., 2008).

The building components have parametric and associative rules that dictate their behaviour, such as a door that can only exist hosted in a wall, which help ensure that the building components behave more like their real counterparts. These rules also facilitate the designer's job by propagating changes in the design.

For the GD field, the implication is that the differences between the CAD and BIM paradigms entail differences in the corresponding GD programming methodologies which, so far, have not been properly addressed.

### 1.1. MOTIVATION

The BIM paradigm, like the CAD one, can also benefit from GD and, indeed, tools like Dynamo and GenerativeComponents combine GD with BIM. These tools depend on Application Programming Interfaces (APIs) which provide a programmatic form of interaction with a BIM application. However, the use of these APIs requires extensive knowledge of textual programming languages, such as C# and C++, which few architects possess.

To overcome this, visual programming languages were developed, offering a more beginner-friendly alternative. Although very appealing for developing small programs, these languages become a barrier for complex programs, making them difficult to understand, use, and modify (Leitão and Santos, 2011).

An important feature that is missing from these programming tools is portability: the ability to execute the same program in different tools, producing equivalent results. One could hope that this lack of portability would not imply the lack of portability of the generated models and, in fact, there are solutions for transferring models between BIM applications, such as the Industry Foundation Classes (IFC). However, case studies show that IFC is not an entirely reliable method of transferring models between BIM tools (Golabchi and Kamat, 2013).

In this paper, we address GD in the context of the BIM paradigm, while taking into consideration the problems previously discussed. Our contributions are: (1) a solution for portable GD for BIM; (2) guidelines for a programming methodology for GD, adapted to the BIM paradigm. In the end, we evaluate our solution using a practical example.

## 2. Related work

There are several tools that address programming for BIM, including tools that are already available in BIM applications and plug-ins developed for the production of GD programs.

Grasshopper is a visual programming language for Rhino. Programs written in this language represent a data flow graph that consists of components and connections between them (Payne and Issa, 2009). Grasshopper can be extended with plug-ins for interoperating with BIM tools.

Lyrebird is a plug-in developed by LMN Architects to structure the information needed to identify and instantiate the correct BIM families in Revit (Logan, 2014).

Rhino-Grasshopper-ArchiCAD is another plug-in that allows the creation of BIM objects in ArchiCAD by using geometrical information created in Grasshopper (Graphisoft, 2015).

Dynamo is a plug-in for Revit that is strongly influenced by visual programming languages. Just as Grasshopper, users create a workflow by introducing nodes that are connected to each other through wires associated with the ports that each node contains (Autodesk, 2015).

GenerativeComponents (GC) is a parametric and associative system developed for Bentley's Microstation. GC has three ways of user interaction: (1) by direct manipulation of geometry; (2) by defining relationships among objects with simple scripts in GCScript; and (3) by writing programs in C#, allowing the definition of complex algorithms (Aish and Woodbury, 2005).

RevitPythonShell is a plug-in developed for Revit that allows users to take advantage of the RevitAPI but using Python. This tool was developed to simplify the workflow needed in order to use the RevitAPI (Thomas, 2009).

## 3. RosettaBIM

One flaw of the discussed tools is their lack of portability: a GD program written in one of those tools will only work with one specific BIM tool. In order to support the portability of GD programs, we propose RosettaBIM, a solution that considers BIM tools as back-ends for model generation.

RosettaBIM is composed of two components that exchange information through a communication channel. The first component is an abstraction layer that provides parameterised operations to create BIM objects, while the second is a plug-in that enables the production of the specified objects in a BIM tool. This architecture allows the creation of a common ground between the supported tools, enabling the portability of GD programs. Figure 1 shows a diagram of the proposed solution.

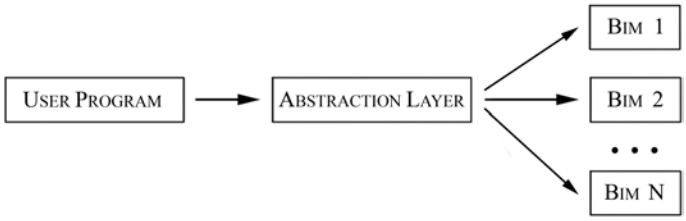



*Figure 1. A simple diagram depicting the overall architecture of RosettaBIM.*

In order to achieve the desired portability, the operations provided by the abstraction layer allow the creation of BIM objects in different back-ends. These operations are independent of the chosen back-end, which means that they have the same parameters. However, they are used differently according to the requirements of each plug-in. For example, to create a slab in a specific BIM tool, the operation might require a relative height while, in another tool, it might require an absolute height. To make this behaviour uniform, the operation in the abstraction layer requires the absolute height and the necessary conversions are made in the respective plug-in.

RosettaBIM is also designed to support the associative rules of the BIM paradigm, as these rules work both on the user's program and in the generated model. For example, to create a window in a BIM application it is necessary to have a wall as a host. This is reflected in RosettaBIM by forcing the operation that creates the window to also receive the wall as a parameter. This imposes the intended constraint in the creation of objects and in how the user organises his program.

In spite of the normalization done, we also want to enable the full exploration of a specific tool's capabilities. To this end, we grant the ability to relinquish portability in order to use those specific capabilities.

### 3.1. IMPLEMENTATION

In order to support several BIM back-ends we extended Rosetta (Lopes and Leitão, 2011), a tool that already provides portable GD for CAD. Although Rosetta did not support any BIM tools, it provided features that are useful in the BIM paradigm, such as coordinate systems and geometric abstractions. Moreover, Rosetta uses DrRacket (Findler et al., 1997), a pedagogical programming environment.

To support BIM tools, we established a communication channel to exchange information between the abstraction layer of Rosetta and the new BIM back-ends, and we extended that abstraction layer to provide new operations that support the BIM paradigm, particularly to create and manipulate BIM objects, including walls, doors, and stairs, among others.

Currently, this approach only supports Graphisoft's ArchiCAD and Autodesk's Revit as back-ends but can easily be extended to support other BIM tools. While all these tools share the same paradigm, there are substantial differences in some of the provided features. For example, Revit's API offers a more complex and detailed range of attributes for the creation of stair objects, while ArchiCAD's API allows the user to change attributes of slabs, like its thickness, without changing families.

Some of these differences were overcome through normalization while others were made available as BIM-specific features. In the next section, these trade-offs are further explained in the context of the case study.

## 4. Evaluation

To evaluate RosettaBIM, we selected an architectural case study: the Absolute Towers, designed by MAD Architects (Figure 2). In the next sections, we address GD for BIM, proposing guidelines for a BIM programming methodology, we analyse the portability of RosettaBIM, and we discuss the advantages of GD for BIM.



*Figure 2. Absolute Towers, designed by MAD Architects and located in Mississauga, Canada (taken from Welch, 2014).*

### 4.1. GENERATIVE DESIGN FOR BIM

In order to analyse GD programs for BIM, it is important to understand the main differences between working with CAD and BIM tools. Due to the differences in both paradigms, the corresponding GD programs will also differ. To understand these differences, we generated one of the Absolute Towers

both with a GD program for CAD (henceforth, designated AT-CAD) and a GD program for BIM (henceforth, designated AT-BIM).

One major difference is that, contrary to a CAD tool, a BIM tool does not just create geometry; it creates digital representations of building components containing all the semantic information related to that component (AGC, 2005). As an example, consider generic slabs and walls: although they are geometrically similar, they are semantically different and, in a BIM tool, they must be created using different operations.

Fortunately, to increase the legibility of programs, good programming practices already promote the use of intermediate abstractions. For example, to make AT-CAD more legible, we implemented different user-defined functions for each building component, namely slabs and walls. These abstractions, although useful for organising the program, do not have any additional effect on the CAD tool besides the creation of the corresponding geometric objects. However, in the case of a GD program for BIM, the abstractions are, in fact, pre-defined operations and, thus, transfer the intended semantics to the generated objects. A positive side-effect is that, by dispensing the intermediate user-defined abstractions, AT-BIM becomes smaller than AT-CAD.

Pre-modelled building components are another difference between GD for CAD and GD for BIM that makes the creation of these components easier, since their geometry does not need to be created from scratch. For example, a door can be selected from a BIM library, while in CAD all of its subcomponents might need to be modelled. To overcome this disadvantage, CAD tools can import external blocks that are pre-modelled shapes or forms which can facilitate the design process of complex geometry. However, typically, these objects are not as parametric as the ones available for BIM tools, restricting the designer's ability to manipulate the geometry as they see fit.

Finally, BIM tools are more restrictive in the manipulation of the geometry of created objects and, as such, have several limitations regarding, e.g., Boolean operations. Nonetheless, we found such operations to be useful in the modelling of the Absolute Towers, namely in the adaptation of the walls to the rotation of the slabs which results in different wall lengths in every floor, as is visible in Figure 3. Using CAD tools, this could be achieved with an intersection between the walls and the volume corresponding to the interior of the building in each floor. Using BIM tools, the same had to be done using a different method: we implemented intersections between walls and slabs which compute the length of the walls in relation to the outline of the slab.

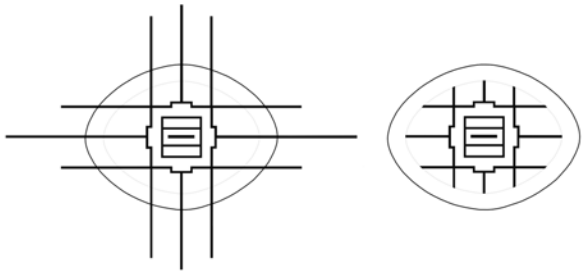


*Figure 3. The length of the walls is computed by an intersection with the slab represented by a grey line.*

## 4.2. PORTABILITY

In order to evaluate the portability of RosettaBIM, we tested it with a GD program that generates one of the Absolute Towers and we compared the generated models in the two supported BIM tools (Figure 4).

Given that the data from the used operations is manipulated by the plug-ins to meet the tool's requirements, we noted that the generated building components are created with the attributes that are relevant for each BIM tool. For example, whereas the slab created by RosettaBIM in Revit belongs to a Revit family and possesses its properties, the same slab created in ArchiCAD has properties according to the structure of the created slab.

Although we were able to normalize most operations, there are specific operations that are substantially different between Revit and ArchiCAD. For example, Revit allows the specification of an object's family, while ArchiCAD allows the specification of an object's properties. The corresponding BIM-specific implementation of these operations reflect these differences by accepting either a family, in the case of the Revit back-end, or the properties values, in the case of ArchiCAD. However, we also provide default values for all these parameters so that the generic use of the operation becomes identical in both back-ends, making the code portable and mitigating the differences between back-ends.

In order to further test RosettaBIM's portability, we compared it to another alternative based on the generation of the desired model in one BIM application and its transfer to another one via IFC. We tested the viability of this alternative in both directions: from ArchiCAD to Revit and conversely.

When transferring from ArchiCAD to Revit, although the geometry of the building remained the same, there were inconsistencies in the transferred building components. For example, the stair element, despite being named as such, did not have an associated Revit family.

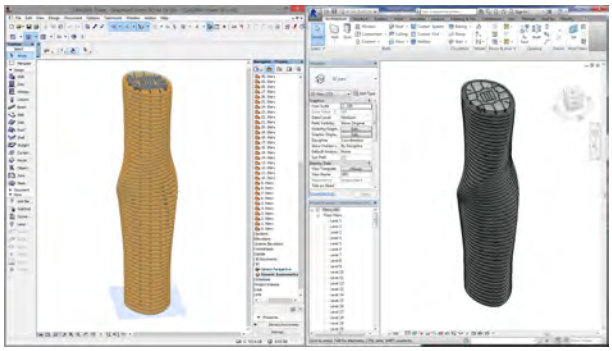


*Figure 4. The Absolute Tower generated in ArchiCAD (on the left) and Revit (on the right).*

Regarding the transfer from Revit to ArchiCAD, there were problems in the correct identification of some objects. Such was the case of roofs and stairs that lost their BIM properties, turning them into generic objects. In addition, the transferred stairs used a generic IFC material that did not match the original one.

### 4.3. ADVANTAGES OF GD FOR BIM

RosettaBIM provides GD for BIM applications, that is, an Algorithmic-based Building Information Modelling, which we name A-BIM. Given its potentially disruptive nature, it is important to identify the advantages that A-BIM can bring to the BIM paradigm.

A-BIM creates a paradigm shift in the design process, since the designer, instead of constructing the model directly in the BIM application, constructs the algorithm which generates the model in the BIM application.

Due to its algorithmic origin, the generated model is highly parametric, allowing us to easily experiment with different values of parameters, producing a wide range of possibilities that can be explored and evaluated. This is visible in Figure 5, where we explore different shapes for the tower's slabs.

In addition, because the generated objects are parametrically interdependent, changes are propagated to the entire model. Although this feature is not exclusive to A-BIM, it is more flexible than the one typically available in BIM tools. For instance, whilst in manual BIM a change in the torsion angle of the tower requires the manual update of all building components, in A-BIM it is possible to automatically propagate that change to all building components, with the result visible in Figure 5.

Although our approach allows the exploration of parametric models, it requires programming knowledge and an initial investment to produce the algorithm, which might take more time than producing the model manually.

On the other hand, this initial effort can be rewarded in projects where a high level of exploration is required or in highly parametric buildings.

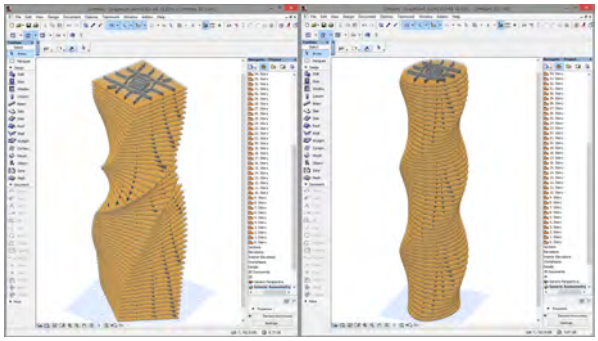


*Figure 5. Absolute Tower variations. On the left: different slab shapes. On the right: different torsion angle.*

## 5. Conclusion

RosettaBIM implements portable GD for BIM. This is achieved by an abstraction layer that provides normalized operations for every supported BIM application. However, when necessary, the user can relinquish this portability in favour of accessing tool-specific features.

In order to use RosettaBIM, users need programming skills and an initial time investment for the development of the GD program. This might be seen as a barrier, but the rewards of this investment become clear as the project grows and reaches a higher complexity. This is noticeable in projects where design exploration and frequent changes are a requirement.

RosettaBIM, by supporting GD for BIM, introduces changes in the way GD programs are written compared to how they are written in GD for CAD. Given that the modelling operations in BIM have semantics and introduce dependencies between objects, this requires the user to organise his program in a way that respect those dependencies.

In this paper, we demonstrated that RosettaBIM supports the development of portable GD in the BIM context by showing an algorithmic version of the Absolute Towers that creates equivalent models in two different BIM applications. Also, every generated building component has the corresponding properties that are appropriate for each BIM application.

Furthermore, we showed that the commonly accepted alternative for portability – the IFC data model – still has problems, such as loss of information. Be that as it may, IFC would not be the ideal solution for porting models generated by programs, since any modification would require the generation of the model in one tool just to transfer it to the other one.

With RosettaBIM we can explore a methodology for GD in the BIM paradigm that we name A-BIM, acronym for Algorithmic-based Building Information Modelling. Using this methodology, we could achieve a higher degree of flexibility than what is possible with the manual approach.

In the future, we will expand RosettaBIM to support more BIM tools as back-ends, such as Digital Project or Microstation; and add more modelling operators and constraints, allowing the generation of more complex models.

## Acknowledgements

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# MÖBIUS

*A parametric modeller for the web*

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**Abstract.** For complex parametric modelling tasks, systems that use textual programming languages (TPLs) currently have clear advantages over visual programming languages (VPLs) systems. Their support for a rich variety of programming mechanisms means that the complexity of the program can remain commensurate with the complexity of the modelling task. A prototype parametric modelling system called Möbius is presented that aims to overcome the limitations of existing VPL systems. The proposed system integrates associative and imperative programming styles and supports iterative looping and higher order functions. In order to demonstrate the versatility of the Möbius, a modelling task is presented that requires the model to be modified.

**Keywords.** Parametric procedural modelling; generative design; visual programming; human-computer interaction.

## 1. Introduction

Parametric modelling is a form of programming. Two types of programming languages are Textual Programming Languages (TPL systems) and Visual Programming Languages (VPL systems) (Myers, 1990). Historically, the debate surrounding TPL systems versus VPL systems has not been conclusive, with researchers arguing in favour of both approaches (Menzies 2002). TPL systems are continuing to evolve rapidly and are becoming more user-friendly due to simplifications in syntax and improvements in the IDEs (Leitão et al, 2012). The evolution of VPL systems on the other hand seems to be slower.

In the design domain, a number of parametric modelling systems use VPLs for generating models. However, these systems are known to have

poor scalability (Stouffs and Chang, 2010; Park and Holt, 2010; Janssen and Chen, 2011; Chok, 2011; Leitão et al, 2012; Janssen, 2014) due to their weak support for fundamental programming mechanisms. Two important mechanisms are iterative loops and higher-order functions.

Iteration refers to mechanisms for repeating a sub-procedure, and includes for loops, while loops and recursive function calls. VPL systems for parametric modelling typically use a graph-based programming approach consisting of nodes and wires, and as a result do not support iteration very well. With dataflow and procedural modelling systems, it is possible to create models that incorporate iterative procedures (Janssen and Stouffs, 2015). McNeel Grasshopper is an example of a dataflow system, while SideFx Houdini is an example of a procedural system. However, creating sophisticated types of iterations in these types of systems (such as nested loops) remains prohibitively difficult (Janssen and Stouffs, 2015).

Higher-order functions refers to any functions that take another function as an argument or returns a function as a result. In parametric modelling, such functions can be very useful as they allow components in the design to be represented and manipulated using functions (Leitão, 2014). Most VPL systems do not support higher-order functions. Two recent exceptions are Autodesk Dynamo and Autodesk 3DS MCG. However, the dataflow interface makes it difficult to leverage the full power of higher-order functions. Another powerful parametric modelling system that specifically supports higher-order functions is Rosetta (Lopes and Leitão, 2011), but this is actually a textual programming system.

Another important aspect that needs to be considered is the learning curve. The context for this research is the Department of Architecture at the National University of Singapore. During the last seven years, electives have been taught teaching both Grasshopper and Houdini. Typically, students need to both learn the tools and apply them in an architectural design project within a single 12 week semester. For both VPL systems, this proved to be very challenging. In the electives teaching Grasshopper, students could make simple models quite quickly, but once more complex parametric tasks were attempted, the learning curve quickly steepened. In the electives teaching Houdini, students found the initial learning curve to be quite steep, but then discovered that some quite complex tasks were easily achievable. Nevertheless, with further increases in parametric complexity, the learning curve again steepened. Thus, although the learning curve for TPL systems is typically higher than VPL systems, the experiences with Grasshopper and Houdini show that learning these VPL systems to a level required for complex parametric modelling is also very time consuming.

A related issue with current VPL systems is that they do not allow for a graceful progression towards learning a TPL (Aish, 2013). Given that TPLs may always have certain advantages over VPLs, it would be desirable if the use of a VPL system would allow users to gradually start to learn TPL concepts. This would allow expert users of the VPL system to transition over to a TPL without having to restart their learning process from scratch. However, the concepts used in most graph-based VPL systems have limited relevance when learning textual programming.

For complex parametric modelling tasks, TPL systems therefore currently have clear advantages over VPL systems. Their support for a rich variety of programming mechanisms means that the complexity of the program can remain commensurate with the complexity of the modelling task. However, it may be possible to overcome many of the shortcomings of existing parametric modelling VPL systems. This research has developed a prototype VPL system called Möbius for creating complex procedural models. One of the key objectives is to create a system that students can become proficient in within one 12 week semester. This proficiency should go beyond simple 'toy' models, and should allow students to build parametric models that incorporate complex nested iterative loops and higher-order functions.

Section 2 will describe the key features of Möbius, and Section 3 will present an experiment that demonstrates the versatility of Möbius. Finally, section 4 discusses future work.

## 2. System overview

Möbius is a web-application that runs in the browser on the client side. As a result, Möbius is platform independent and there is no need to install software. Figure 1 shows the Möbius user interface.

Möbius will be introduced using the Killian Roof modelling task as an example, based on a tutorial for Generative Components developed by Axel Kilian in 2005. The task consists of building a simple parametric roof with a diagrid structure (Woodbury at al, 2007). The ridge of the roof remains at a constant height while the base of the structure varies in height in response to an undulating ground surface. An instance if the Killian Roof is shown in Figure 1.

Möbius integrates imperative and associative programming styles. The imperative style of programming is supported through blocks-based programming, where the user constructs procedures by creating sequences of code blocks (Resnick et al, 2014). The associative style of programming is supported through dataflow programming, where the user constructs net-

works consisting of nodes and wires. Each node has an imperative procedure that is defined using the blocks-based approach.

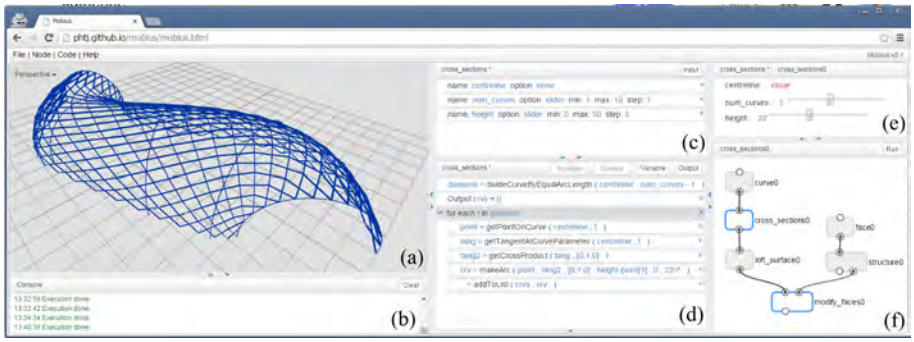



*Figure 1. The Möbius interface, showing a model of the Killian roof.*

## 2.1. IMPERATIVE PROGRAMMING

Nodes have types and instances. A node type is defined by specifying a procedure with a set of input and output ports. Each node type can have multiple node instances, all of which will have the same procedure with the same input and output ports. The input and output data for each instance will differ.

Node procedures are defined with the imperative programming style, using panes (c) and (d) in Figure 1. Pane (c) is used to define the input ports for the node type. Pane (d) is used to define the procedure and output ports for the node type using the blocks-based programming approach. In the example in Figure 1, the procedure and inputs for the *cross_section* node type are shown.

In the procedure pane, Möbius provides buttons to create five types of code blocks. Variable blocks define new variables. Function blocks call a specific function, selected from a drop-down list. Looping blocks create loops such as *for-each* loops and *while* loops. Conditional blocks create *if-then* conditions. Finally, output blocks create output variables, which result in node output ports being added to the node.

Once a code block has been created, the user can customize the block by clicking on the links and typing in values. For example, in Figure 1(d), the first code block is a function block that calls the function *divideCurveByEqualArcLength*. The user has created a variable called *divisions* to store the result, and has edited the function arguments.

When defining variable values or function arguments, the user can enter single-line Javascript expressions. These expressions avoid the need to have code-blocks for simple operations such as arithmetic operations. Expressions

can also be used to navigate topological data structures that link geometric entities such as vertices, edges, and faces. This allows lower level entities to be extracted from higher level entities using simple expressions that navigate through the data structure. For example, the expression *'mesh.faces[3].vertices[0].z'* will return the z coordinate of the first point of the of the fourth face in the mesh. This ability to extract specific pieces of data from deep within geometric objects significantly simplifies the procedures.

## 2.2. ASSOCIATIVE PROGRAMMING

Node networks are defined by placing and wiring together a set of node instances. At the network level, these node instances are treated as black boxes.

The node network is defined with the associative programming style, using panes (e) and (f) in Figure 1. Pane (e) is the node parameters pane, and is used to set certain input values for the node instance selected in pane (f). Pane (f) is the network pane, and is used to define the dataflow network. The inputs to a node instance can either be defined by connecting a wire to the input port (in which case the parameter will be hidden), or by entering a specific parameter value through the user interface widget. In the example in Figure 1, the *cross_section0* node instance is selected, and the parameters being shown are therefore for this node.

When the dataflow network is run, the network is converted into a single Javascript program that is then executed in one go. This represents a synchronous type of execution, where the nodes are first topologically sorted and then executed in a fixed sequence. This differs from most other dataflow system, where nodes are executed asynchronously in response to changes to their inputs.

The generation of a textual program from the dataflow network has the advantage that it allows a wide range of more advanced programming mechanisms to be used. Two mechanism will be described in more detail: iterative loops and higher-order functions.

## 2.3. ITERATIVE LOOPS AND HIGHER ORDER FUNCTIONS

Iterative loops can be created at both the procedure level and the dataflow level. At the procedure level, users can easily define nested loops using the blocks-based programming style. However, it may also be necessary to create loops at the dataflow level. For example, when creating performance-based models, dataflow networks may need to be repeatedly executed in an iterative optimization process. Creating iterative loops at the dataflow level

is possible due to the fact that all nodes are also callable as functions. This means that a procedure inside one node can include function blocks that call other nodes.

Higher order functions are supported by an additional output port which returns a reference to the function that wraps the procedure for that node. When this output is wired into another node, it results in a dashed wire, which indicates to the user that it contains a reference to a function rather than actual data. These wires can be used to provide a function as an input to another downstream node. That node can then have a procedure that executes that function.

The dataflow network for the Killian Roof example, as shown in Figure 1(f), includes a higher-order function to create the diagonal struts. This function takes a single mesh face as an input and generates two diagonal struts. The *modify_faces0* node uses this function to replace each mesh face with diagonal struts.

## 3. Experiment

In order to demonstrate the versatility of the Möbius, an example developed by Leitão et al (2012) is used. The modelling task consists of two phases: (1) implementation of a parametric model to create a structure made of cylindrical spirals; and (2) the modification of the original model to create sinusoidal variations of the cylindrical spirals. The aim of the two-phase experiment was to investigate how easily users were able to adapt the phase 1 model to the new requirements in phase 2.

In the experiments conducted by Leitão et al (2012), a user-based study was conducted to compare a TPL system with a VPL system. The TPL system was Rosetta (Lopes and Leitão, 2011) (using VisualScheme as the textual language) and the VPL system was Grasshopper. Six designers with varying levels of expertise were asked to complete the modelling tasks, and the resulting models and modelling times were compared. The results showed that the models created with Rosetta were easier to understand and significantly more adaptable than those created with Grasshopper.

The aim of revisiting this example is to demonstrate that while it is true that Rosetta models are more adaptable than Grasshopper models, this cannot necessarily be generalizable to all TPL and VPL systems. As discussed in the introduction, Grasshopper suffers from restrictive mechanisms that make it difficult or impossible to tackle complex parametric modelling tasks without resorting to scripting. Möbius is much less restrictive and as a result Möbius models are more easily adapted.

### 3.1. PHASE 1: CYLINDRICAL SPIRAL TOWERS

In the first phase, the task is to create a parametric model capable of generating the structures shown in Figure 2a.

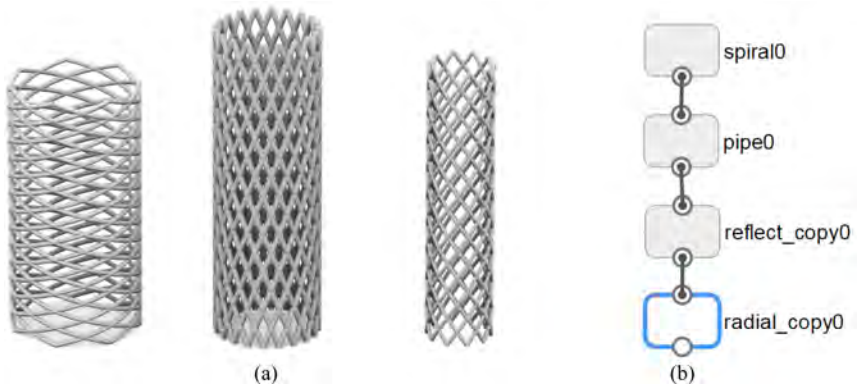



*Figure 2. (a) Phase 1 cylindrical spiral towers (taken with permission from Leitão et al, 2012). (b) Möbius dataflow network for phase 1.*

In Möbius, this can be achieved in many different ways. In this example, we implement what might be considered as the most straightforward approach within Möbius.

The first decision the user needs to make is how to apply associative and imperative programming styles. This comes down to the question of how many nodes to create. In general, it is possible to implement everything in one complex node, or to implement many simple nodes. The most desirable approach is to create a small number of modular reusable nodes.

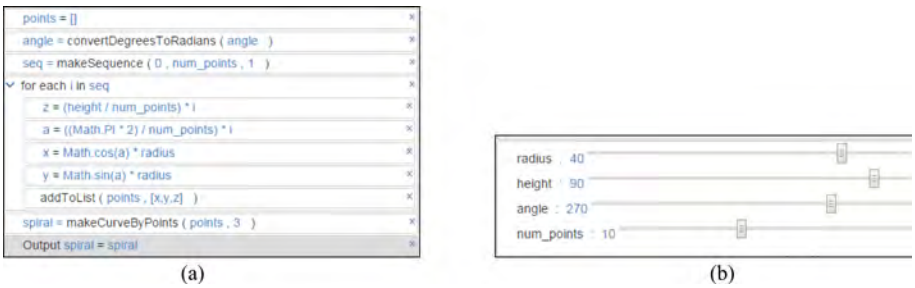



*Figure 3. (a) Procedure for the spiral node. (b) Parameters for the spiral node.*

In this case, four nodes are created, as shown in Figure 2b. All four nodes are highly generic and reusable. The *spiral0* node creates spirals, the *pipe0* node creates pipe surfaces from curves, the *reflect_copy0* node creates a copy of objects by reflection, and the *radial_copy0* node creates radial cop-

ies of objects. The procedure for the spiral is shown in Figure 3a. Figure 3b shows the parameter interface for the same node.

### 3.2. PHASE 2: SINUSOIDAL CYLINDRICAL SPIRAL TOWERS

In the second phase of the experiment, the parametric model needs to be modified in order to be able to create the structures shown in Figure 4a. Only the spiral node needs to be modified so that the radius variable in the procedure (see Figure 3a) changes with height. The easiest way to achieve this is to use a higher-order function.

The modified dataflow network is shown in Figure 4b. The *radius_func0* node takes a height factor as an input and outputs the radius. The procedure for this node is shown in Figure 5a. The calculation combines a linear function and a Sine function. The parameters for the linear function are the radius at the top and bottom of the structure. The parameters for the Sine function are the frequency and amplitude of the sinusoidal wave.

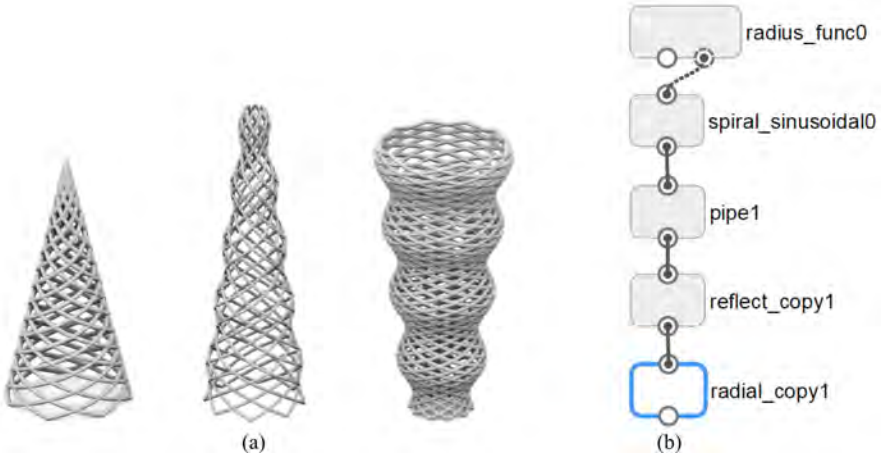



*Figure 4. Phase 2 sinusoidal cylindrical spiral towers (taken with permission from Leitão et al, 2012). (b) Möbius dataflow network for phase 2.*

The modified *spiral_sinusoidal0* node is almost the same as the original spiral node. The procedure is shown in Figure 5b. The only difference is that the radius is replaced by the radius function.

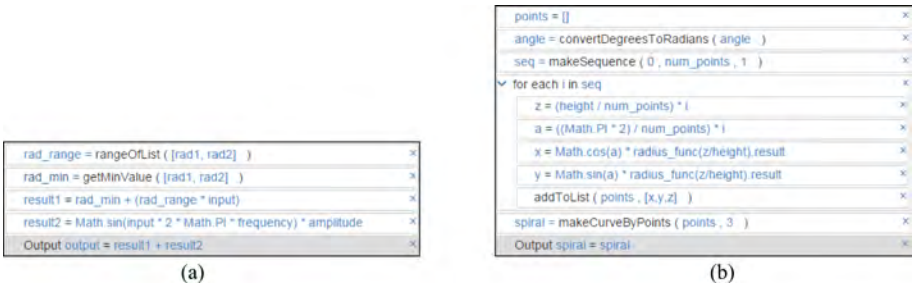



*Figure 5. (a) Procedure for the 'radius_func0' node. (b) Procedure for the modified 'spiral_sinusoidal0' node.*

### 3.3. EVALUATION

The example demonstrates that the complexity of the dataflow networks and procedures created using Möbius remain commensurate with the complexity of the modelling task. As a result, the model is relatively easy to modify and adapt. For users that have learnt certain basic concepts of higher order functions, the transition from phase 1 to phase 2 can be implemented in a way that is natural and intuitive.

One of the key objectives of developing Möbius is to have a system that students can become proficient in within a 12 week semester. At this stage of the research, no user studies have been conducted yet and this objective can therefore not yet be evaluated. The two examples above were used as a preliminary test of the Möbius VPL. In the future, Möbius will be used as a tool for teaching parametric design. User studies will then be conducted for a variety of modelling tasks, allowing further data and feedback to be gathered.

An additional benefit of using Möbius is the fact that the creation of procedures using blocks teaches users the basic concepts of textual programming. As users become more experienced, they can then gradually transition over to textual programming.

## 4. Future work

Möbius is under active development, and various additional components and user interface enhancements are being worked on. Additional viewers and function modules are being developed for BIM and GIS. Support for debugging parametric models is being enhanced with more visual feedback. In addition to these ongoing development efforts, there are also two more fundamental areas that will be tackled in the future.

First, the execution of the code generated from the dataflow networks will be optimised for performance using memorisation techniques. Traditional dataflow systems have the advantage that they only need to re-execute

nodes whose inputs have changed. However, in Möbius this is not possible due to the fact that code is generated for the whole dataflow network and then executed as one standalone script. Memorisation is an optimization technique that stores the results of function calls and returns the cached result when the same inputs occur again.

Second, the current Javascript geometry libraries will be replaced by more complete geometry engines supporting a wider range of geometric functions. Möbius currently uses the Verbs geometry library developed by Peter Boyer (http://verbnurbs.com). Future geometry engines being explore include OpenCascade (http://www.opencascade.com) and CGAL (http://www.cgal.org).

## Acknowledgements

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# REVEALING PATTERNS

*Using parametric design patterns in building façade design workflow*

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**Abstract.** The objective of this paper is to provide a way of viewing design knowledge imbedded in the design workflow. By reviewing known design projects, we have observed common occurrences of design patterns in different stages of parametric façade design workflow. We demonstrate the application of parametric design patterns in practices as preliminary studies of forming a pattern language of parametric design.

**Keywords.** Design pattern; parametric design; façade design.

## 1. Introduction

Using parametric design tools to generate building envelopes is becoming a common practice. Parametric modelling plays an important role in the façade design workflow through stages of conceptual design to construction. We are interested in documenting the knowledge of building façade designs. Design patterns have been shown to be a good way of recording knowledge of parametric modelling (Qian et al, 2007; Maleki and Woodbury, 2008; Woodbury, 2010). By tracing the design patterns used in known cases and by testing patterns in our own practices, we demonstrate a way of viewing a design project and its workflow.

Design projects benefit from a fabrication-informed design process where an early integration of construction concerns is emphasized. In a fabrication-informed digital design process, methods of pre-rationalization and post-rationalization have been widely discussed (e.g., Attar et al, 2010; Dritsas, 2012; Vrouwe and Van Swieten, 2013). Rationalization is a key task in architectural design workflow. In the conceptual design stage, before rationali-

zation, schematic designs are often created from unlimited conceptual and geometric explorations. After rationalization, designs are modified to fit in known geometric principles and construction techniques. By observing the process of rationalization, we hope to obtain design knowledge and relate the rationalized design outcomes to their initial schematic designs.

This paper presents a midterm result from an ongoing research. We have implemented a pattern-based knowledge repository of parametric design (Chien et al, 2015) and are continuously collecting examples and cases to illustrate applications of design patterns. We envisage the formulation of a pattern language of parametric design by means of identifying design patterns used in known design projects, as well as demonstrating their applications in our own practices.

## 2. Background

Woodbury and his colleagues pioneered the research on design patterns for parametric modelling (e.g., Qian et al, 2007; Maleki and Woodbury, 2008; Woodbury, 2010). Referencing on their works, Hudson (2010) demonstrated through uses of design patterns for different design stages. Caetano, Santos and Leitão (2015) presented a framework with various strategies for façade designs. Design patterns offer potentials for parametric design strategies and in building façade design workflow. Moreover, design patterns provide opportunities for forms of motifs or ornaments that may emerge from the subdivided or modular in construction of building façades or cladding systems.

The power of design pattern methodology, beyond individual design patterns, lies in the formation of pattern languages. A critical point of forming pattern languages is the relationships between patterns (Zimmer, 1995, Noble, 1998). Kruschitz and Hitz (2009), Schobert and Schümmer (2006), and Schümmer (2003) illustrated various ways of visualizing the relational structure (or network) within a pattern language to assist designers navigating in the network and search for relevant patterns. We see the visualizations of pattern network a key step to turn parametric design pattern collection into a pattern language. Our research team has tried to illustrate pattern-network of a design project with an overview diagram showing the evolution of parametric models driven by applications of design patterns (Chien et al, 2015).

## 3. Building façade design workflow

In a digital design workflow, parametric design patterns can be used repeatedly and varyingly in stages of concept development, design development and design documentation. The concept development stage involves form finding from site context to explore ideal designs. The design development

stage includes surface representations and rationalizations. Rationalization is a parametric task and plays an important role in design problem solving. During rationalization, parametric modelling is a powerful tool to generate design alternatives and conduct quick evaluations. Selections of solutions are based on criteria related to performance, ease of construction, budget requirements, aesthetic principles and so on. The results then drive the revision towards to a rationalized design rapidly. Lastly, in the design documentation stage, information management is important since the construction materials for parametric façades are usually more complex than those of conventional façades.

## 4. Applying parametric design patterns

To investigate the application of parametric design patterns, we have conducted studies of parametric design patterns in known design cases, by recreating parametric models of building façades through deliberate uses of design patterns. Figure 1 illustrates a result of our studies.

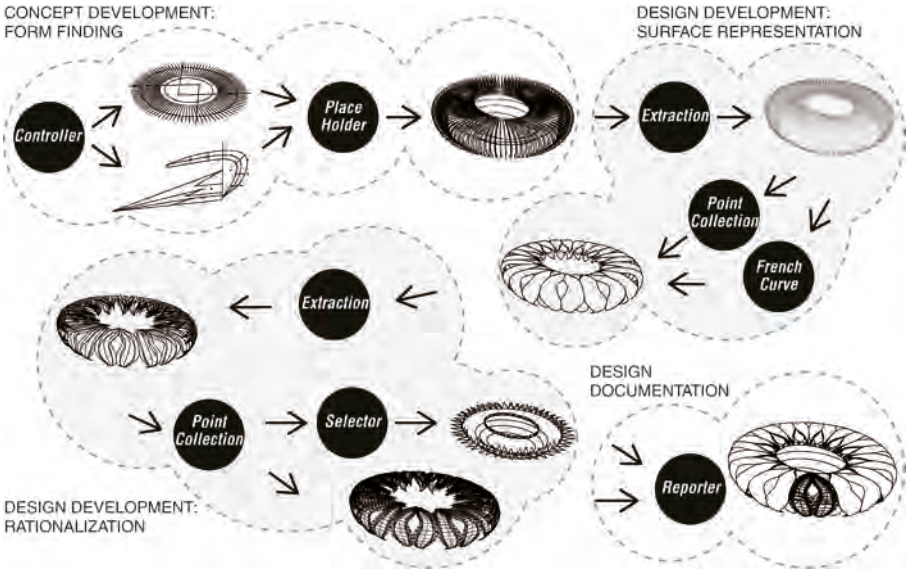



*Figure 1. An overview diagram of patterns used in a case (Hangzhou Stadium).*

Among the cases we studied, three of them were investigated extensively because we have acquired more design workflow data. The cases are Wulai Parking Structure (WPS), Swiss Re Building (SRB) and Hangzhou Stadium (HS). We have observed common occurrences of design patterns in different

stages of parametric façade design workflow, as well as common combinations of design patterns (Table 1).

Table 1. Patterns used in parametric facade design workflow

| | CONCEPT DEVELOPMENT: FORM FINDING | DESIGN DEVELOPMENT: SURFACE REPRESENTATION | DESIGN DEVELOPMENT: RATIONALIZATION | DESIGN DOCUMENTATION | |
|---|---|---|---|---|---|
| WPS | *Jig* | *Point Collection* | *Extraction*<br>*Point Collection* | *Extraction*<br>*Reporter* |  |
| SRB | *Controller*<br>*Mapping* | *Increment* | *Extraction*<br>*Point Collection* | *Reporter* |  |
| HS | *Controller*<br>*Place Holder* | *Extraction*<br>*Point Collection*<br>*French Curve* | *Extraction*<br>*Point Collection*<br>*Selector* | *Reporter* |  |

In the form-finding stage, the *Jig* and the *Controller* pattern (Woodbury, 2010) are applied in all cases. The combination seems to be a common way to relate and translate abstract concepts to geometries. Using geometries derive from a controlled system is a basic practice of parametric design. For example, the façade of WPS took shape through three principle horizontal curves, and its form is enclosed by vertical bars. We employed *Jig* (using the silhouette of the mountains as the jig) to guide the formation of the three principle curves.

The *Place Holder* pattern (Woodbury, 2010) is often applied in the early design development stage (Hudson, 2010). Before rationalization, an ideal design using *Place Holder* can easily express continuous differentiations, which is the main feature of parametric design (Jabi, 2013). However, its related pattern, *Jig*, can be further applied at the rationalization stage. The *Jig* pattern serves a model with preciseness and associated construction techniques.

The *Extraction* pattern (Lai, 2011) and the *Point Collection* pattern (Woodbury, 2010) are key patterns when working on building façade subdivision at design development stage. Based on intention, different surface information is first extracted and then *Point Collection* is used to re-order the extracted data to fit various situations. Therefore, an architectural surface representation is basically implemented.

The *Extraction* pattern (Lai, 2011) and *the Reporter* pattern (Woodbury, 2010) are usually used in making design documents. Therefore various data

for prefabrication and construction can be extracted and generated separately to spread sheets. In the case of City Hall in London, this technique is used to layout the glazing panels in a flatten pattern, scheduling areas and listing panel node coordinates (Whitehead, 2003).

The *Recursion* pattern (Woodbury, 2010) can be applied when working with hierarchies in design. It may appear not only in the programming interface but also the visual order in model. The façade design for Dongdaemun Design Park and Plaza in Seoul demonstrates the recursive grid visual order which is derived from both aesthetic principles and engineering constraints (Schumacher, 2014).

## 5. Parametric systems in building façade design

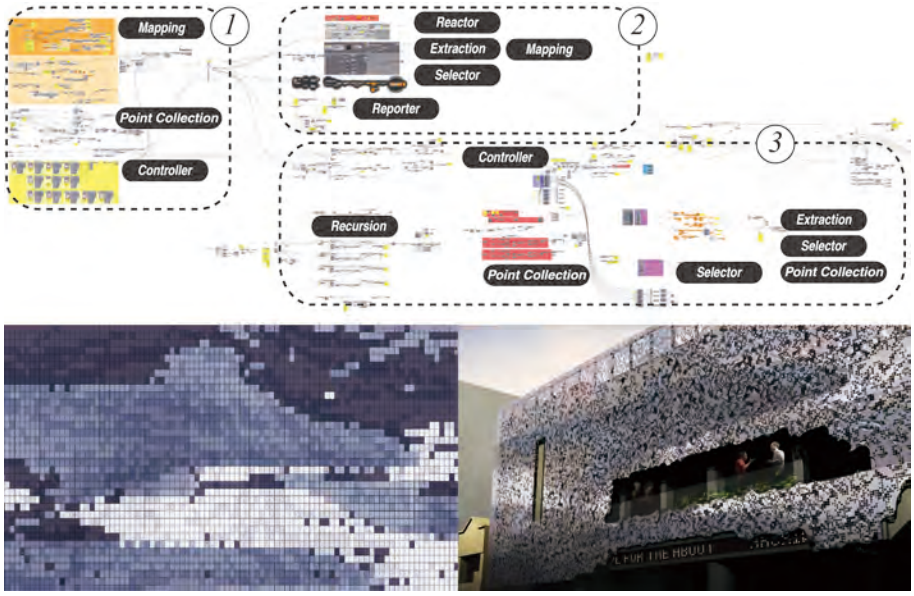



*Figure 2. Patterns employed in PGS façade design workflow.*

Besides recreating parametric models of known projects, we deliberately employed parametric design patterns throughout our own projects. Here, we report, in depth, on the façade design of Project Grand Stage (PGS). PGS is a double-skin façade renovation project. The *Controller*, *Mapping* (Woodbury, 2010), and *Point Collection* patterns were used in the concept development stage for form finding (e.g., Area 1 in Figure 2). The *Extraction*, *Reactor* (Woodbury, 2010), *Mapping*, *Selector* (Woodbury, 2010) and *Reporter* patterns were used for processing of surface information (e.g. Area 2 in Figure 2), while the *Recursion*, *Controller*, *Point Collection*, *Selector*, *Extrac-*

*tion* and *Reporter* patterns were repeatedly used for rationalization in the design development stage (e.g. Area 3 in Figure 2). The *Extraction*, *Point Collection* and *Reporter* patterns were used in the design documentation stage.

## 5.1. FORM FINDING IN DATA SPACE

During the concept development stage, the *Controller* pattern was used to set up a friendly interface to manipulate light sources in clusters or individually. We envisaged a surface that is deformed by lights. A parametric system was developed to simulate how the surface can be pulled by two opposite forces, that is, the intensity and the condition of lighting from the external environment and the internal spaces.

The lighting conditions of external environment were formulated from the location defined by azimuth, altitude, and orientation, as well as reflectiveness of surrounding buildings. The lighting conditions of internal space were derived from the volume and utility of each space (Figure 3, left). Sunlight is the primary lighting source externally, in particular, from southwestern direction with the given PGS site. From internal spaces, for each volume, a representative light source, based on illumination requirements of proposed utility of each space, could be turned on or off.

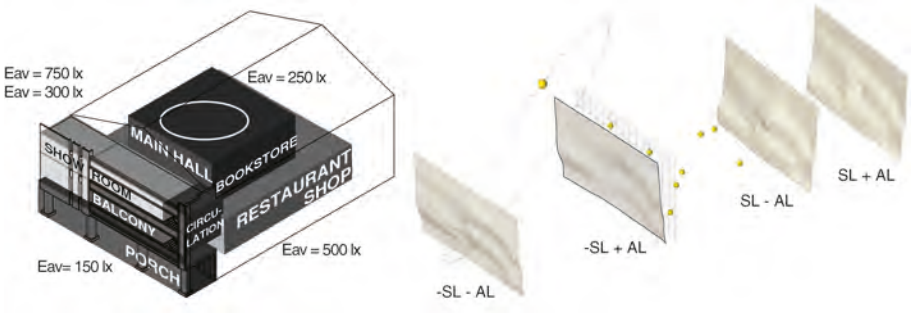



*Figure 3. A diagram of proposed utility and its average illumination (left). Surfaces pulled by forces from opposite directions (right).*

The *Mapping* pattern was always used in the process of abstraction and simplification. The *Point Collection* pattern was used for sorting data in various ways to address different needs. These patterns provided us the ways to work on numerical data calculations and transmissions that were initially vague and complicated. In PGS, we simplified the façade plane into an image of 5400 pixels arranged in 60 rows and 90 columns. Different types of data, such as solar radiation, artificial illumination and collision status with existing façade, were processed separately. The façade of PGS was deter-

mined with the consideration of streetscape, self-shading during day, and light effect at night (Figure 3, right).

## 5.2. REPRESENTATION OF SURFACE INFORMATION

In the design development stage, the *Extraction*, *Reactor*, *Recursion*, *Mapping*, *Selector* and *Reporter* patterns were used for representations of surface information. These patterns afforded different ways of extracting information form the façade surface. For PGS, we used cellular automata to generate perforation patterns (Figure 4, right). The *Selector* was used for deciding the distribution of perforation densities. Three zones were defined by filtering values of lighting intensity related to the solar radiation, existing façade opening and proposed average illumination (Figure 4, left).

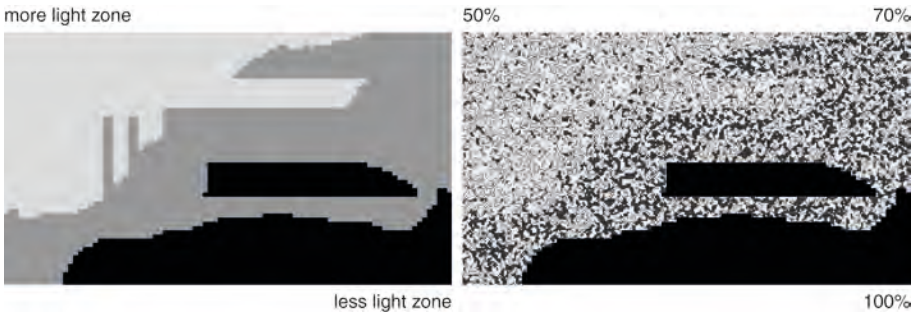



*Figure 4. Three zones were defined by filtering values of lighting intensity (left). Distribution of various perforation densities on the whole surface (right).*

By setting attractors and using *Reactor*, we could visualize the gradient in multiple ways. The gradient trails and contour lines were further developed into carving texture. Colors from bright to dark were picked from site photos and mapped to the surface based on slope gradient to emphasize the mountains and valleys on the surface. Contrast is an important element when people perceive geometries. We kept the maximal and minimal brightness at the same time. But the steps in between were decided through the process of rationalization at later stages.

## 5.3. RATIONALIZATION

The *Recursion*, *Controller*, *Point Collection*, *Selector*, *Extraction* and *Reporter* patterns were repeatedly used for rationalization during the design development stage. For PGS, after considering manufacturing constraints, options for panel assembly system were investigate. To ensure the feasibility of manufacture and construction, panels were designed to be planar and the

size was limited 340 mm in length and 236 mm in width. We used *Jig* (instead of *Place Holder*) to create a seamless modular assembly on the PGS façade. We designed universal joints on edges of the panels so that they could be assembled into large size units.

We used *Recursion* to perform uneven subdivisions (Figure 5). There were two goals in the subdivision stage: to reduce the number of assembly units; and to reduce deviation gap. Using a larger assembly unit could reduce the total number of units. However, using a larger planar unit to compose the free form surface might cause larger deviation gap. So the size of a unit and the number of units were decided by these relevant considerations.

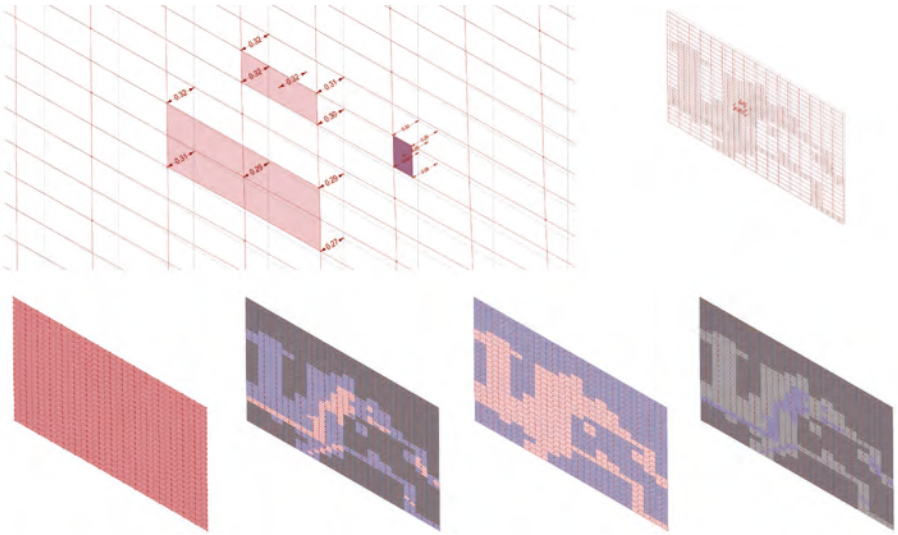


*Figure 5. Uneven recursive subdivision based on slope gradient of the surface.*

## 5.4. DESIGN DOCUMENTATION

In the design documentation stage, the *Extraction* and *Reporter* patterns were used. When continuous differentiation and mass-customization took place in practice, designers and fabricator face many complicated tasks. We managed to extract the geometry and categories of items data, exported to spread sheets and delivered to the fabricator. For PGS, selected samples from design documents were sent to the fabricator for prototyping, and feedbacks of prototyping informed further adjustments of detail designs to fit in construction constraints but without changing the overall design.

## 6. Discussions and conclusion

We tried to identify the parametric design patterns used in design workflow from cases, and applied them in our own practice. We found that a pattern may appear repeatedly in different design stages; a composite of patterns may be often used together. We demonstrated the uses design patterns from concept development, design development to design documentation. In our own case of PGS, more design patterns were used in design development stage (Figure 6). In this stage, the tasks of synthesizing an ideal design and rationalizing it require lots of design efforts. Documenting of these design efforts could not be obtained from case studies of known projects.

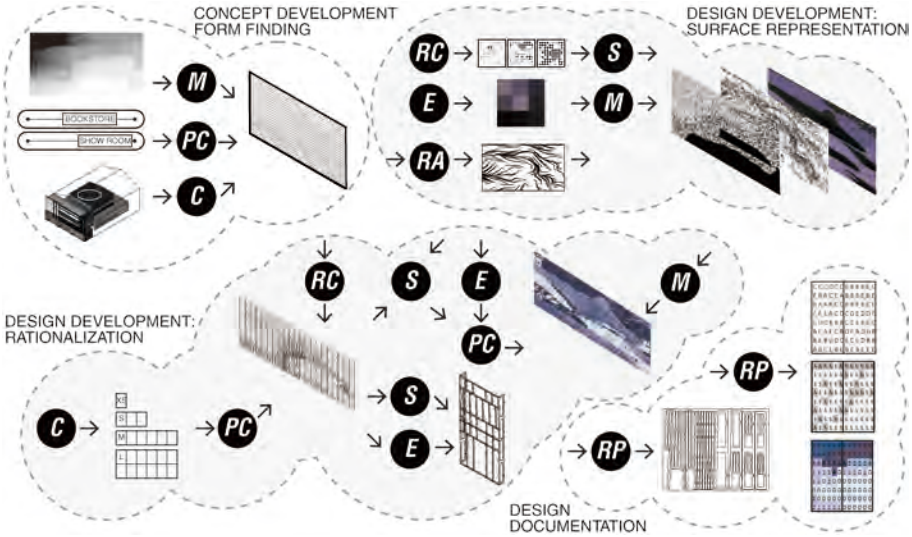



*Figure 6. Overview diagram of patterns application in PGS design workflow.*

There are compositional uses of design patterns re-occurring in our studies. For example, in Table 1, the *Extraction and Point Collection* patterns are repeatedly used together to serve the intension of new creation from existing. In Figure 6, there are design patterns used across early design stages and others for later design stages. The figures seem to hint at a form of grammatical rules.

In summary, we believe there are potentials to turn parametric design pattern collection into a pattern language. We see our demonstrations of using parametric design patterns in practices as preliminary studies of forming a pattern language of parametric design. We hope to reveal more patterns of compositional uses of design patterns in parametric modelling to identify a pattern language of parametric design through our continuing research.

## Acknowledgements

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# BLACK-BOX OPTIMISATION METHODS FOR ARCHITECTURAL DESIGN

*An overview and quantitative comparison of metaheuristic, direct search, and model-based optimisation methods*

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**Abstract.** Black-box optimization methods play an important role in automated design space exploration, but to-date have not been systematically compared on problems from architectural design optimization. This paper presents a quantitative comparison of the three major types of black-box optimization: metaheuristics, direct search, and model-based methods. We compare the performance of one representative algorithm of each type (including a genetic algorithm) on four performance-based design problems of varying complexity and characteristics. Our results show that metaheuristics are greatly outperformed whenever evaluating tens of thousands of design candidates is not an option, and suggest direct search and model-based methods as viable and more efficient alternatives.

**Keywords.** Black-box optimization; simulation; direct search; surrogate models; genetic algorithms.

## 1. Introduction

With parametric design gaining currency among architects (Oxman, 2006), mathematical optimization receives renewed interest as an architectural design tool (Evins, 2013). Once architects have formulated a parametric design, they can quantify some aspects of the designs' performance (for example via numerical simulations) and use an optimization method, such as genetic algorithms, to find designs that perform well with respect to these aspects (e.g., Lin and Gerber, 2014). The mathematical optimization of architectural designs has special relevance with respect to performance-oriented architectural design, which strives for building designs that are

more efficient in terms of their energy and resource consumption. Employing appropriate optimization methods plays an important role in achieving this goal by allowing efficient design exploration even when very complex and time-consuming simulations are necessary. Nevertheless, researchers and professionals have so far given scant attention to the question of which optimization method might be the most effective for architectural design problems, with genetic algorithms appearing as a little reflected upon default choice. This paper presents a broad overview of three types of black-box optimization methods, discusses the pros and cons of these types, and provides a quantitative benchmark based on a set of four design problems.

## 2. Three types of black-box optimization methods

Mathematical optimization encompasses a great diversity of methods, with numerous applications in engineering and operations research. Most of these methods assume some knowledge about the underlying objective function, and especially its rate of change, i.e. the gradient. When one can formulate an optimization problem numerically (i.e., without the use of simulations), such gradient-based or other problem specific optimization methods often present the most efficient choice. But in architectural design practice, an explicit formulation of the objective function and of its gradient often is unavailable. Architectural designers generate and evaluate design candidates employing simulations and other quantitative measures derived from a parametric model (Oxman, 2006) without specifying a closed-form mathematical expression that relates the model parameters to the fitness criterion.

As a mathematician might put it, designers that simulate instances of a parametric model derive values from an unknown, underlying function. One optimizes such unknown functions with so-called black-box methods, especially in cases where it is too time-consuming to estimate the gradient by evaluating a large number of design candidates (Conn et al, 2009; Nannicini, 2015). In other words, optimization problems involving numerical simulations are one of the primary applications of black-box methods. All optimization methods considered in this paper are global, black-box methods, since in architectural practice explicit problem formulations are usually not available. There are three large classes of black-box methods: metaheuristics, direct search methods, and model-based methods. Metaheuristics (Yang, 2010) often rely on randomization and biological analogies, and usually examine p of design candidates; the most famous example is genetic algorithms. Direct search methods (Kolda et al, 2003) tend to deterministically (i.e., in a fixed sequence of steps) examine a series of individual design candidates. Model-based methods (Koziel and Leifsson, 2013) take an indirect approach in con-

structing an approximate model of the underlying black-box function –also known as a surrogate model– that guides the search for better design candidates. We discuss these categories in more detail below. For the benchmarks in this paper, we test one optimization method from each category.

## 2.1. METAHEURISTICS

Metaheuristics, and especially genetic algorithms, are the only optimization methods regularly mentioned in the writings of architectural theorists (De Landa, 2002; Oxman, 2006) and enjoy popularity among both researchers and practitioners (Evins, 2013). In a review of optimization in structural design, Hare et al (2013) even suggest that "evolutionary algorithms may be overused". Beyond theoretical grounds, we identify three possible reasons for this popularity: Metaheuristics are applicable to any problem type, typically easy to implement, and suited to multi-objective optimization (e.g., Lin and Gerber, 2014). Grasshopper™, a visual programming software for parametric design, natively implements a genetic algorithm, as does DesignBuilder™, an integrated 3D modelling, simulation, and optimization package aimed at architects. In our benchmarks, we use the (single objective) genetic algorithm of Grasshopper as one of the three methods we compare.

Nevertheless, the optimization community has remained sceptical of metaheuristics, with Conn et al (2009, p. 9) characterizing them as "methods of last resort". One reason for this scepticism is the lack of mathematical rigor and generally poor performance of metaheuristics in comparative benchmarks (Rios and Sahinidis, 2013). In practice, one often needs to evaluate tens of thousands of design candidates to find a high-quality solution (e.g., Hasançebi et al, 2009). Such slow rates of convergence are especially problematic when evaluations are "costly"; for example, when simulations take minutes, hours, or even days to complete, as is often the case in environmental analyses such as daylighting or wind flow.

## 2.2. DIRECT SEARCH

Direct search methods sequentially examine design candidates according to a deterministic strategy, avoiding the construction of a model for the unknown objective function or its gradient. A well-known direct search method is DIRECT (Jones et al, 1993). DIRECT proceeds by subdividing the design space into hyper-rectangles, excluding those that, based on the estimated properties of the black-box function, cannot contain the global optimum. DIRECT is included in Goat™, a free optimization plugin for Grasshopper, and one of the three methods compared in this paper. Although, on mathematical test problems, state-of-the-art direct search methods typically outper-

form metaheuristics by orders of magnitude (Rios and Sahinidis, 2013) – with performance measured in terms of the improvement achieved with each function evaluation– they are rarely applied in the architectural context, probably due to their lower availability and publicity relative to genetic algorithms.

### 2.3. MODEL-BASED OPTIMISATION

In model-based optimization, one interpolates a mathematical function through known function values, and uses this interpolated function as a model of the unknown fitness landscape. A surrogate model thus provides instant estimates of the performance of design candidates. Model-based optimization strategies alternate between improving the surrogate model (exploration), and using the surrogate as a guide to find good design candidates (exploitation). Model-based methods typically require only a small number of function evaluations, and thus are especially appropriate for cases where such evaluations take a long time. The combination of finding good design candidates and estimating the performance of the whole design space is unique to model-based optimization methods and makes them seem especially appropriate for the architectural design process. The surrogate model allows playful interactions, while the discovered good design candidates provide starting points for further exploration (Bradner et al, 2014). For our benchmark, we employ a prototypical Grasshopper implementation of a model-based optimization method based on Radial Basis Functions (RBF) (Regis and Shoemaker, 2007). This implementation relies on the RBFOpt optimization library (Costa and Nannicini, 2014).

## 3. Benchmark problems

This section discusses four benchmark problems –two from structural design and two from daylighting design– that we employed to compare the three black-box optimization algorithms. The structural optimization literature has previously employed the two structural benchmark problems (Hasançebi et al, 2009), while the two daylighting design problems have been designed by the authors. For these problems, we integrate multiple objectives into a single objective via “soft constraints”. We formulate the problems in Grasshopper, and use the plugins Karamba™ and DIVA™ for structural and lighting simulations, respectively. Originally a parametric modelling software, Grasshopper is increasingly used as a platform for architectural simulation and optimization, often with user-developed plugins providing links to simulation and optimization tools. By employing a software that is well known among architectural practitioners and students as a testbed, we ensure the

relevance of our results for architectural practice. Since this software is based on "visual programming" and does not require explicit programming, we also address concerns about the lack of user-friendly optimization tools for architectural practice (Bradner et al, 2014). Although limited in scope, the selection of the benchmarks problems discussed below provides diversity in terms of the number and type of variables (integer and continuous), problem complexity, evaluation time (i.e., the time required for one simulation run, see table 1), and problem domain. Despite the limited size of the test bed and to the best of our knowledge, the three different types of black-box optimization algorithms discussed in section 3 and this problem selection provide the most comprehensive comparison of black-box optimization methods in architectural design to date.

### 3.1. PROBLEM 1: 8-VARIABLE STRUCTURAL PROBLEM

The first benchmark problem is employed in the structural optimization literature (Hasançebi et al, 2009) and concerns a small transmission tower with 25 structural members belonging to one of eight beam sets. Each beam set can be assigned one of 30 pre-selected, circular cross sections. The optimization problem consists in finding an assignment of cross sections to the eight beam sets that minimizes the weight of the tower while meeting stress and displacement constraints under horizontal and vertical point loads. In other words, the design problem is to find the lightest selection of cross sections that is structurally feasible, given a fixed geometry and load. As is typical for black-box optimization problems, we formulate the objective function with "soft constraints". Such a problem does not formulate constraints explicitly, but includes constraint violations as penalties in the objective function. We model the objective function f(x) as indicated below, where p(x) are the penalty parameters for constraints of the form c(x) <= $c_{max}$. The parameters $p_{min}$ and $w_p$ are chosen as 0.1 and 200 kg respectively.

$$p(x) = \begin{cases} 0 & c(x) \leq c_{max} \\ \frac{c(x)}{c_{max}} + p_{min} - 1 & c(x) > c_{max} \end{cases} \quad (1)$$

$$f(x) = w(x) + w_p * \sqrt{p_1(x) + p_2(x) + p_3(x)} \quad (2)$$

### 3.2. PROBLEM 2: 22-VARIABLE STRUCTURAL PROBLEM

The second structural design problem, also drawn from (Hasançebi et al, 2009), involves the assignment of cross sections to the 22 beam sets of a braced dome truss. The dome has a diameter of 40 meters and a height of 8.28 meters. This problem is a more complex variant of the previous prob-

lem and considers displacements and stresses for three different load cases. The objective is to minimize the weight of the dome, subject to the two "soft" constraints of displacement and stress and stability of the structural members. Accordingly, the objective function is the same as for Problem 1, but with two instead of three constraints, and $w_p$ as 20 tons.

### 3.3. PROBLEM 3: 15-VARIABLE DAYLIGHTING PROBLEM

In the third problem (first presented in Wortmann et al, 2015), we are searching for a façade configuration that maximizes daylight while avoiding heat gains and glare and maintaining an unified appearance. This problem draws its inspiration from an unrealized design by the Singaporean architecture firm Schröpfer + Hee, and consists of façade components that modulate the harsh tropical sun. Every façade component is 1.25 meters wide and perforated with a grid of 426 circular holes, with a diameter of 50 millimetres each. The holes have "flaps", or micro-louvers, that, for each façade component, can take angles between 0° and 180° (in increments of five). In this way, we standardize the façade components into 37 different types that modulate daylight in a differentiated manner. The optimization problem considers a single room (11.25 by 7.5 meter, with a floor to ceiling height of 4.3 meter), located on the Southwest corner of the third floor of a building in Singapore. The room has two facades, one with nine façade components, and one with six. The optimization problem aims to find a configuration for the fifteen angles of the louvered components that maximizes Useful Daylight Illuminance (UDI) (Mardaljevic et al, 2012). In addition, we penalize design candidates for angle differences larger than 10° degrees between neighbouring façade components, to ensure a coherent appearance of the façade from the outside, and a subtle modulation of daylight on the interior. The penalty function below computes a penalty value pi for an individual façade component with angle di. If the angle difference with the previous neighbour is smaller than ten degrees, the penalty $p_i$ is zero, otherwise it is a squared error term. The objective value to be maximized is the difference of the average UDI u(x) and the sum of the penalties of the fifteen façade components p(x).

$$p_i(x) = \begin{cases} 0 & d_i - d_{i-1} \leq 10° \\ \left(\frac{|d_i - d_{i-1}| - 10°}{170°}\right)^2 & d_i - d_{i-1} > 10° \end{cases} \quad (3)$$

$$f(x) = \bar{u}(x) - \sum_{i=0}^{n} p_i(x) \quad (4)$$

### 3.4. PROBLEM 4: 40-VARIABLE DAYLIGHTING PROBLEM

The final problem also revolves around modulating daylight with a perforated façade, but aims to create a more specific daylighting situation via a more differentiated facade. We consider a single room in Singapore. The rectangular room has a West-facing, 10.8 meter-long and 3.6 meter-high façade, and is 7.2 meter deep. For the façade, we propose a screen with a triangular grid of 426 circular openings. Every opening can have an individual radius between 0 and 5 centimetres, with radii below 0.1 centimetres considered as completely closed.

Varying the radii of these openings creates differentiated daylight conditions inside the room without physical barriers. Specifically, we divide the room into three, 3.6-meter wide zones. The northern and southern zones should be “partially daylit”, which corresponds to a minimum threshold for daylight availability of 150 lux, while the zone in-between them should be “fully daylit”, with a minimum threshold of 300 lux (see Reinhart et al, 2014). Such a zoning of daylight conditions could for example correspond to a partially lit open-plan office space that includes a brighter meeting area.

To avoid controlling each of the 426 openings with an individual variable and to create a graduated, cloudy appearance, we control the openings with a grid of forty “attractor points”. Every attractor point can have a weight between zero and one. To create a soft falloff, we calculate the radius of every opening as the average of the values of all attractor points, weighted according to the inverse cubes of their distances to the opening. This formulation results in a problem with forty continuous variables (ranging from zero to one) and with a maximization objective of the average of the daylight availabilities of the three zones, measured as a percentage (with over-lit areas counted zero).

## 4. Benchmark Results

This section presents benchmark results of the four problems discussed above. We applied standard settings wherever possible to ensure the practical relevance of our benchmarks. We ran the direct search method –Goat (DIRECT)– with standard settings and the genetic algorithm of Galapagos with standard settings for problems one and two, and with a reduced generation size of 25 and without an enlarged first generation for problems three and four to achieve a reasonable number of generations. RBFOpt employed the SRSM algorithm (Regis and Shoemaker, 2007) with 200 samples and a box size for local search of 20%. We ran each problem for a set amount of time (see Table 1).

Table 1. Benchmark Timings

| | CPU | CPU Speed | Function Evals. | Total Runtime | Total Runs |
|---|---|---|---|---|---|
| Problem 1 | Intel i5-4200M | 2.5 GHz | ≈ 45 ms | 600 s | 10 |
| Problem 2 | Intel i5-4200M | 2.5 GHz | ≈ 500 ms | 1,800 s | 5 |
| Problem 3 | Intel Xeon E3-1220 | 3.1 GHz | ≈ 1,500 ms | 14,400 s | 5 |
| Problem 4 | Intel Xeon E5-1620 | 3.6 GHz | ≈ 3,000 ms | 21,600 s | 5 |

On the first problem (see Table 2), the results are relatively close together, with the lightest structure found by Galapagos (220.10 kg). RBFOpt displays the fastest convergence, with an average result after 200 iterations that is only 17 kg heavier than the best solution found (21 kg for DIRECT and 72 kg for Galapagos). RBFOpt performed hundreds, DIRECT thousands, and Galapagos more than ten thousand iterations in the allotted time.

Table 2. Problem 1 (Structural, 8 Integer Variables)

| Algorithm | Avg. 200 | Avg. Best | Best | Worst | Avg. Evals. |
|---|---|---|---|---|---|
| Galapagos | 291.62 kg | 223.11 kg | 220.10 kg | 238.77 kg | 12,910 |
| DIRECT | 241.04 kg | 234.07 kg | 227.46 kg | 235.86 kg | 2,596 |
| RBFOpt | 237.13 kg | 230.42 kg | 220.58 kg | 241.85 kg | 389 |

On the second problem (see Table 3), DIRECT finds both the overall best solution and the best solution after 200 evaluations. Galapagos and RBFOpt perform similarly, although the latter converges faster. As in the first problem, the total number of iterations varies considerably per algorithms.

Table 3. Problem 2 (Structural, 22 Integer Variables)

| Algorithm | Avg. 200 | Avg. Best | Best | Worst | Avg. Evals. |
|---|---|---|---|---|---|
| Galapagos | 65,152 kg | 31,760 kg | 27,928 kg | 36,068 kg | 3,180 |
| DIRECT | 26,116 kg | 15,101 kg | 14,947 kg | 15,263 kg | 1,782 |
| RBFOpt | 45,020 kg | 34,199 kg | 27,711 kg | 53,637 kg | 352 |

On the third problem (see Table 4), DIRECT and RBFOpt display similar performance, with the best result found by RBFOpt (86% UDI), and with DIRECT displaying a slightly faster convergence. Galapagos converged very slowly and achieved only a small improvement over the starting configuration (all louvers closed, with 0% UDI). Galapagos and RBFOpt performed a similar number of iterations (around 300), and DIRECT about one third less. Evidently, the performance of Galapagos greatly deteriorates when only a few hundred design candidates can be evaluated within the time limit.

Table 4. Problem 3 (Daylighting, 15 Integer Variables)

| Algorithm | Avg. 100 | Avg. Best | Best | Worst | Avg. Evals. |
|---|---|---|---|---|---|
| Galapagos | 0% UDI | 10% UDI | 19% UDI | 4% UDI | 310 |
| DIRECT | 79% UDI | 80% UDI | 81% UDI | 80% UDI | 196 |
| RBFOpt | 71% UDI | 86% UDI | 88% UDI | 84% UDI | 308 |

The similarity of the results for Problem 4 (see Table 5) indicates that it is easy to find a feasible solution, but difficult to further improve such a solution. Additionally, the use of a different metric results in values that overall are much smaller than those for Problem 3. That said, on average, RBFOpt displays both the fastest convergence (32% DA after 50 evaluations) and finds the best result (39% DA).

Table 5. Problem 4 (Daylighting, 40 Continuous Variables)

| Algorithm | Avg. 100 | Avg. Best | Best | Worst | Avg. Evals. |
|---|---|---|---|---|---|
| Galapagos | 31.85% DA | 32.37% DA | 34.89% DA | 31.41% DA | 150 |
| DIRECT | 29.46% DA | 29.55% DA | 32.61% DA | 26.48% DA | 102 |
| RBFOpt | 32.40% DA | 39.05% DA | 42.69% DA | 35.12% DA | 150 |

## 5. Conclusion

This paper presented a quantitative benchmark of three different types of black-box optimization methods: metaheuristics, direct search methods, and model-based methods. We tested the performance of one representative for each type on a set of four design problems with different characteristics, stemming from structural and daylighting optimization. The metaheuristic genetic algorithm seems a viable choice only when thousands of design candidates can be evaluated within the allotted time, and exhibits poor performance when this is not the case. Direct search and model-based methods exhibit comparable performance in our tests, with neither method emerging as a clear winner. However, both find designs of much better quality in a shorter time than genetic algorithms, requiring considerably fewer simulation runs. While further studies are needed to confirm the validity of this result, it is consistent with previous benchmarks derived from mathematical test functions (e.g. Costa and Nannicini, 2014; Rios and Sahinidis, 2013). In the context of performance-oriented architectural design, where complex numerical simulations can be necessary to assess the performance of a design candidate, time requirements stress the need for parsimonious, efficient algorithms. In this paper, quantitative results clearly indicate that the architecture

community has much to gain from a reflection on the choice of the preferred optimization method.

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# TOWARDS THE IMPLEMENTATION OF A COMPOSITE CELLULAR AUTOMATA MODEL FOR THE EXPLORATION OF DESIGN SPACE

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**Abstract.** In this paper, we introduce a novel composite Cellular Automata (CA) model to explore the space of design for human environments. Consisting of multiple, regularly spaced, interleaved 1D CA, our model provides a mechanism to evolve flexible spatial units, where the 'cells' are not defined as programmatic elements but as 'form-making' elements. The efficacy of this approach is evaluated via a standard methodology, typically used in the study of complex adaptive systems. We systematically examine the dynamics of a series of instances of the composite CA by varying initial conditions and transition rules. A measure of entropy is used to validate emergent patterns. Subsequently, we investigate whether the composite CA is capable of generating aggregate spatial units to match specific spatial configurations, using a well-known example as a benchmark. This phase allows us to bring an understanding of the results into the context of architectural design.

**Keywords.** Cellular automata; generative design; design space.

## 1. Introduction

Design can be conceived as a purposeful, constrained, decision-making process where the aim is to transform an existing situation into a desired one (Press, 1995; Simon, 1996). When designing environments for humans, such transformations are typically developed by generating some sort of physical form (Woodbury, 1991), where the aim is to characterise the space and make it suitable for different forms of inhabitation to take place.

Given the 'wicked' nature of most design problems (Buchanan, 1992), designers are forced to use a combination of data and intuition in order to

generate an outcome to satisfy intended purposes (Alexander, 1964). In order to test their assumptions, they go through a synthetic process, generating a series of potential candidates, and evaluating them to find the most suitable for their purposes (Swann, 2002). Under this perspective it can be said that design is not problem solving, but it relates to art, as defined by Danish author Piet Hein: 'Art is solving problems that cannot be formulated before they have been solved. The shaping of the question is part of the answer' (cited by Arup, 1972). More succinctly, architectural design can be thought of as a particular method of problem solving that considers the search through a set of alternatives in order to find a desired output: architecture then, appears as a generative process (Mitchell, 1977).

In this paper, we introduce a novel composite Cellular Automata (CA) model to explore the space of design for human environments. Our generative system is capable of producing a design space by defining initial conditions, rules and design criteria. This approach represents a departure from the oversimplification that the 'form-follows-function' paradigm, main design motto of the modern movement (Coates et al, 1996), as it explores new techniques, capable of enabling the discovery of emergent structures suited for a contemporary conception of human inhabitation. Significantly, the overarching goal of this research is to define a way in which low-level design elements (Lynch, 1981) interact in, and with space, in order to enable the exploration of a design solution space.

## 2. Background

CA is an abstract mathematical framework or 'generative method' that have been used with some success, in the production of search spaces, especially during the early stages of the design process. They are discrete dynamical systems comprising a number of typically identical simple components (cells), with local connectivity over a regular lattice whose global configuration changes over time, according to a local state transition rule. CA implementations and functions, regardless of their complexity, regularity and constraints, require the definition of characteristics (cells, cell-states and neighbourhood) that can be directly interpreted as spatial configurations, which makes them appear suitable for applications in design-related fields (O'Sullivan and Torrens, 2001).

In architecture, 3D implementations of CA have been typically used to produce diagrams of spatial configurations in early design stages. In these applications, the cells of the CA generally represent 3D spatial units with programmatic characteristics (e.g. housing units, rooms, public spaces, circulation spaces, etc.), which results in functionally deterministic outputs. Ex-

amples include work by Coates et al (1996), Krawczyk (2002), Herr et al (Herr and Ford, 2015, Herr and Kvan, 2007) and Araghi and Stouffs (2015).

There are a few examples that use 'Game of Life'-based 3D CA models for the generation of diagrams at early design stages. Coates et al (1996) developed one to search for emergent patterns, as Conway did with his original model (Gardner, 1970). For this purpose, a series of rule combinations and neighbourhood manipulations are explored, aiming to understand the possibilities they open for architecture. Krawczyk (2002) uses CA to generate a starting point for design, but the main focus is on how the outcomes of the model can be translated into architectural form, by changing the characteristics of cells. The desired outcomes or other parameters that allow for the evaluation of the system's performance are not defined.

Herr and Kvan (2007) present an approach where the designer is provided with a certain degree of freedom to reconfigure the lattice and to intervene in the process, steering the evolution of the CA to attain design goals. This implementation iterates between solving and reformulating the design problem, which helps reducing the post-processing of outcomes to detailing.

Araghi et al (2015) present a CA that generates variety for the development of high density housing, by addressing accessibility and lighting as additional design requirements. These requirements translate into cell states that depend on the configuration of the neighbourhood, as well as update rules that inform the development of the system. The definition of 3D cells implies a design operation that binds the form of the cell to a function, rendering the results of the development of said models functionally static.

## 3. Composite CA model

We introduce a composite CA model, consisting of multiple, regularly spaced, interleaved 1D CAs (Fig 1a) arranged in a horizontal-vertical configuration (Fig 1b). This composite model provides a mechanism to evolve flexible spatial units, where the 'cells' are not defined as programmatic elements but as 'form-making' elements. This represents a departure from how CA models are typically used in architecture and urban design. Our approach focuses on the ways in which space can be physically reshaped and reconfigured, where its characteristics (such as open/closed, fragmented/continuous, exterior/interior etc.) emerge from the evolution of the system, rather than being prescribed by design.

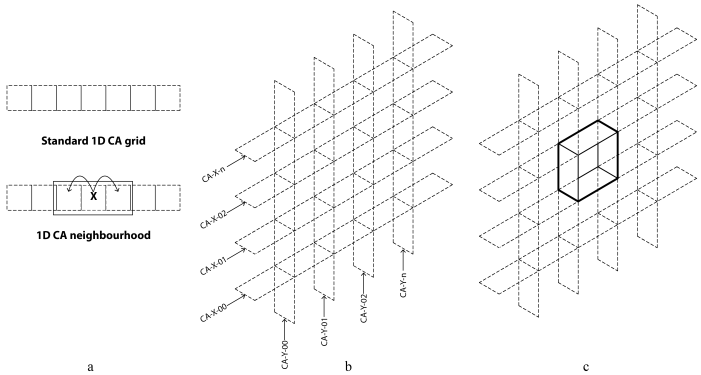



*Figure 1. (a) Standard 1D CA. (b) Configuration of composite 1D CA: interleaved horizontal and vertical 1D CAs. (c) Representative example of one spatial unit, (four active boundaries).*

What differentiates our approach from a standard 2D CA is the fact that the multiple 1D CA act as the edges of encapsulated 'spatial units' (Fig 1c). This approach is similar in some respects to bond percolation models in that the state of the cells in the 1D CA (edges of the individual spatial units) is either active (*on*) of inactive (*off*). If a cell in a 1D CA is off, the spatial units on either side of it are connected. If the cell is on, the spatial units are separated. The main difference between a traditional 2D CA and the composite CA model proposed is that in the former, the states of the cells are predefined, whereas in the latter the individual spatial units embedded do not have prior meaning; their characteristics are defined by the configuration of the 1D CAs that constitutes their boundaries.

In our composite CA, there are two possible states for each cell ($k$=2). Given the configuration of the interleaved 1D CAs, this results in 16 different possible configurations for each of the encapsulated spatial units. In Fig 2, we illustrate these configurations in 3D to emphasise the boundaries of the encapsulated 2D spatial units, rather than their faces. Significantly, our approach provides a robust and flexible alternative to a $k$=16 state 2D CA.

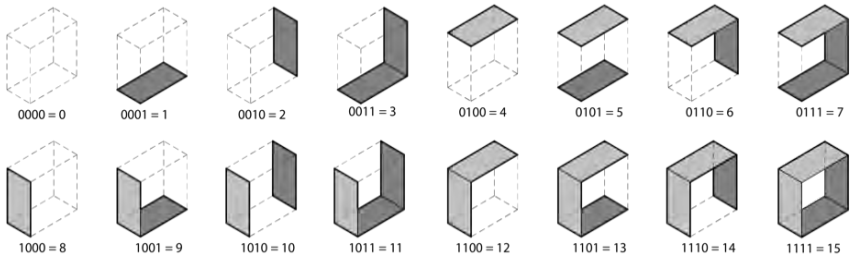



*Figure 2. 3D representation of the 16 spatial configurations the model is capable of producing for a single 2D spatial unit. Binary counting is used to number the active edges.*

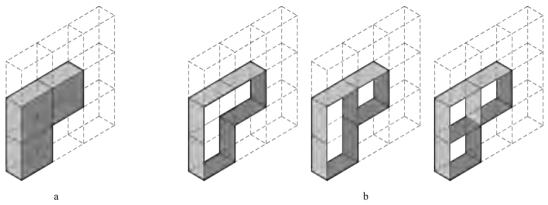


*Figure 3. (a) Standard 2D CA. Each cell is a spatial unit in itself. 3 cell configuration depicted. (b) 3D representation of three possible spatial unit configurations that can be produced with the proposed composite CA model.*

In Fig 3, we illustrate the exploratory power embedded in the composite CA model. Here, we show representative examples of the complex spatial topologies that emerge as a result of the concatenation or combination of multiple edges being active/inactive at the same time. It is this formation of aggregates or clusters of 'enclosed space' that subsequently generates a volumetric matrix for spatial organisation to be used by the designer.

Given the description of the composite CA (*cell states*=2, *neighbourhood*=3, a fixed number of horizontal and vertical 1D CAs), all that remains is a definition of the state transition rules and initial conditions. In our prototype model, we use random initial conditions and have selected representative rules from each of the four Wolfram's (1984, 2002) elementary 1D CA classes: Class I (uniformity) contains rules that generate uniform patterns (i.e. cell states become constant after a number of generations); Class II (repetition) contains rules that produce repetitive patterns, making the outcomes completely predictable. Class III (random) contains rules that generate outcomes with no discernible patterns. Finally, Class IV (complexity) contains rules that generate discernible patterns that repeat as the system develops. However, the frequency and location where these patterns occur is unpredictable.

## 4. Experiments

### 4.1. METHODOLOGY

A key feature of our composite CA model is its ability to evolve (or generate) spatial configurations, defining by spatial boundaries, rather than by using the state of cells to characterise that space. To test the efficacy of this approach, a standard methodology typically used in the study of complex adaptive systems has been followed. We start by systematically examining the dynamics of instantiated instances of the composite CA by varying the initial conditions of each CA and transition rules. We use a measure of entropy to validate emergent patterns.

In the second phase of our investigation we examine whether the composite CA can generate aggregate spatial units to match specific spatial configurations, which allows us to bring an understanding of the results into the context of architectural design. As a benchmark spatial configuration, we use the typical section of the interlocking units of the 'Unité d'habitation' by Le Corbusier (Fig 4a). This choice of benchmark was motivated by its formal characteristics that allow for a series of potentially desirable attributes in terms of lighting, ventilation and circulation performance that could be further investigated as input parameters to be implemented into the proposed system. As shown in Fig 4b, the selected cross section has been 'translated' to the 'language' of the composite CA model, using the alphabet of the 16 possible spatial units illustrated in Fig 2. Model performance is described using standard machine learning similarity measures.

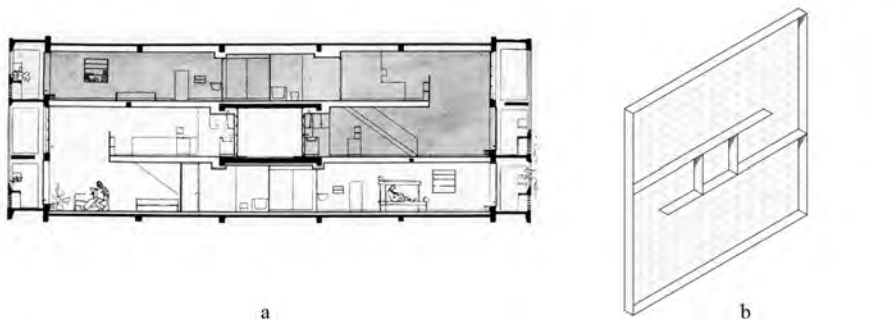



*Figure 4 (a) Typical cross section of interlocking units from the Unité d'habitation in Marseille (Le Corbusier). (b) The abstract representation of the benchmark cross section. The numbers correspond to the key described in Fig 2*

## 4.2. VALIDATION OF THE COMPOSITE MODEL

In our experiments, we set the number 1D CAs to 22 (11 vertical and 11 horizontal), where each 1D CA consisted of 12 cells. Thus, each of the possible encapsulated spatial units can be uniquely defined on one boundary by a cell located at the end of its automaton (see Fig 1b). Table 1 lists the rule combinations/pairing from Wolfram's 1D elementary rules and classes (two rules from each of class II, III and IV), used for sensitivity analysis.

TABLE 1. Rule sets for analysis with corresponding rule classification in parentheses.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Horizontal Rule | 62 (II) | 94 (II) | 62 (II) | 62 (II) | 30 (III) | 30 (III) | 54 (IV) | 54 (IV) |
| Vertical Rule | 94 (II) | 62 (II) | 30 (III) | 54 (IV) | 60 (III) | 54 (IV) | 30 (III) | 110 (IV) |

For each iteration of the composite CA, the cells are updated synchronously, using the given rule associated with the specific orientation (horizontal or vertical). Each of the rule combinations was run for 100 time steps (generations), using three different seed values for the random initial conditions. We refer to a generated time-series data set as an iteration of the system. The key validation step is carried out by calculating the entropy of the system, as it is understood in information theory, where a high value means that a large amount of information is needed to represent the state of the system (Cilliers, 1998). Here, we calculate entropy at each time step using Shannon's equation (Equation 1), which allows us to visualise how the system changes over time.

$$H(x) = -\sum p\,(x_i) \times log_2\, p(x_i) \tag{1}$$

In Fig 5 we can observe that where rules from class II are in use (solid line), the plot shows the value of entropy entering a periodic cycle after a few time steps. However, when combining rules from classes II and III (dashed line), the plot shows that the variation in the value of entropy describes an unpredictable pattern. These observations are consistent with what is expected in the system dynamics from the Wolfram's classes, thus we can conclude that the composite CA is performing as expected.

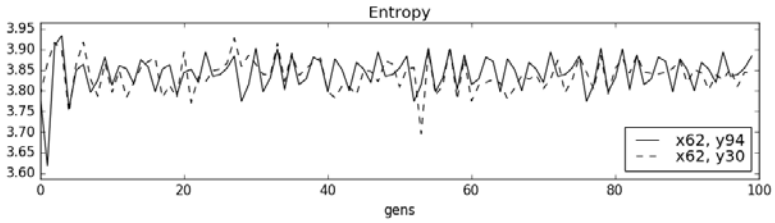



*Figure 5. Entropy calculated for two different sets of rules over 100 generations: solid line shows combination of class II rules. Dashed line shows combination of class II and III rules.*

## 4.3. EVOLVING SPATIAL UNITS

To evaluate the form generating capabilities of the composite CA model, the benchmark configuration described in Fig 4b acts as the target, where the goal is to measure the similarity between this benchmark and the evolved spatial unit configurations.

$$similarity = \frac{\sum A_i \times B_i}{\sqrt{A_i^2} \times \sqrt{B_i^2}} \tag{2}$$

The plot in Fig 6, illustrates the distribution of spatial unit configurations corresponding to the best result obtained from the simulation experiments

(similarity = 0.87). Despite this relatively high similarity score, there are significant differences between the evolved and target configurations. However, an interesting observation is that the evolved configuration encapsulates examples of each of the spatial units listed in Fig 2, whereas the benchmark does not. The graphic representations of both configurations, shown in Fig 7, highlight these differences.

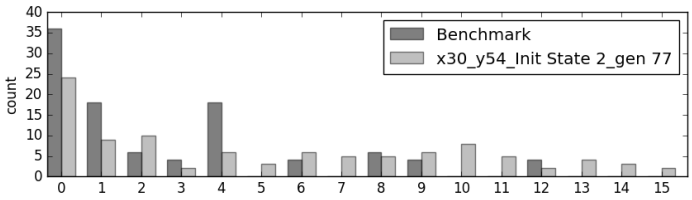



*Figure 6. Distribution of 2D spatial units by type (according to Fig 2) for the benchmark and the composite CA: rules 30 (horizontal), 54 (vertical), with initial state 2, after 77 generations*

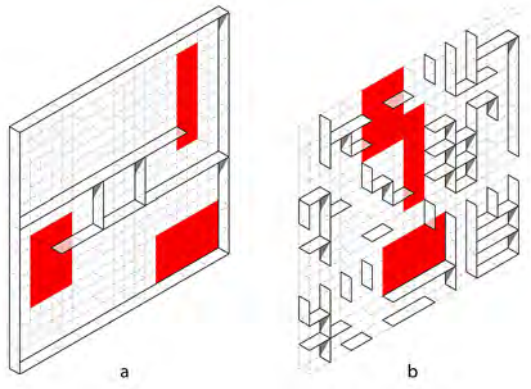



*Figure 7. (a) Spatial representation of benchmark. (b) Spatial representation of configuration with highest cosine similarity score.*

In the next stage of our analysis, we compare the benchmark and the evolved configurations 'element by element' by counting how many different spatial units are identical in both topology and location.

An inspection of the vector of spatial unit counts shows that the minimum number of matches was 6, achieved when using class II rules (94 horizontal/ 62 vertical), initial state 0, and it repeats every 7 generations. On the other hand, a maximum number of 19 matches was reached in two simulation trials: i) Class III and IV rules (30 horizontal/54 vertical), initial state 2, and it appears after 21 and 52 generations; ii) Class IV rules (54 horizontal/110 vertical), initial state 0 and it appeared after 84 generations. Fig 8 presents a visual comparison between the benchmark and trial ii.

Similar to the comparative patterns presented in Fig 7, it is possible to observe in Fig 8 that most of the matching elements are part of sub-patterns. Therefore, the exploration of a search strategy focused on sub-structures, rather than on the configuration of the complete pattern, appears as a method suitable for generating a wider range of usable results. It is significant to note that in the case illustrated in Figs 7 and 8, the sub-patterns only appear as result of the comparison process, as their boundaries are not clearly defined. However, looking at the benchmark configuration, there are three sub-structures clearly defined by their boundaries, the most obvious being the square in the centre.

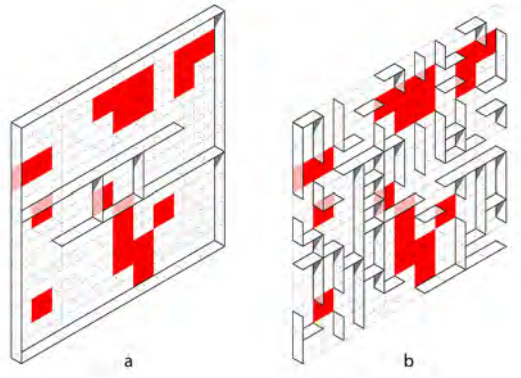



*Figure 8. Matching elements between (a) benchmark configuration, and (b) composite CA: for rules 54 (horizontal), 110 (vertical), with initial state 0, after 84 generations.*

## 5. Discussion

In this paper, we have introduced a novel composite CA that can be used to generate a variety of spatial unit configurations, defining the boundaries of space, rather than by prescribing spatial characteristics of the constituent elements of the system. Our goal was to explore the formation of aggregates (clusters) of 'enclosed' space, representing an 'interesting' spatial organization, which can be detailed, developed or interpreted by a designer at a later stage. Significantly, our model was able to produce a wide variety of aggregate patterns.

It can be argued that the strength of the composite CA system is based on informing a designer about the inherent complexity rather than acting as a tool for generating completed design solutions. The ability to generate/search the state space is defined by transition rules and the time evolution of the model. In our experiments, the benchmark target was pre-defined. Searching for a fixed, static configuration limits the possibilities as to what can be imagined by the user, defeating the ultimate purpose of the model –

generating a design space, and searching through it using design criteria, looking for emergent spatial configurations. Therefore, introducing protocols for searching for characteristics of the space (e.g. open vs. closed space), rather than specific patterns, is seen as a goal to pursue in order to enable the emergence of unexpected spatial configurations. In this regard, the development of mechanisms to incorporate modifications to the rules as the system evolves, as well as the introduction of external influences, are seen as plausible paths to pursue in order to extend the system's capabilities.

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# THE BIOLOGICAL MODEL AND THE BIO-TYPE

*Dynamic simulation tools defining architectural components*

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**Abstract.** Architecture has shown a recurring interest on themes of biological origin, especially since the early days of modernism. With the advent of computation, the related discourse has been enriched with new analogies, in particular when biological systems are described by algorithmic formulas and their parametric functions are inspected with the assistance of simulation tools. An understanding of the architectural object with reference to biology offers breaking from typological preconceptions about form in favour of its operational character supporting organic behaviour, so to speak. In reflection, the present paper puts under scrutiny architectural components such as façade, wall, window, opening, support structure and circulation viewed as topological references also in analogy to biological notions such as skin, membrane, cell, bone structure, energy flows and the nervous system. Form becomes the dynamic effect of forces; a system that manages energy trades being the primary cause of its own shape.

**Keywords.** System; parametricism; type; topology; bio-structuralism.

## 1. Introduction

The present paper draws upon architecture's analogies with biology in order to discuss main architectural components such as façade, wall, window, opening, support structure and circulation. Biological themes presenting dynamic behaviour have often been appointed in studying architecture's relevance to parametric thinking also under a comprehensive view of the architectural object as a system that is integrated with its surroundings and the multiplicity of agents setting broader ecologies. Architectural components may be defined and designed in response to the systemic operations they perform. As a result, their presumed conforming to archetypes of Cartesian

geometry along with their resolution as rigid solids supported by conventional (analogue and/or digital) techniques is being contested. In effect, this paper revisits the notion of type in architecture described as a topological entity informed by dynamic interactions also in relation to parametricism and the bio-type. Types may adapt to systemic change even be blended together offering increasingly complex variations, hybridisations and mixtures. Consequently, derivative notions such as typology and archetype may also respond to systemic fluctuations and be treated as "soft" entities. In the last part, this paper proposes some prototype models of architectural components formed through active parametric agents. Architectural components are being defined by their shared tasks and reunited under a "smooth total" that is impossible to break apart.

## 2. Parametricism and the bio-type

References transferred from biology to architecture, when not limited to mere visual resemblance, may reveal design's dynamic character. The analogies may be summarized as: first, an understanding of the architectural object as an organic entity that relates parts, functions and qualities into its structure; second, its conception as a metabolic entity forming systemic interactions and exchanges with the environment; third, the generative aspect of design seen as a process, endowed with the task to register and translate the set of factors making a system into physical space and form (Hensel and Menges, 2007). The interest in biology has significantly advanced since various digital software and working platforms have been introduced in the design process to assist in testing the dynamic associations among elements, data and other related influences. Digital technology, more than a mere facilitator to design – or, better stated, precisely because of the enormous facilitations tools associated with the digital have brought into design – has helped to understand the architectural project as the result of information exchanges among various, human and technical, agents (Carpo, 2013). As Hight and Perry (2006) have observed, digital technology's potential to transform hitherto prevailing modes of design practice may even be more radical in its implications. Collaboration, participatory authorship and collective decision-making are some of the terms used to describe architecture's agent-based nature, profoundly linking it with parametricism.

Parametricism in architectural practice may be described as a sophisticated strategy that engages all stages of design from the preliminary ones until completion aiming to bring various systems together via increasingly complex processes and institutions (Schumacher, 2009). Early versions of parametricism may be viewed in shared platforms facilitating communication

among different expertise, such as those offered by Building Information Modelling software known as BIM, fostering documentation and data exchanges among the stakeholders that take part in building, construction management and cost control. More recently, and as design computing has expanded beyond representation, it has become possible to foresee a future in which BIM will evolve to a complete parametric tool for design and construction. In these forthcoming versions, BIM may also provide with tools for analysis, simulation and physical object making, as more realistic ways of introducing new organizations being necessary to contend with increasingly mixed programs and building types, promising to revolutionize design practice (Garber, 2009). Advanced design software currently includes highly sophisticated techniques capable of manipulating complex data and their interactions. As such, they assist different stages of design such as data importing and comparing, ideation strategies, conceptualization, schematic development, resolution, refinement and final fabrication. These additions to the making process have allowed architects to better forge their ideas and manage how these will be realized, meanwhile challenging traditional delivery and construction methods with more innovative ones. In consequence, it has been possible to envision an all-encompassing view of architectural practice as a multi-agent approach that reflects the aforementioned advancements along with the project's behaviour and overall performance as an optimized answer to a set of outlined aims. The integration of parametricism in architecture may virtually end when the sum of agents describing a project will be joined together, guiding the architectural components toward finding their final shape, relative positioning and role and so defining form as an extended system. Parametric logic would suffice to address the total range of relationships among the parts and the broader system under inclusive also competent solutions.

The above description reinforces the production of variations in analogy to biology, as adaptations of architecture's parametric logic into changing contexts, from which different types may occur. In biology, variety may indicate discrepancies in an organism's vital functions with reference to environmental constraints, which are given parametric significance (Thompson, 1917). Evolution, the process of defining new species as different phenotypes, becomes an effect of generating and updating the genotype due to limitations that have emerged during an organism's systemic associations with external influences. Variations of the phenotype generally result from the interaction between the genetic code making the genotype and data flows as energy exchanges with the environment. The notion of bio-type may be suitable to outline schemes driven by intensive and extensive operations of recursion and mutual feedback between an organism and its environment, link-

ing the genotype and the phenotype into an ever-ending process of adaptation, mutation and updating.

There are operative similarities as well as differences between the biotype and common uses of the type in architecture, being evident in the ways that type is inherently linked with form's functioning and defining, but may only partially respond to agents and dynamic inputs. Instead, the architectural project may be described as the manifestation of a generic type about a system whose articulations support the parametric connections of multiple subsystems. Its organizing logic may join together elements at various sizes from interior to architectural to urban scale interacting with one another, the result being their interference and compromise. Such an updated view of the type is necessary in order to accommodate within it the dynamic processes of conception and formation about architecture and its components as a total system that is holding, defining and defined by its parts.

The proposed view on type affects derivative notions such as typology and archetype. References to typology would be appointed so that an organizational problem about architectural space be somehow converted to one of Cartesian geometry, that is, a problem of finite resolution addressed by classic aesthetics. Rowe (1947) for example explores the geometric analogies between Le Corbusier's *Villas* and those of Palladio over Renaissance and so he uncovers a grid system as an organizing mode that is also critically adapted in order to meet the particularities of each case. Additionally, Le Corbusier's *Modulor* system describes geometric relations based on variable ratios of the human body with reference to proportional systems describing beauty during Renaissance. The same systemic approach is carried throughout the design, whereby the fabricated typologies are produced under regulating scope and then used as guidelines for producing architectural space through the relative positioning of its components such as walls, openings, columns, roofs and slabs.

There are apparent variations in the produced results, reflected in the descriptions of the grid and other geometry-defined references supporting architectural form. These, however, still produce static morphological transformations of autonomous architectural components (Lynn, 1993) being parts of the total composition, rather than bringing into the project any of the aesthetic effects of the interactions among the agents that have influenced decision making, to the point that they could incite continuous adaptation and updating. Rigidity and permanency about architectural components reinforced by the inert behaviour of materials commonly used in construction further align with the idea that the architectural composition is practically fixed in space and time. The assumption is that architectural form does not need to fully acknowledge its formative causes, mainly due to restrictions

related to standardization and cost, also due to the expressed view that architecture provides its own vocabulary and syntax (Alexander et all, 1977).

Instead, more dynamic views on the type may translate it in ways that it becomes responsive to the agents about a project seen as generative ones; or in analogy to bio-type. In respect, Lynn (1993) suggests viewing the type as a flexible reference, so that it stays indicative of form's own structure, meanwhile accepting form's discontinuous development through interactions with its formative causes. Architecture may still be defined through systemic modes of influence, this time however by also questioning the applicability of rigid geometric references in defining form. Architecture is proposed as a total scheme joining its components together and consequently, any of the graphic abstractions that have traditionally assisted in bringing the various elements together, is introduced as dynamic entities that may interact with the design agents. Some of these elements were formerly considered as being autonomous and also unrelated to, or barely affecting, each other, but within the presented working platform they may be manipulated as systemic parts of a larger whole. Integration through heterogeneity is the product of intensity describing the local – i.e. inner – connections between the parts, along with the dynamic incorporation of external influences causing transformations. The type should be able to expand or contract, extend or bend, even be combined to offer hybrid compounds, constantly internalizing external influences and forces within its limits supporting new affiliations. These features challenge a long-term tradition, helping to understand and effectively use the type as a point of departure in studying form, rather than an idealized reference to which design must always return and compromise.

Accordingly, attention may shift from form's geometric characteristics to its propensity to represent data being activated to produce variations. Rather than assuming it to be the output of aesthetic-driven manipulation, form is seen as a system that may be managed indirectly through data tweaks concerning the forces that are set to generate and influence it, having an effect on its external appearance and internal structure. Form becomes a mixture of elements defined by shared tectonic functions. Tectonic in this case describes a condition whereby the architectural components transcend their utilitarian aspect (Lim, 2009) and through synergetic interaction reveal compound meaning. This has happened along with recent updates in perceptions of the physical world from classical definitions of harmony, proportion and order to ones stressing out exchange, mutation, transformation and movement. Cartesian geometry has given its place to topology and mathematics, so that form may not be defined by applying geometric rules, but instead it may be calculated (Cache, 1995). Design has become process-driven as opposed to object-driven and beauty is pursued with reference to the organiza-

tion and making, further attained through the dynamic aesthetics of process, as opposed to the traditional aesthetics of object (Lim, 2009). Success is measured in relation to the degree that different elements are integrated in the composition. Performance-based criteria are gradually replacing ones based on representation predominantly assuming architectural form an aesthetic object. Optimizing standards are approximated and refined in simulations running onto abstractions of concepts during form-finding and carrying them onto next levels of refinement as more information gradually enters the design scene (Garber, 2009). The produced models may be viewed as advanced versions of BIM in a broader sense, capable of linking data of various kinds. Recent theories have embraced this paradigm shift, whereby system-oriented thinking is increasingly informed by biological themes and parametric modes of data management assuming design the organic output of progressively refined functions. In effect, new opportunities have emerged for BIM software to integrate dynamic form-finding with pragmatic management and tools of construction in driving design towards its physical manifestation.

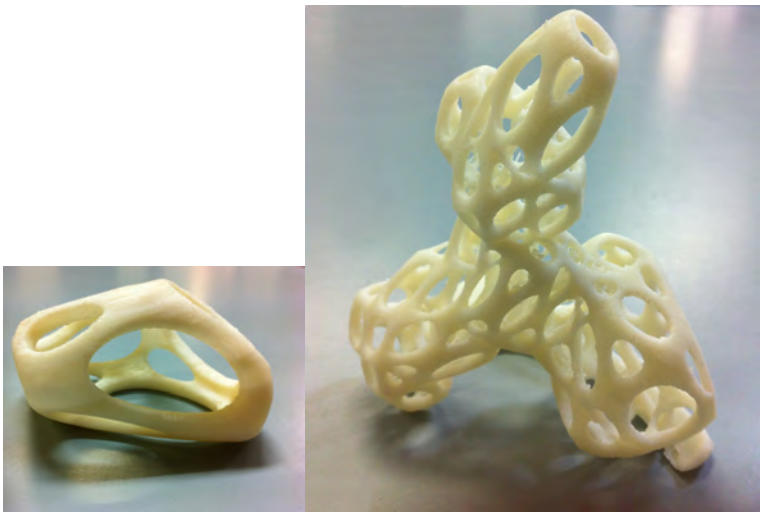
### 3. Redefining architectural components: the bio-structural model

Next, the above discussion is implemented onto main architectural components specifically with regards to dynamic processes of formation, offering solutions that are not defined by geometric regularity. Components such as walls, openings, rooms, slabs, columns, staircases and corridors have set the main architectural vocabulary during many centuries of architectural production. Especially during modernism, these elements were defined with reference to Cartesian primitives, aiming for standardization, profoundly linking the building industry with techno-economic factors. Compliance with Cartesian geometry has been reinforced by a variety of tools for drawing such as the ruler, the orthogonal triangle and the T-square, further supported by elements used in miniature model-making such as cardboard sheets and wood sticks representing slabs, roofs, columns and beams. It is worth noting that the same geometric logic has been transferred into the mainstream digital design tools. Design software such as Sketchup and FormZ and also ArchiCAD and Revit based on BIM are set to describe entities with reference to Cartesian primitives such as planes, cubes, spheres and cylinders. These packages, due to a point-based logic, satisfy demands related to accuracy and so they are better in supporting geometric regularity; however, they present limitations in handling complex geometries, not being suitable for relating dynamic data inputs with form's outlook. This restriction has given room for software that can handle geometric transformations more efficiently, also

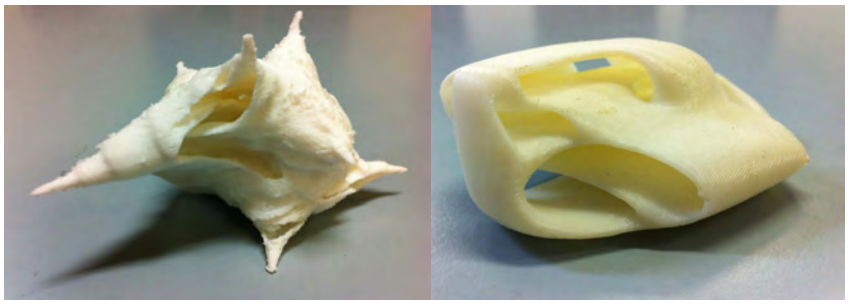
with reference to behaviours due to a number of programmed factors. In effect, designers often resort to software initially developed for purposes being foreign to architecture, such as Maya Autodesk and Rhinoceros with its parametric plug-ins. With this software, an instance on the screen is a topological entity defined by is inner structure, properties and behaviours. The available tools also provide with capabilities for simulating the effects of forces, fields and other dynamic instances onto form, even in real time. Such a dynamic approach may further be aligned with bio-systemic views describing the different stages of the production process, setting the basis for extended versions of BIM software.

The above view is applied to produce prototypes of architectural components created under the notion of Bio-structuralism. Components are translated as open systems interacting with different agents set as generative forces. Various outputs emerge from homogenized strategies supported by advanced operations. These strategies incorporate the parameters of design, whose influences are simulated to interact with other ones also with form. Parameters such as social factors, economy and function have been included in digital-assisted approaches dating since the late-1990s (MVRDV, 1999), exceeding, however, this paper's scope. An updating of the semantics about architectural components is proposed by examining the dynamic effects of various agents acting onto "soft" primitives, whose behaviour is defined by their inner logic.

Biological themes such as skins, cells, bone structures, energy flows and the nervous system are borrowed to interact with agents influencing spatial phenomena. Interactions include applying forces onto materials and evolving generic elements to generate self-sustaining also proliferating systems, as the output geometries become increasingly complex. These experiments produce bone-like supports such as advanced three-dimensional scaffolding multiplied at varying directions and sizes (Figures 1); stratified skin shells taking different shapes in response to external forces and internal resistances (Figures 2); ground and slab structures converting to beams, columns, platforms and roofs (Figure 3); ground platforms, slabs and beams forming aggregates of smooth transitioning and expansion (Figure 4), and; façade walls translated to flexible membranes offering fluidity between the interior and the exterior and efficiency in weight support (Figure 5). Form is conceived as a topological entity subdivided and programmed to follow changing data inputs. As a result, the simulation of the interactions between form and the agents creates sequences of variable outputs whose parts are immersed into a system logic.



*Figures 1. Bio-Structuralism (Zavoleas, 2014). Primitive bone-like support structure as advanced three-dimensional scaffolding multiplied at varying directions and sizes.*



*Figures 2. Bio-Structuralism (Zavoleas, 2014). Stratified skin shells taking different shapes in response to external forces and internal resistances.*



*Figure 3. Bio-Structuralism (Zavoleas, with Michelis and Tzemou, 2013-14). Ground and slab structure converting to beams, columns, platforms and roofs.*

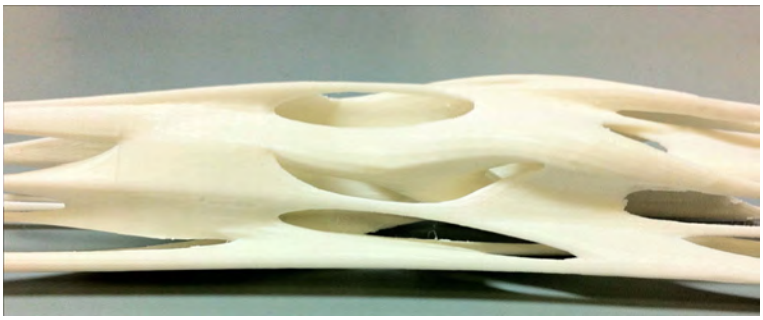


*Figure 4. Bio-Structuralism (Zavoleas, 2014). Ground platforms, slabs and beams forming aggregates of smooth transitioning and expansion.*

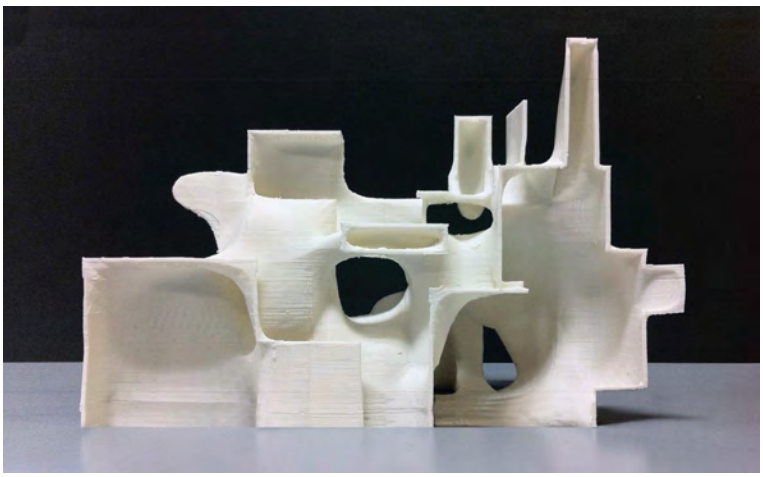


*Figure 5. Bio-Structuralism (Zavoleas, 2014). Façade wall transformed to flexible membrane offering fluidity between interior and exterior and efficiency in weight support.*

Future BIM software will handle unique compounds, being fully customized, calculated and fabricated under total control. At any phase of the process, production systems will support back-and-forth testing between data tweaks and variable schemes. Detailed resolution will be instant, as long as every bit of information is digitized. Until then, the software industry must strive continuously to align with the pioneering minds in the field, providing tools that better respond to the increasing expectations of design.

## 4. Conclusion

The prototypes presented above aim at updating definitions of commonly used architectural components through their interaction with the design agents during form-finding. Each one shows potential for further study, along with the influences it has been programmed to undergo at micro and

macro level. A discussion on the dynamic comprehension of architectural components has led to questions on the type in architecture. Its adaptations may be set in analogy to biological models and the bio-type, also alongside theories that touch upon architecture's parametric character. It is suggested viewing the type as a topological reference of a systemic logic, one that can be manipulated and transformed according to parameters that are addressed to have an impact upon form. Moreover, with significant advancements in construction technology, restrictions referring to product standardization may no longer be relevant. In effect, references to Cartesian geometry may reflect aesthetic criteria and not to necessities of construction.

As an alternative to aesthetics, this paper advocates extensive data management reinforced by experimentation from the initial phases towards completion. Dynamic simulation tools appointed for testing architectural object's systemic behaviour may be suitable for linking the data from analysis with the design choices. The biological theme is an aid in identifying the relationships among the agents of design and conveying them into the general logic, the organizing schemes and the strategies of resolution. Further to this endeavour, advanced simulation tools incorporated into future BIM software may be added to the list of means including drawings and models describing the process of making, as ones also fostering creativity.

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**COMPUTATIONAL DESIGN ANALYSIS**

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# TOWARD THE WIND-RELATED BUILDING PERFORMATIVE DESIGN

*A wind-related building performance optimization design system integrating Fluent and Rhinoceros based on iSIGHT*

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**Abstract.** The integration of optimization algorithms and building performance simulation tools make it possible to carry out performative design or performance-driven design, which aims to guide the design synthesis process of the simulation results to continuously improve the design. However, the associated research work of wind-related building performance is still deficient, resulting from lack of applicable interface and the time consumption. Meanwhile, in the industrial design realm, the aero-dynamics or fluid-dynamics behaviour of the production under development has been vastly analysed and optimized based on the multi-discipline optimization (MDO) techniques. Owing to offering numerous built-in interface and integrated optimization algorithm, MDO application software has begun to be used in building optimization design with the complex relationship between various objectives. With the advantage of MDO tools and aimed to provide an efficient optimization approach from the perspective of architect, this paper proposes a wind-related building performance optimization design system integrating Rhinoceros and Fluent based on iSIGHT - a MDO application software. In addition, the lighting performance is considered in this research as well for implementing the multi-objective optimization. Two case studies of tall building optimization design based on varied generative approaches are introduced to investigate the effect and efficiency of this system.

**Keywords.** Performative design; wind-related building performance; MDO; parametric generating design.

## 1. Introduction

Digital building performance simulation tools let architects and engineers undertake performance-based design at different design stages. The development of heuristic searching or optimization algorithms makes it possible to carry out performative design (Kolarevic and Malkawi, 2005; Oxman, 2009) or performance-driven design, which aims to guide the design synthesis process of the simulation results to continuously improve the design. Many studies conducted on this approach intended to assist architects to dig up the environmental potential of design scheme (Nguyen et al, 2014). As research continues, offering user-friendly application and efficient optimization approaches from the perspective of architect is becoming a dominant trend in this area (Shi and Yang, 2013).

However, in the associated research field of wind-related performance, related work is still deficient, resulting from the time consumption and lack of applicable interfaces. Recently, based on the solver approximation (Chronis, 2011; Karagkouni et al, 2014) or solution approximation (Wilkinson and Hanna, 2014) several studies have been conducted to investigate the wind-related performance behaviour of varied building configurations. The intention of these two kinds of studies is either to balance the time-accuracy issue or to predict the predefined performance by machine learning approach alternatively. However, such studies conducted mostly focus on the methodology exploration, which are for the academic purpose rather than real-world application. Therefore, the resulting complicated approaches are also hard to use in design practice or to be further developed by most architects. To conclude, there is still a large unexplored research space in the field awaiting further investigations.

In the field of industrial design, the approach based on multi-discipline optimization (MDO) aimed at improving the aero-dynamics or fluid-dynamics performance of the productions under development has been widely applied. To offer an efficient tool for user to perform the optimization, MDO tool equips numerous built-in interfaces to connect with some simulation programs and CAD/CAE tools, and they have powerful functions of analysis and optimization. As integrated with CFD simulation tools, some advanced MDO tools, iSIGHT for example, can perform the wind-related performance optimization design for different realms. Recently, to tackle the more complex design problems with complex relationship between multiple objectives, MDO tools also have begun to be employed in building performative design. Hence, by integrating with specific simulation tools and running the optimization process, MDO tools can be used to support decision making in architectural design (Gerber et al, 2012).

With the advantages of MDO tools, this paper proposes a wind-related building performance optimization design system based on iSIGHT. By integrating with Rhinoceros and Fluent, the presented system can offer an efficient way to assist architects to design a building with excellent wind-related environmental fitness in the conceptual design stage. In addition, the presented system characteristic of extensible, which enables it to optimize the design with multiple objectives, and, therefore, the lighting performance, evaluated by DIVA which is a lighting performance simulation tool of Rhinoceros, is considered in this research as well.

## 2. System framework

Typically, an optimization system is comprised of generating, evaluation and selection. Following this basic framework, Figure 1 shows a diagram of the framework for the presented optimization system to link the generating design tool (Rhinoceros) to the performance simulation programs (Fluent and DIVA). iSIGHT is connected with both of them to automatically generate new sets of input variables and perform selection based on the evaluation results. The ranges of parameters are provided to the input variables and the objectives are defined to guide the algorithm to optimize the design. Based on the above system framework, an automatic testing workflow is to be established to enable the wind-related and lighting building performances optimization.

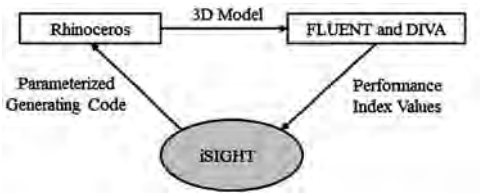



*Figure 1. System framework.*

Rhinoceros is chosen as the generating design platform in this system due to its familiarity to most architects. To establish a dynamics generative design system, the parameterized generating code file is scripted in RhinoPython, which is gaining popularity among the users of Rhinoceros. The correspondent model is generated and exported in IGES format file in the specific directory. For the sake of the CFD software can correctly identify the varied model, the different parts of the model will be named (like IN, OUT, WALL, BUILDING) and exported separately according to the allocation of boundary condition in CFD simulation.

The given building performance simulations can be performed based on the above generated model. The working flow of CFD simulation will be recorded in the specific format files, which will be loaded to guide the relevant programs to conduct the given jobs including meshing, simulation and result output. In addition, the command to call DIVA to perform simulation and result output is also scripted in RhinoPython.

After the above works have been done, iSIGHT will be configured to connect these programs for establishing the automatic testing workflow. Although the employed programs cannot be directly integrated with iSIGHT, one can conveniently write a batch file with DOS Command lines to link these programs to iSIGHT. By loading the customized batch files, iSIGHT can drive the connected programs to conduct the appointed jobs. To implement the dynamic change of generated model, iSIGHT will reassign the value of parameters in the generating code by varied input variables before generating process. The result file outputted by simulation programs will be read by iSIGHT, and the contained performance index values will be restored and then evaluated by the optimization algorithm.

After properly configuring the parameters setup in iSIGHT and getting ready the abovementioned support files, the automatic testing workflow as illustrated in Figure 2 can be established. Based on this workflow, the optimization process can be performed by running it iteratively. First, a selected optimization algorithm of iSIGHT generates sets of input variables as the genes of initial generation in the optimization process. By sending them asynchronously, iSIGHT drives the connected programs to perform the modelling and simulations one set at a time. As the instances generated from these sets are all tested, the performance index values will be evaluated and the crossover and mutation will be performed by optimization algorithm. Then, the optimization algorithm will generate new sets of input variables and a new iteration step will be started. After reaching the maximum iteration steps or achieving the convergent criteria, iSIGHT will report and output the optimization result.

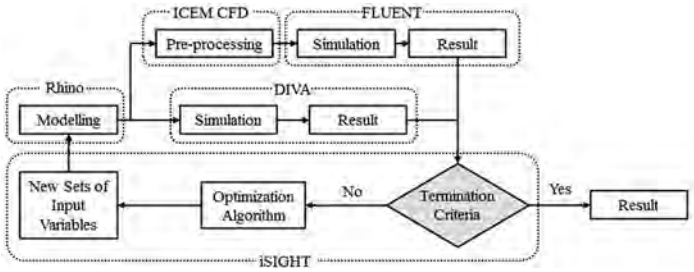



*Figure 2. Workflow.*

## 3. Case study

Optimizing or improving the performance of tall building has been the subject of several studies (Gerber, 2012; Wilkinson and Hanna, 2014). In this section, two case studies on tall building design and characteristic of different generative design systems are introduced. Respectively based on parametric and rule-based model, these two generative design systems are used in investigating the effect and efficiency of the presented optimization design system under the different generative approaches characteristic of continuity or discontinuity.

In the case studies, passive cooling is taken as the only overall objective in this paper for simplifying the environmental consideration, and the meteorological condition is based on Nanjing, China. Wind load is considered an important aspect in tall building design (Wilkinson and Hanna, 2014). The excessive surface wind pressures on a tall building will cause many hazards to its safety and utility. Therefore decreasing the absolute value of average surface wind pressure (ASWP) is taken as the main objective in the case studies. Additionally, reducing the average surface solar irradiance (ASSI) in summer, which is evaluated by DIVA, is taken into account as well, to decrease the energy load of air conditioning by reducing the heat gaining.

### 3.1. GENERAL SETUP

In CFD-based optimization, time consumption is a significant problem, which should be elaborately managed. To control the time span of optimization process, two measures are adopted in this research. First, a loose precision setup is employed in CFD simulation to ensure the convergence can be achieved in a less iteration steps. Second, a relatively small population size of optimization is adopted, which can roughly fulfil the completeness of optimization for the employed algorithm of this research (Hu et al, 2013).

In the following case studies, the multi-island genetic algorithm (GA), an evolutionary-based algorithm is chosen as the optimization algorithm (Hu et al, 2013). Based on this algorithm, the feasible domain of parameters is first divided into several “islands” each optimizing by its own. Then the elite genes are migrated among the islands iteratively during the whole optimization process. This mechanic can avoid the phenomena of “premature”, which usually occurs in simple GAs. The identical setups of multi-island GA are adopted in both cases. The rate of crossover is 1.0, the rate of migration and mutation is 0.1, the number of generation is 12, and the number of islands and sub-population size is 10. In addition, the default setup is used in other parameters. Based on the above parameters setup, there are 1200 individuals going to be tested in each optimization process.

### 3.2. CASE STUDY 1

The first case study is a curvilinear building shape optimization design of an ellipse planed tall building. The purpose of this case study is to find an improved building shape under the basic design prototype without intervention of subjective design intentions. The shape of the tested building is generated by lofting from 6 identical ellipses in the given heights (Figure 3a). By rotating these ellipses in the given angles (Figure 3b), the building shape will be varied depending on different combinations of these angles (Figure 3c). Meanwhile, to avoid the phenomenon of a generated shape with excessive twist, the seams of these ellipses have been adjusted before lofting. The rotation angles (ra1-ra6), range from -60 to 60 degrees, act as the input variables in the optimization process.

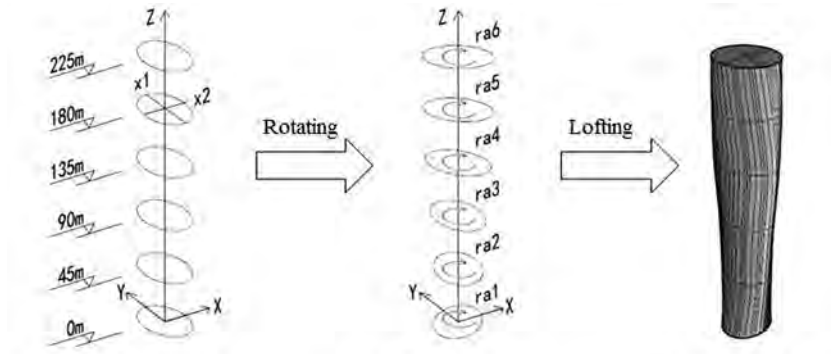



*Figure 3. Generating method.*

Before running the optimization design of the objectives of ASWP and ASSI, two tests respectively aimed at these two objectives are conducted separately. Figure 4a and 4b shows the graduated improvements (from left to right) in both tests. From the result coming from the test guided by ASWP (Figure 4a), one can observe that the performance index values are decreasing while the building shape approaches a stream line form but still with a certain degree of twist. The fittest shape does not match the empirical conceived one similar to the original shape with 0.555Pa in ASWP whose rotation angles are all 0. In the ASSI-oriented test (Figure 4b), the fittest shapes have an indistinctive but identifiable trend of self-shading forms along with the decreasing of ASSI. The different morphologic trends also demonstrate that it is less possible to achieve an impeccable solution in real-world design when facing a trade-off relationship with various considerations.

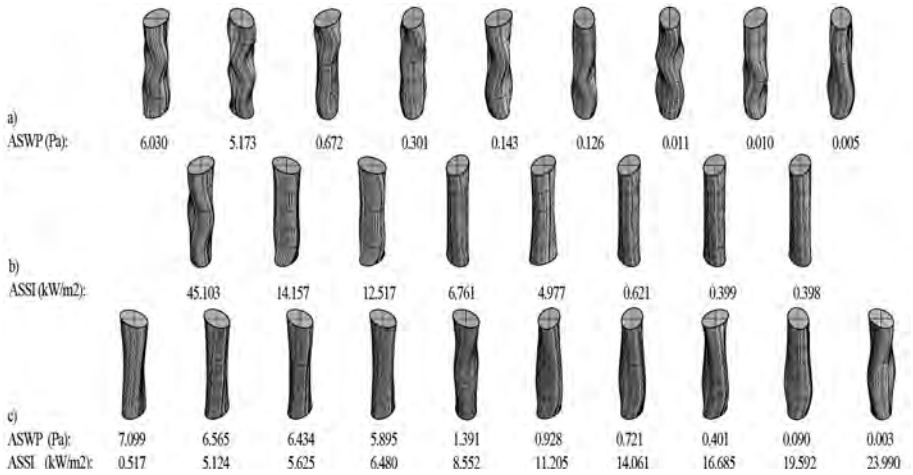



*Figure 4. Optimization results.*

Figure 4c shows the optimization result instructed by the objectives of ASWP and ASSI. Because this optimization design is a multi-objective one, a Pareto set – a list of optimal solutions - is obtained after implementation. The two ends in this set respectively represent the best solutions from the consideration of ASWP (right) and ASSI (left). Between these two ends, a series of shifting instances with improved performance from ASSI to ASWP (from left to right) have been identified as well. A clear morphologic tendency similar to the result of first two tests can also be observed.

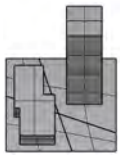
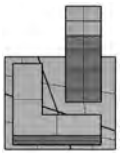
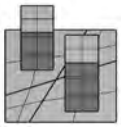
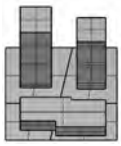
In the first case study, the feasibility of the presented optimization system has been primarily tested, where the shape is driven into an intelligible and reasonable form from the chaotic ones in the initial stochastic searching phase. The optimization results demonstrate that using such a system integrating with the proper generative approach, one can find a shape not only with excellent environmental fitness but also with a practicable morphological sense, considering the architectural design. Moreover, the morphologic feature of these optimized building shapes also reveals the fact that the building shape characteristics of better environmental performance are hard to generalize or achieve through the known rules of thumb.

### 3.3. CASE STUDY 2

The second case study is a configuration optimization design of a tall building with a separated podium within a 150×150 $m^2$ square. Different from the previous case study, a generative design system of rule-based model is employed in this scenario. By containing different generative rules all in itself, the generative design system features discontinuity.

The generative design system is a four-quadrant based generative method (Table 1). The square lot is first divided into 4 pieces by the controlled points on each side of it, whose parameters range from 0.2 to 0.8 as the domain of each side is 0 to 1. The purpose of such restriction is to avoid extreme imbalance between the areas of these shapes. By comparing the areas, the biggest one (rule #1 and rule #2) or the biggest two (rule #3 and rule #4) of these 4 pieces will be selected to generate the tower or towers with square plans. The width is determined in a fixed ratio to the area of the piece where it stands and building height is no higher than 200 meters. Meanwhile, in the circumstances where there are two towers, an area distribution ratio range from 0.3 to 0.7 will be given to differentiate between building volumes. After that, according to the corresponding generative rules and the spatial relationship between the left pieces, a podium in 5-storey-height and in L (rule #2) or I shape (rule #1 and sub rule #3.2), or no podium in some other circumstances (rule #4 and sub rule #3.1), are generated. The dimensions of podium are related similarly to the pieces where it stands. In this generative design system, the rule index number, the parameters of the controlled points' position and the areas distribution ratio are taken as the input variables.

Table 1. Generative design system.

| Rule #1 | Rule #2 | Rule #3 | | Rule #4 |
|---|---|---|---|---|
| | | Sub rule #3.1 | Sub rule #3.2 | |
|  |  |  |  |  |
| One tower with an I shape podium | One tower with a L shape podium | Two tower without podium if the towers in the adjacent quadrants | Two tower with an I shape podium if the towers in the adjacent quadrants | Two towers without podium |

Based on this generative design system, some constraints have been defined to control the generated instances to have a reasonable architectural sense, including the minimum storey height (≥ 3.3m) and the minimum building spacing between tower and podium (≥ 9m). In addition, maximum absolute value of surface pressure (< 33Pa) is also taken as constraint.

During the optimization process, there are 15 instances that were punished by excessive maximum wind pressure and 45 instances that did not satisfy the minimum building spacing or minimum storey height. By carefully inspecting and analysing the resulting Pareto set (Figure 5), some basic inferences can be drawn. Concerning the aspect of ASWP, the instances with

lower building heights and less windward areas should be better than the higher ones, because the wind pressure will increase along with the altitude. While in the aspect of ASSI, the instances with less south-facing surface area or mutual blocking of sunlight between buildings will perform better. Thus, the reason is highlighted why the rule #1, #4 and sub rule #3.1 in Table 1 are eliminated in the optimization result for having a larger area either on the windward side or on the southward side or both under the same gross floor area requirement.

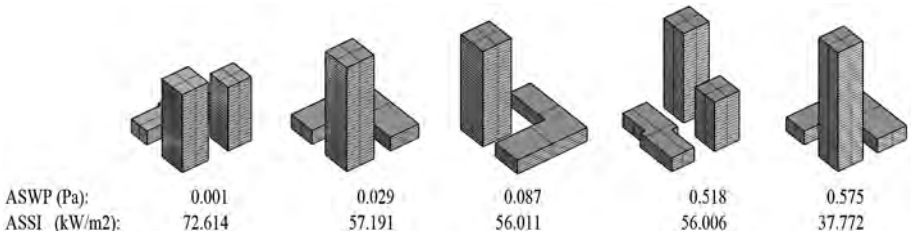



*Figure 5. Optimization result.*

As demonstrated in the second case study, the feasibility of the presented optimization system has been further investigated. Due to the factor of varied generating rules, the corresponding optimization result means much higher practicality to architects in decision making during the initial stage of design. The result is more of a list of optional promising design strategies rather than merely a set of references. By offering architects a comprehensive perception of the environmental behaviours between various building configurations under the given conditions, the result can facilitate architects with a better awareness of the advantages and disadvantages of environmental performance among different design strategies.

## 4. Conclusion

Based on iSIGHT, this paper presents a wieldy building wind-related and lighting performance optimization design system, which can potentially stimulate the development of performative design. Significantly, the optimization system and generative approach can be easily established without advanced scripting or programming knowledge. Additionally, a more convenient approach taking Grasshopper as the generating platform is available as well. However, this approach has not been adopted in this paper, as it would cost more time in the generating process.

The two case studies show the effect and efficiency of the presented optimization system, where the optimization results are cognitive and rational. Although, the convergence is not achieved in both case studies resulted from

the limited iteration step, the clear morphological tendencies can be distinguished from the optimization results. Additionally, while the trio of the time consumption, the accuracy of performance simulation, and the completeness of optimization have been elaborately balanced, the CFD-involved optimization processes still take 6-10 days in the case studies. However, on the bright side, with the development of processing ability of computer, the time span of optimization process will be predictably reduced in the future, and such approach will be more practicable in real-world application.

Concluded from this research, a reciprocal conversation between form and performance can be strengthened by making the environmental adaptability to become a driving factor in form-finding process. The possibility of architectural design may be enriched by the information provided from the performance attribute of building.

## Acknowledgements

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# BREATHING SKINS FOR WIND MODULATION THROUGH MORPHOLOGY

*Toward integrating turbulence studies within tectonic scale for design of façade components*

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**Abstract.** This study aims to investigate the design power to manipulate the behaviour and characteristics of air through geometrical manipulation of building skins. The simple cubic cells in the global system of a porous screen were manipulated to investigate the impacts of screen's morphology on the air movement pattern within and around it. The results we discovered from the evaluation of several screen systems revealed trends in response to the careful manipulation of effective shape parameters within a designed matrix of variations as a Matrix of Possible Effective Typologies (MPET). In this research, the main principles of framing the initial matrix were based on: a) Creating pressure differences across the screens as a result of surface intrusion and extrusion compositions. b) Changing the nature of the airflow (velocity and turbulence variation) with geometrical manipulations of the inlet and outlet of the screens' components. Experimental and numerical studies were undertaken in parallel including the use of a wind tunnel with very smooth flow with precision wind sensors and the numerical studies by Computational Fluid Dynamics. The aim of this paper is to present part of the empirical investigations to demonstrate the power of geometry in shaping the air patterns, altering pressure and velocity through geometrical modification of porous surfaces for future applications.

**Keywords.** Porous screens; microturbulance; facade component; microclimate; parametric CFD.

## 1. Introduction

Our surrounding microclimate consists of the complex synergy of invisible meteorological elements: wind, heat, and humidity. These factors strongly influence our thermal sensations and perceptions, as found in studies by Rohles et al (1974), Fanger et al (1988) and de Dear (2011). In such complex contexts, designers are shaping space through composing and repeating elements of geometry, colour and material; the patterns that are changing the invisible environmental elements and can be used to form pleasant microclimates around us. This hidden part of the design context poses challenges for designers while it also provokes them to understand how they could change the surrounding microclimate with the aid of patterns as influential artistic-scientific systems. To be precise: patterns which comprise of variation in colour, material and geometry. Geometries, as components of such a system, metamorphose the invisible forces. To discover its power in this metamorphosis, designers need to be supported to have a better understanding of the relationship between the morphology of a building's skin and the possible modification of obscure meteorological elements. This trend enables them to consider microclimate studies within their design stages. This study aims to demonstrating the power geometries in changing air movement patterns as one of the main meteorological elements that can directly modify human perception of heat and humidity.

### 1.1. WIND MODULATION THROUGH GEOMETRIES: FROM URBAN TO POROUS SCREENS STUDIES

Engagement with the complex dynamic system of our surrounding atmosphere poses challenges for the designer due to invisible phenomena that are both influenced by and influencing architectural designs. This challenge becomes critical in extreme environmental conditions such as hot and arid climates, where the thermal performance becomes an essential aspect of design. In such conditions air movement and turbulence intensity are important factors for removing high-temperature air and providing greater perceived air quality. Additionally, air movement improves heat transfer from the body (Zhao et al, 2004). This raises the question of how geometry can affect air flow characteristics such as velocity, turbulence intensity and pressure. Different studies at diverse scales reveal compelling evidence of impacts of geometries on changing the air movement and the resultant thermal improvement; from the macro level studies of a city to micro level studies of porous screens. For instance: the impact of street geometry (Golany, 1996); the shape of domed roofs (Yaghoubi, 1991) in the large-scale studies of a city and shapes of balconies in the smaller scales of facades (Montazeri et al,

2013). In the micro scale studies, investigations of Hrynuk et al (2012) show how the density of porosity affects the micro-scale flow patterns near porous screens. Studies carried by Hasheminejad et al (2014) demonstrate the significant influences of leading edge shapes on the air flow pattern for enhancing the mixing effect and heat transfer rate. Nonetheless, few investigations consider comparable studies of porous screens for architectural applications.

## 1.2. POROUS SCREENS

Porous screens were traditionally used as a device for passive ventilation of private or semi-enclosed spaces while protecting the interior from thermal radiation (Figure 1). Mashrabiyas are examples of such systems, used for multiple functions such as controlling light, reducing temperature and increasing humidity (Fathy, 1986) while also adding aesthetic characteristics to buildings located in hot and arid regions.

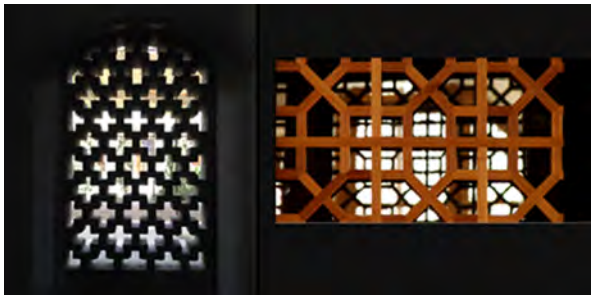


*Figure 1. Sample of traditional porous screens location: Esfahan, Iran -2013*

These lattice-opening systems within the facades are formed by repeating two-dimensional timber components. They display a variety of designs with pattern differentiation by utilizing various opening size and shape. While most of the existing literature and studies are focusing on the light analysis of such opening systems, the versatility of their function raises the question of how the variation of the screen morphology could affect airflow patterns within and around the screens for different applications. This on-going research answers this question by illustrating different wind patterns occurring in such a system in response to the geometrical manipulation of cells and their global composition through parametric design of its sub-components (Figure 2). The aim of this paper is to present empirical investigations to demonstrate the power of geometry in shaping the motion of air through geometrical modification of porous surfaces for future architectural applications. Rather than focusing on wind analysis at the architectural macro-scale

(building scale) - this study aims to analyse the architectural micro-scale (i.e. millimetre (mm) scale) studies of porous screens.

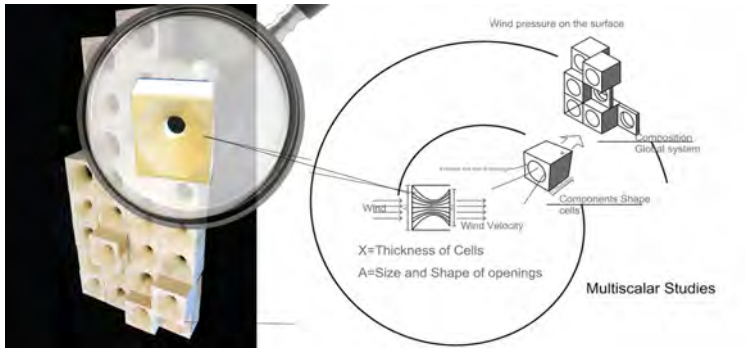



*Figure 2. The proposed porous skin as a system comprise of varied cubic (subsystems)*

## 2. Form exploration and experimental system

Visualizing and analysing the dynamic behaviour of wind, forming by porous screens systems, posed the following challenges:

- Possible versatility and differentiation of pattern making in the porous system. To simplify this challenge and reduce the complexity of pattern making, we designed a matrix of possible effective typologies from simple cubic cells (Figure 2 and 4).

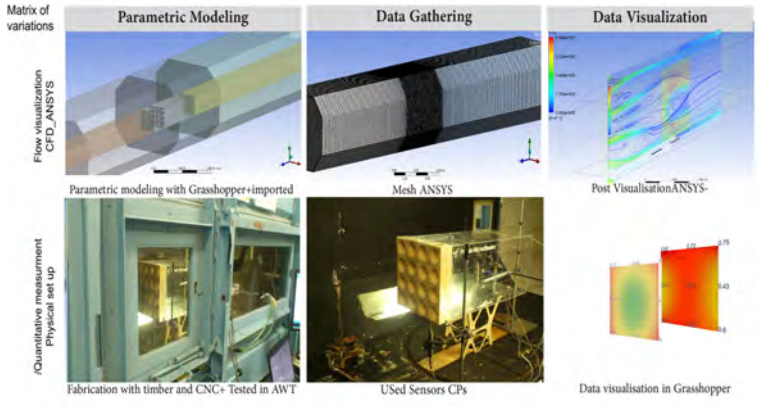



*Figure 3. Parametric modelling, Data gathering and Data visualisation in both physical and virtual platforms.*

- The Complexity of wind visualization at this scale since most of the currently available tools in the field of architecture such as Vasari and Flow Design are

for supporting outdoor wind analysis and studying global building forms. For solving this challenge an Aeronautical Wind Tunnel (AWT) was utilized for the quantitative measurements and numerical simulations with ANSYS CFX were used for flow visualisation (Figure 3). Figure 3 illustrates the three main stages in the individual physical –digital setup for the wind analysis of parametric designed porous screens (including the tools used for data gathering and data visualisation).

## 2.1. MATRIX OF POSSIBLE EFFECTIVE TYPOLOGIES (MPET) AS AN ESSENTIAL STARTING POINT

The matrix of possible typologies was an essential guideline and starting point. It enabled us to identify the correlated effective parameters and have higher control of possible generations out of the proposed simple cubic system. The effective primary parameters for generating the elements of this matrix could be identified from pieces of literature and primitive investigations. In this case, multiple configurations were defined by varying parameters such as: surface undulation; the depth of apertures (changing across the rows of the matrix in Figure 4); the porosity (increasing along the columns in Figure 4); and the shape of the screens' porous openings (Figure 4).

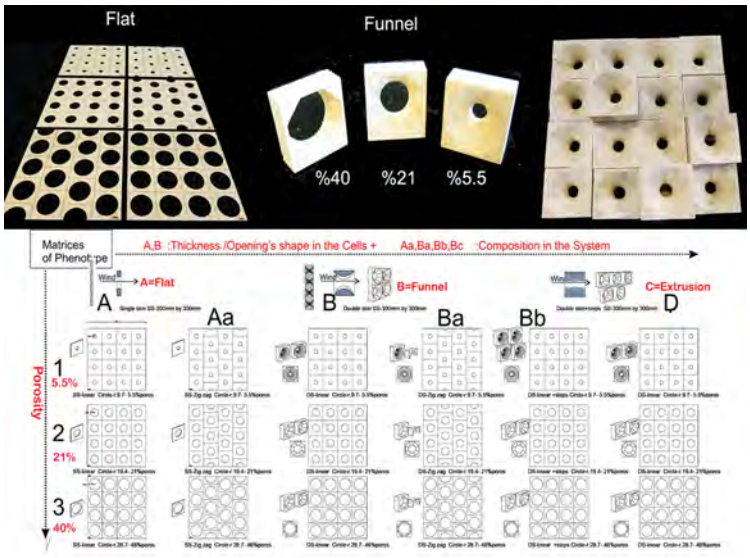



*Figure 4. Matrices of Possible Effective Typologies (MPET) designed based on cells' shapes and possible global compositions e.g. the column A=iterations with flat section with varied porosity ratio across the rows of the matrix while Column B= Iterations with funnel shape of profiles and Column D= iterations have extrusion profile shape*

Two main principles, extracted from literature, informed the typologies for the mentioned alterations: a) creating pressure differences across the screens as a result of surface configurations, and b) changing the velocity and turbulence intensity within the façade and surrounds by changing inlet and outlet shapes of the screens' components. The shape study in this cluster began with the exploration of the Venturi effect to accelerate and decelerate the wind flows: the funnel shape of the cells' ingress channelled the airflow through the funnel causing a decrease in static pressure and an increase in dynamic pressure; hence an increase in local velocity (Bernoulli's principle). This matrix has been designed to vary logical parameters e.g. the iterations A and Aa (Figure 4) have different configurations and opening positions with the equal porosity increasing across the columns of the matrix. Using the modular cubic components for the MPET enabled us to form several configurations during the physical investigations. It was a practical approach for the rapid design and construction of porous screen prototypes created with CAD /CAM. This MPET is a valuable systematic method for performance analysis of complex systems.

## 2.2. PHYSICAL EXPLORATION FOR THE SPEED MEASUREMENT USING THE WIND TUNNEL

The AWT was a closed-circuit wind tunnel with an octagonal tunnel test section measuring 2,100 mm long, 1,370 mm wide and 1,070 mm high and the test domain was a 30cm by 30cm by 60cm box to present a room with a totally open outlet. The graphs in Figure 5 are the measurements from the Cobra Probes (CP) across the 3x3 grid (9 locations), visualised in Grasshopper for screens A3 and B3 (these have 40% opening with different profile shapes). CPs are precision tools for detecting the pressure of air to resolve velocity and local static pressure in real time at a point in the flow field (Prohasky et al, 2014). The reference value for the non-dimensional wind speeds was the free stream velocity generated with the wind tunnel. The measurement was done for both ~5m/s and ~14m/s average wind speed. These measurements show that variation across the grid is independent of wind speed (within this range of average wind speeds). The results indicate that, on average, the turbulence intensity of iteration A3-40%-Flat is higher than B3-40%-Funnel in the opening section. The top rows in Figure 5 are the non-dimensional average wind speed (for each position in the grid).

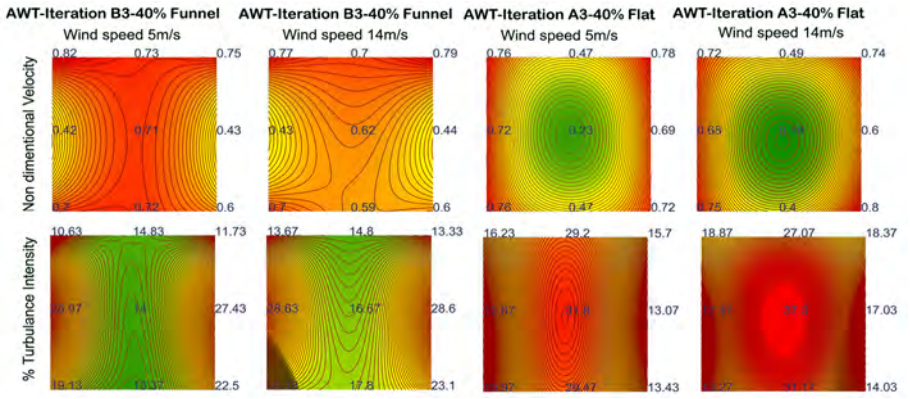



*Figure 5. Turbulence intensity and velocity from AWT physical experiment for iterations A3 - 40% Flat and B3-40% Funnel –with 5m/s and 14m/s wind speed for inlet-Grasshopper3D was used for post visualisation of the extracted data from the CPs*

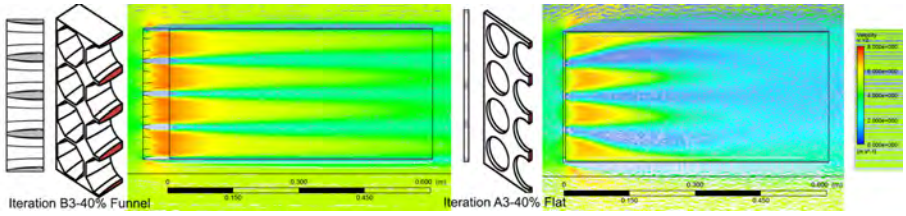



*Figure 6. CFD Flow visualization for iterationsA3-40% -Flat and B3 -40% -Funnel*

## 2.3. DIGITAL SIMULATION FOR THE FLOW VISUALIZATION USING ANSYS

The physical tests involved grid point measurements at 300mm from the leeward face of the porous screen. These measurements did not provide information of the flow field around and behind the screens. Hence, for better understanding of flow visualisation behind and within the screens, the numerical simulations were conducted with ANSYS-CFX using a K-Epsilon turbulence model, 5m/s inlet velocity with a turbulence level set to <1%..The qualitative CFD outcome matched reasonably well with the physical wind tunnel results. e.g. the represented colour maps of the AWT results show a higher local average velocity behind the funnel shapes compared to the other with the equivalent porosity (40%) and different aperture profile (Figure 5), which matched the CFD measurements for the same iteration (Figure 6).

## 3. Discussion

Variation in opening profile shape (horizontal on MPET Figure 4) demonstrated significant differences in the flow pattern behind the screens with the

equal porosity. The gradation of geometric profile towards a funnel (e.g. sharp edges towards continuous topology) creates more ordered flow (Figure 7), hence less mixing and extended jets. In other words, the shapes of the openings form different wind patterns behind and within the porous system. The edges of the test chamber tend to separate the airflow away from the exterior walls - the effect of this flow dispersion directly influences the interior when the screen is flatter. By extending the depth of the screen and creating more of a funnel shaped profile – the flow can be projected further into the space (e.g. this information is especially useful for the design of apertures near the corners of a building). This demonstrated how screen iteration B3-40%-Funnel extended the boundary effects of wind with significant changes of the flow in the openings' throat section with respect to the equivalent flat screen (Figure 6). This does not accelerate the airflow globally - there was still a global deceleration caused by the screen. However, the flow was more ordered which caused the airflow pattern to penetrate further into the room - hypothetically mitigating wind gusts, but allowing greater air changes within the space. Though, it is important to consider the incident wind characteristics within the building's context when applying this in situ (full scale in situ experiments are required to verify this).

## 4. Research implications for architectural applications in diverse design scenarios

This study demonstrated the value and possibility to consider the versatility of opening shapes across facades based on air movement, local acceleration of the wind, desired turbulence intensity and fluctuations. The scenarios and implications of such studies are diverse. From the viewpoint of energy saving - this study has several applications in architecture: façade components for second skins; ventilated facades and porous screens for cross ventilation to the larger scale of façades and balcony forms. For instance, it is predictable that for double skin facades the profile shape of holes could enhance air circulation and turbulence intensity within the two layers of skins for cooling purposes. For cross ventilation scenarios, the results highlight the power of geometry to magnify the wind velocity by creating smooth contraction profile shaped openings rather than a flat screen with the equivalent porosity. Furthermore, the strategic allocation of the opening position across a façade for the desired distribution of localised airflow jets e.g. using funnelled and extruded profiles closer to walls, ceilings or floors to extend the penetration of wind and increase air changes within a space without disturbance in working areas.

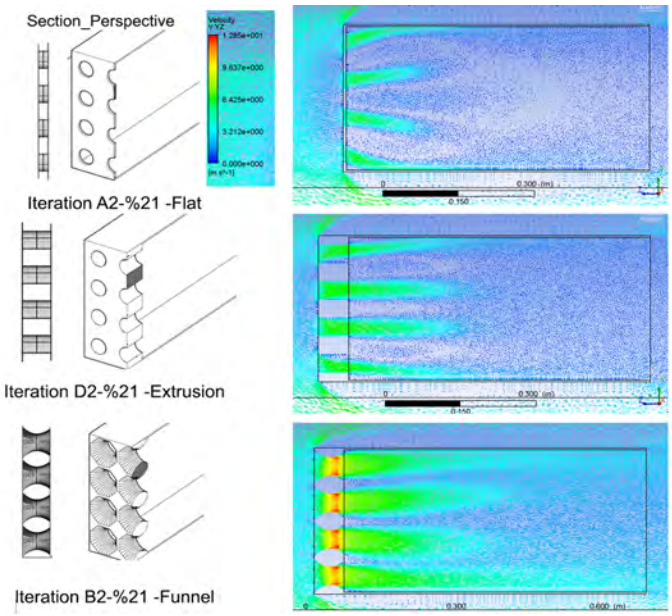



*Figure 7. Flow visualization from CFD-ANSYS for iterationsA2,Bb2 and B2. (21% porosity with different inlet shapes*

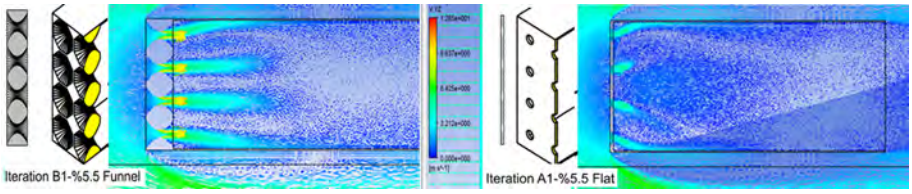



*Figure 8. CFD Flow visualization for iterations A1-5.5% flat and B1 -5.5% funnel shapes*

## 5. Conclusion and future research

The series of results presented in this paper, point toward the possibility of empowering designers in making informed design decisions based on predicted wind phenomena. This study shows how we could project air fluctuations within indoor space, to offset high air temperature, promote better-perceived air quality as suggested by (Zhao et al, 2004) and introduce opportunities to create moments of positive alliesthesia experienced through the dynamics in the wind (de Dear, 2011) (assuming cooler temperatures are desirable). Based on these studies it was possible to train variation in airflow through porous screens using the versatility of shape e.g. both wind tunnel and CFD results indicated the effects of funnel shapes in extending jets of air - delaying the dissipation of the turbulent pattern within the interior apartment space (Figure 6, 7 and 8). The CFD results demonstrated that the ex-

truded and flat porous screens produced greater flow resistance which were similar to the wind tunnel results. However, further work is needed to verify the quantitative analysis of the CFD simulations which will be documented in the near future. This study has shown how geometry in building skins can morph the wind and thus the microclimate within buildings. The results shed light on the role of detailed studies of façade components and their possible impacts on shaping the wind and consequently sculpting our surrounding microclimate. It also demonstrates design simulation strategies to support designers to understand the relational dynamics between airflow and porous screens for building facades. Additionally, it highlights the need of designers for having parametric platforms for simulation of airflow within the architectural applications. Although in these studies the test box (test domain) had a completely open outlet to simplify the experiments, it would be interesting to consider other scenarios, such as closed and semi-closed domains to simulate effects of such variations.

## Acknowledgements

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# MICRO-SCALE WEATHER DATA FOR ENERGY PERFORMANCE ASSESSMENT IN SINGAPORE

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**Abstract.** Weather data plays an important role for energy performance assessment in the design of buildings and urban environments. Many researches have been carried out to generate and analyse various weather files for different simulation platforms. However, investigations have been lacking in the development of weather files that account for urban heat island (UHI) problems. As a result of global warming and the complexity of the urban environment, the weather file for a modern city cannot be simply based on climate information from 20 years ago. The objective of this research is to demonstrate a method for creating different micro-scale typical meteorological year (TMY) weather files based on different urban texture values. This research includes three steps: 1) Recent years weather data is obtained. 2) Considering the UHI impact, a series of new TMY weather files are generated for different micro-scale areas in Singapore based on relevant urban texture variables. 3) A comparison of the results shows that there is a big difference between the new and the old TMY. The temperature of the new TMY is 1-2°C higher, while the solar radiation is lower than the original TMY data. Hence the new weather files will be more credible than the original TMY for energy performance simulation in the design process.

**Keywords.** TMY; UHI; Sandia method; energy performance.

## 1. Introduction

Thermal and energy performance simulation requires hourly weather data such as dry bulb air temperature, relative humidity, solar radiation, etc. Since weather conditions can vary significantly from year to year, there is a need to derive a set of typical weather year data to represent the long-term typical weather conditions over a year. There are various types of typical weather

data sets including the Typical Meteorological Year (TMY, TMY2 and TMY3), Weather Year for Energy Calculations (WYEC and WYEC2), International Weather Years for Energy Calculations (IWEC), etc. However, it is recognized that a TMY weather dataset is more reliable in replicating average historical conditions (Chan et al, 2006; Crawley 1998).

Singapore has a tropical rainforest climate with no distinctive seasons. The current TMY file for Singapore was developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in the early 1990s. However, as a result of global warming, the current weather conditions are different from those 20 to 30 years ago. Hence, current simulations would need an updated weather file based on more recent data.

At the same time, Singapore, as many other cities in the world, suffers from the urban heat island (UHI) phenomenon. The UHI effect means that an urban area is significantly warmer than its rural surroundings due to the influence of human activity. The currently available weather data used in building simulation software mainly comes from weather stations located at airports or in areas with relatively low urban influence. Therefore, without considering the UHI impact, the current TMY file for evaluating the thermal and energy performance of buildings located in Singapore will not be accurate, or the average energy consumption of buildings may be underestimated.

The objective of this research is to create micro-scale TMYs considering the urban heat island effect in Singapore. The research includes the following steps: 1) Data sources: the recent 13-year basic weather data is obtained from the National Oceanic and Atmospheric Administration (NOAA) and the Geography Weather Station at the National University of Singapore (NUS). 2) Development of micro-scale weather files: using the Sandia method and considering the UHI impact (Wong, 2011), new TMYs are generated for three different locations in Singapore. 3) Comparison: the current weather file is compared with the four newly generated weather files. There is no doubt that TMYs should be developed for Singapore to better assess the energy performance and to assist energy efficient building/urban design.

The remainder of the paper is organized as follows: first, the literature review is presented; next, the proposed method is described; subsequently, the resulting weather files are compared with the original TMY file; finally, a conclusion and future work are presented.

## 2. Literature review

The literature review is conducted in two parts: TMY development and urban texture variables.

## 2.1. TMY DEVELOPMENT

Although there are a number of methods to generate the TMY files, most of these methods are modified from the Sandia method (Hall et al, 1978), developed by Sandia National Laboratories. Pissimanis et al (1988) utilized the root mean square difference of global solar radiation as the last step within the Sandia method to generate TMY files for the city of Athens. The selection criteria for weather parameters, however, remained the same. Both Petrakis et al (1998) and Kalogirou (2003) developed TMYs for the city of Nicosia, Cyprus considering additional selection criteria for weather parameters, including visibility, precipitation, snow fall, etc. Sawaqed et al (2005) used a similar method to create the TMYs for different cities in Oman. However, they changed the weight value for the weather parameters in order to satisfy the simulation objectives. Chan et al (2006) followed the Sandia method to develop the TMYs for Hong Kong based on a 25-year hourly measured data record (1979-2003). Chan (2011) considered the UHI influence in an update of the previous weather file of 2006. Most of these studies exhibit the same limitation: they did not take into account the impact from urban texture values into the development of TMYs. Hence this research proposes a new modified Sandia method to construct the TMYs by considering urban texture variables. This will not only help to bridge the knowledge gap between weather file data and urban texture variables, but also support energy simulation with respect to design parameters.

## 2.2. URBAN TEXTURE VARIABLES

The influence of urban texture variables on building/urban energy performance is obvious from previous research. However, urban texture involves a complex interaction between many miscellaneous parameters. Wong et al (2002) evaluated the impact of the surrounding urban morphology on building energy from different parameters, such as: air temperature, green plot ratio (GnPR), sky view factor (SVF), surrounding building density, the wall surface area, pavement area, albedo, etc. They identified a varying degree of impact for each variable. The highest impact is attributed to GnPR, which relates to the presence of greenery, followed by height and density. Wong et al (2011) investigated how the air temperature variation of the urban condition can affect the building energy consumption in the tropical climate of Singapore. The results show that GnPR has the most significant impact on the energy consumption by reducing the temperature by up to 2°C. Zhang et al (2012) developed a case study to reveal the relationship between density, urban block typology and sky exposure. The results indicate that the existing

environmental performances as indicated by facade and ground level sky exposures vary across the built form typologies under study.

In order to develop TMYs by considering the urban texture variables, this research adopts the following variables as reference:

- Percentage of pavement area over 50 m radius (R) surface area (PAVE %) (Wong et al, 2011);
- Average height to building area ratio (HBDG) (Wong et al, 2011);
- Total wall surface area (WALL $m^2$);
- Green Plot Ratio (GnPR): total leaf area / site area (Ong, 2003);
- Sky View Factor (SVF): illuminance E / arbitrary luminance L * π (Compagnon, 2004).

## 3. TMYs development

The raw weather data is collected from the National Oceanic and Atmospheric Administration (NOAA) and the Geography Weather Station at the National University of Singapore (NUS), from 2003 to 2015. NOAA does not contain the hourly global solar radiation; the data read from the sensor of solar radiation at NUS can complement this missing part. Considering the total area of Singapore (about 720 $km^2$), we can argue that the solar radiation data from NUS is effective enough to represent the entire city. The raw data from NOAA is decoded by the Integrated Surface Reporting Hourly (ISH) format. Hence the two data sources can be integrated by their time series.

Using the new integrated database, the proposed modified Sandia method for TMYs development contains four main steps (Figure 1). The first three steps follow the original method. The last step carries out the morphing algorithms to modify the dry-bulb temperature by considering the UHI impact.

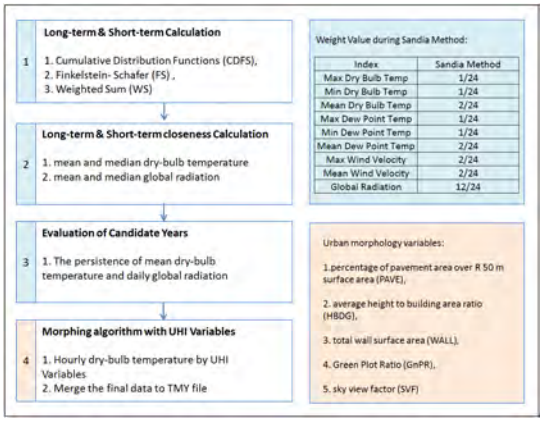



*Figure 1. TMY Progress sequence diagram.*

### 3.1. FIRST STEP

Based on the 13-year weather data, there are three functions to produce the weight value for each of the parameters from the short-term and long-term perspective. The parameters are the dry bulb temperature (mean, min, max), relative humidity (mean, min and max), wind velocity (max and mean) and global solar radiation data. The Cumulative Distribution Functions (CDFs) for a given parameter for a given month data are calculated as follows (1):

$$CDF(x) = \begin{cases} 0, & x < x_1 \\ \dfrac{k-0.5}{n}, & x_k \le x < x_{k+1} \\ 1, & x \ge x_n \end{cases} \tag{1}$$

where $n$ is the number of days in a given month and $k$ is the ranking number for each parameter.

The Finkelstein-Schafer (FS) statistic (Finkelstein and Schafer, 1971) measures the monthly closeness between the short-term and the long-term CDFs (2):

$$FS(y,m)_x = \frac{1}{n}\sum_{k=1}^{n}\left|CDF(x)_{y,m} - CDF(x)_m\right| \tag{2}$$

where $n$ is the day number of the month, $m$ is the month, $y$ is the year and $x$ represents each parameter.

Due to the difference in importance among the parameters for energy performance simulations, each FS value is multiplied by a corresponding weight factor $w$. This research adheres to the original weight values: 1/24 for dry-bulb temperature (max, min) and 2/24 (mean); 1/24 for dew point temperature (max, min) and 2/24 (mean); 2/24 for wind velocity (max and min); 12/24 for global solar radiation. The weighted statistics (WS) is then defined as (3):

$$WS(y,m) = \frac{1}{d}\sum_{k=1}^{d} w * FS(y,m)_x \tag{3}$$

where $d$ denotes the day number of the month, $y$ is the year, $m$ is the month and $w$ represents the weight of each parameter.

### 3.2. SECOND STEP

The five candidate months are ranked with respect to closeness of the month to the long-term mean and median with the two parameters: mean dry-bulb temperature and global radiation. The final result is shown in Table 1.

Table 1. Ranking results of five candidate years.

| Year\Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2003 | 8.46 | 9.15 | 9.00 | 7.91 | 7.64 | 7.42 | 8.30 | 8.21 | 7.18 | 7.32 | 7.06 | 7.19 |
| 2004 | 10.80 | 8.59 | 8.73 | 7.34 | 9.77 | 9.05 | 9.27 | 9.38 | 8.93 | 9.33 | 8.32 | 9.42 |
| 2005 | 6.51 | 6.07 | 5.99 | 8.66 | 8.77 | 6.19 | 7.10 | 7.79 | 8.80 | 8.65 | 7.11 | 10.07 |
| 2006 | 6.51 | 7.55 | 5.89 | 8.95 | 8.57 | 9.56 | 8.88 | 9.96 | 7.97 | 9.19 | 8.73 | 7.93 |
| 2007 | 9.05 | 8.04 | 8.26 | 8.89 | 10.61 | 7.94 | 10.01 | 8.32 | 9.33 | 7.90 | 8.68 | 9.70 |
| 2008 | 8.57 | 7.13 | 9.52 | 9.01 | 8.33 | 9.12 | 10.59 | 10.29 | 9.50 | 8.53 | 9.39 | 9.99 |
| 2009 | 7.77 | 7.90 | 10.15 | 9.37 | 9.04 | 9.83 | 8.29 | 9.44 | 10.35 | 9.79 | 7.77 | 9.74 |
| 2010 | 9.17 | 8.36 | 9.54 | 8.81 | 9.77 | 9.61 | 10.14 | 8.58 | 9.44 | 9.06 | 9.78 | 8.54 |
| 2011 | 9.01 | 8.51 | 8.17 | 9.21 | 10.51 | 9.11 | 10.44 | 8.77 | 9.36 | 11.40 | 9.93 | 10.64 |
| 2012 | 8.75 | 9.55 | 8.73 | 9.95 | 9.66 | 8.87 | 8.91 | 9.27 | 8.18 | 8.96 | 9.84 | 9.79 |
| 2013 | 8.22 | 9.75 | 9.82 | 8.44 | 9.66 | 8.44 | 8.01 | 10.72 | 9.11 | 9.15 | 9.53 | 8.94 |
| 2014 | 7.41 | 9.42 | 7.42 | 8.60 | 9.39 | 9.27 | 9.37 | 9.35 | 9.15 | 8.75 | 9.43 | 10.23 |
| 2015 | 8.38 | 7.60 | 9.17 | 8.48 | 9.52 | 9.06 | 9.07 | 9.97 | 7.79 | 15.92 | N/A | N/A |

| Ranking\Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2005 | 2005 | 2006 | 2004 | 2003 | 2005 | 2005 | 2005 | 2003 | 2003 | 2003 | 2003 |
| 2 | 2006 | 2008 | 2005 | 2003 | 2008 | 2003 | 2013 | 2003 | 2015 | 2007 | 2005 | 2006 |
| 3 | 2014 | 2006 | 2014 | 2013 | 2006 | 2007 | 2009 | 2007 | 2006 | 2008 | 2009 | 2010 |
| 4 | 2009 | 2015 | 2011 | 2015 | 2005 | 2013 | 2003 | 2010 | 2012 | 2005 | 2004 | 2013 |
| 5 | 2013 | 2009 | 2007 | 2014 | 2009 | 2012 | 2006 | 2011 | 2005 | 2014 | 2007 | 2004 |
| 6 | 2015 | 2007 | 2004 | 2005 | 2014 | 2004 | 2012 | 2012 | 2004 | 2012 | 2006 | 2007 |
| 7 | 2003 | 2010 | 2012 | 2010 | 2015 | 2015 | 2015 | 2014 | 2013 | 2010 | 2008 | 2009 |
| 8 | 2008 | 2011 | 2003 | 2007 | 2013 | 2011 | 2004 | 2004 | 2014 | 2013 | 2014 | 2012 |
| 9 | 2012 | 2004 | 2015 | 2006 | 2012 | 2008 | 2014 | 2009 | 2007 | 2006 | 2013 | 2008 |
| 10 | 2011 | 2003 | 2008 | 2008 | 2004 | 2014 | 2007 | 2006 | 2011 | 2004 | 2010 | 2005 |
| 11 | 2007 | 2014 | 2010 | 2011 | 2010 | 2006 | 2010 | 2015 | 2010 | 2009 | 2012 | 2014 |
| 12 | 2010 | 2012 | 2013 | 2009 | 2011 | 2010 | 2011 | 2008 | 2008 | 2011 | 2011 | 2011 |
| 13 | 2004 | 2013 | 2009 | 2012 | 2007 | 2009 | 2008 | 2013 | 2009 | 2015 | N/A | N/A |

## 3.3. THIRD STEP

The persistence of mean dry bulb temperature and daily global radiation is validated by the frequency and length of runs of consecutive days, following the original Sandia method. Table 2 shows the final 12-year of the months constituting the TMY. In order to address the discontinuities at the month interfaces, each side is smoothed using curve-fitting techniques for 6 hours.

Table 2. The final selected candidate years for the months of the typical year.

| Month | Candidate Year | Number of Runs | Max Run Length | Month | Candidate Year | Number of Runs | Max Run Length |
|---|---|---|---|---|---|---|---|
| 1 | 2005 | 4 | 5 | 7 | 2003 | 5 | 5 |
| | 2006 | 4 | 2 | | 2005 | 3 | 2 |
| | 2009 | 6 | 2 | | 2006 | 2 | 2 |
| | 2013 | 2 | 2 | | 2009 | 2 | 2 |
| | 2014 | 2 | 2 | | 2013 | 2 | 2 |
| 2 | 2005 | 2 | 2 | 8 | 2003 | 3 | 3 |
| | 2006 | 4 | 2 | | 2005 | 2 | 2 |
| | 2008 | 2 | 2 | | 2007 | 1 | 2 |
| | 2009 | 4 | 2 | | 2010 | 1 | 2 |
| | 2015 | 3 | 2 | | 2011 | 3 | 2 |
| 3 | 2005 | 1 | 2 | 9 | 2003 | 1 | 2 |
| | 2006 | 4 | 2 | | 2005 | 2 | 2 |
| | 2007 | 5 | 2 | | 2006 | 5 | 3 |
| | 2011 | 3 | 2 | | 2012 | 2 | 2 |
| | 2014 | 5 | 3 | | 2015 | 3 | 2 |
| 4 | 2003 | 4 | 2 | 10 | 2003 | 1 | 2 |
| | 2004 | 3 | 3 | | 2005 | 3 | 2 |
| | 2013 | 1 | 2 | | 2007 | 3 | 2 |
| | 2014 | 1 | 2 | | 2008 | 2 | 3 |
| | 2015 | 3 | 2 | | 2014 | 4 | 2 |
| 5 | 2003 | 4 | 5 | 11 | 2003 | 1 | 2 |
| | 2005 | 0 | 0 | | 2004 | 1 | 3 |
| | 2006 | 3 | 2 | | 2005 | 3 | 2 |
| | 2008 | 4 | 4 | | 2007 | 3 | 3 |
| | 2009 | 3 | 3 | | 2009 | 3 | 3 |
| 6 | 2003 | 3 | 2 | 12 | 2003 | 3 | 2 |
| | 2005 | 1 | 2 | | 2004 | 3 | 3 |
| | 2007 | 4 | 4 | | 2006 | 3 | 3 |
| | 2012 | 5 | 2 | | 2010 | 3 | 2 |
| | 2013 | 2 | 3 | | 2013 | 0 | 0 |

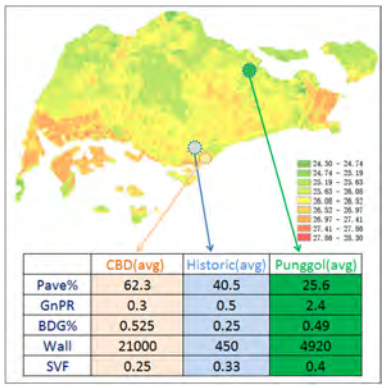
## 3.4. FOURTH STEP

According to the research result by Jusuf and Wong (2009), equation (4) gives the correlation between the urban texture variables (building, pavement and greenery) and temperature:

$$T(℃) = 2.347 + 0.904 * orgT(℃) + 5.786 * 10^{-5} * radiation(w/m^2) + 0.007 * pave(\%) - 0.06 * GnPR - 0.015HBDG + 1.311 * 10^{-5} * Wall(m^2) + 0.633 * SVF \quad (4)$$

where *T* is the air temperature, *radiation* is the global solar radiation, *pave* is the percentage of the pavement within the site, *GnPR* is the green plot ratio, *HBDG* is the average height to building area ratio, *Wall* is the total area of the wall of the buildings, and *SVF* is the sky view factor.

Considering the UHI daytime temperature map by Jusuf et al (2007), this research identified representative locations and texture values from the central business district (CDB), the historical and a residential area (Figure 2).




| | CBD(avg) | Historic(avg) | Punggol(avg) |
|---|---|---|---|
| Pave% | 62.3 | 40.5 | 25.6 |
| GnPR | 0.3 | 0.5 | 2.4 |
| BDG% | 0.525 | 0.25 | 0.49 |
| Wall | 21000 | 450 | 4920 |
| SVF | 0.25 | 0.33 | 0.4 |

*Figure 2. Different locations and urban texture variables in Singapore.*

## 4. Comparison and discussion

We distinguish four different TMY files: the new TMY without UHI, the new TMY for the CBD area, the new TMY for the historical area and the new TMY for residential Punggol. The dry-bulb temperature of the new TMYs is consistently higher than the original TMY data (Figure 3). Ignoring the UHI impact, the temperature is about 1°C higher. With UHI impact, the temperature difference increases to 2°C. For the dew point temperature, the new TMY without UHI is lower than the original TMY before May and higher after June (Figure 4). With the UHI impact, the dew point temperature is 1-2°C higher. Because we did not apply the UHI impact for wind velocity and global solar radiation, we only compare the original and new TMY without UHI impact (Figure 5). The wind velocity is similar to the original. This is important when using the TMY for ventilation simulation. For solar radiation, Figure 6 shows that the original TMY is higher than the new TMY data. Since higher solar radiation should cause higher temperature, the UHI impact on the temperature proves to be even more important.

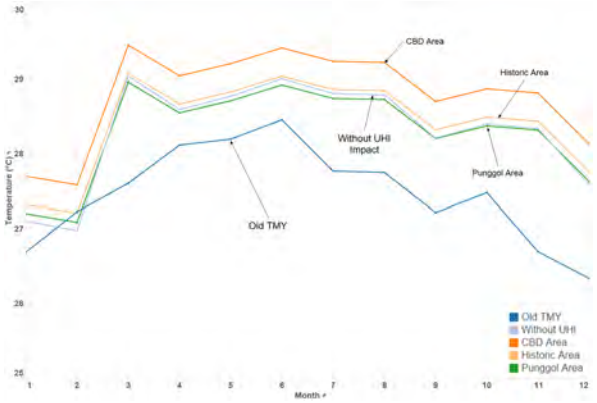



*Figure 3. Dry-bulb temperature comparison among the five TMYs.*

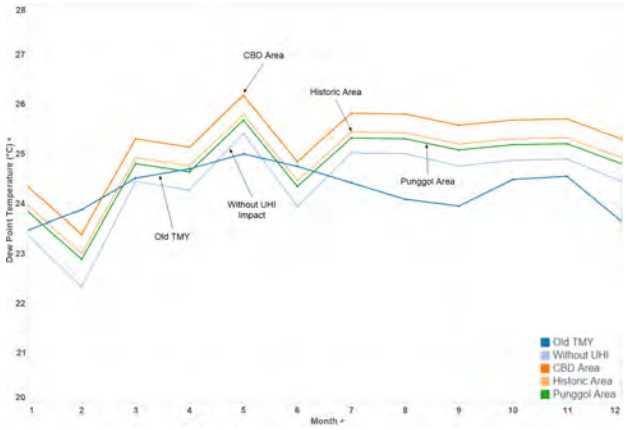



*Figure 4. Dew point temperature comparison among the five TMYs.*

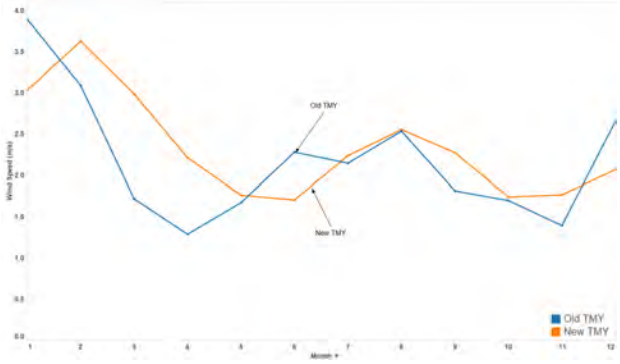



*Figure 5. Wind velocity comparison between the old and new TMY.*

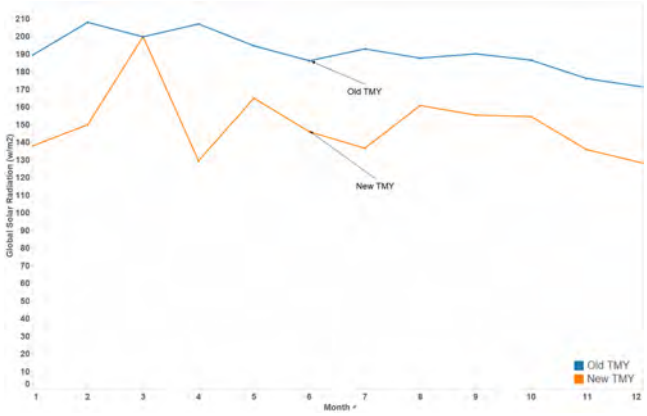



*Figure 6. Global solar radiation comparison between the old and new TMY.*

In order to understand the impact of the new TMY for simulation, we consider a typical 3-bedroom design as simulation model and run the simulations for all five TMYs. The differences with respect to the old TMY for the cooling load are: 1) 1% without UHI impact; 2) 0.75% for Punggol; 3) 2.5% for the historical area; and 4) 8.1% for the CBD area. This result again proves the importance of considering the UHI impact. However, this research only considers the UHI impact for temperature; other variables like wind velocity, illuminance, etc., are also affected by the urban variables. The study of the impact of UHI on wind velocity and illuminance remains to be done. Considering that temperature and solar radiation are the most important for simulation of solar energy conversion systems and building systems, the new TMYs with the different urban texture variables will be more adequate than the original TMY.

## 5. Conclusion

The objective of this research is to create micro-scale typical meteorological weather files (TMY) for different urban texture values. The results show that there is a considerable difference between the new TMYs and the original TMY for Singapore. From the performance simulation of solar energy conversion and building energy-efficiency, the differences of temperature and solar radiation prove that the original TMY is not suitable for energy simulation analysis. Although the accurate deviation of energy consumption between the real-world and the new TMYs has not been calculated, the impact from UHI can be confirmed. Hence using this proposed modified Sandia method for generating TMYs will be more adequate. The generated micro-scale TMYs will also benefit energy efficiency building and urban design. In the future, we will further compare energy simulation results when using the

new and old TMYs. The impact for wind velocity and solar radiation from UHI will also be included for different simulation objectives.

## Acknowledgements

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# DESIGN DRIVEN PHYSICAL EXPERIMENTATION

*A flexible wind sensing platform for architects*

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**Abstract.** Architectural design in this 'digital age' is becoming more embedded within virtual computer aided design environments. This study expands this virtual design environment back into physical realms through the use of microelectronic wind sensing technology. An interactive and flexible wind sensing system (open source miniature portable wind tunnel and wind sensors) was evaluated for its ability to simulate and measure the effects of wind. Physical models of four high-rise buildings were constructed to evaluate ground level pedestrian comfort resulting from the degree of torsional twist in the building form. The model investigation formed a case study for evaluating of the low-cost miniature portable wind tunnel and microelectronic wind sensing system for comparison with an industrial aeronautical wind tunnel and high precision wind sensors.

**Keywords.** Architectural wind tunnel; microelectronic wind sensing; twisted building; wind visualisation.

## 1. Introduction

Engineers tend to create idealised wind simulations where there is a uniform wind velocity and very low turbulence intensity distribution (commonly for aerofoils) or, in the case of explorations of wind around buildings, the model-scale replication or digital simulation of the atmospheric boundary layer (ABL) (Baker et al, 2012). Whereas, architects, in general, tend to want to explore, adapt and interact with the wind with qualitative explorations (Salim, 2014; Williams et al, 2015). These interactions may happen in digital or physical realms or both (Salim, 2011).

Wind phenomena around buildings and architectural elements such as facade systems are a challenge to predict. Wind engineers and fluid dynamicists have utilised extremely high fidelity and fine resolution computational fluid dynamic (CFD) models to further understand these phenomena (Watkins et al, 2015). However, the fluid dynamicist is still restricted by the tools by which they can attempt to provide visualisations of the dynamics in the wind. The state of the art in wind sensing extends to the nano-scaled and high frequency spectrum for 'point-based' measurements of wind (e.g. nano-scaled hot-wire and laser-Doppler anemometry) (Smits and Hultmark, 2014). Two-dimensional slices of the wind are desirable when observing macro-scaled wind phenomena (e.g. particle image velocimetry (PIV)). Techniques that are used by wind engineers include: the pitot static tube, manometers and hot-wire anemometry (Baker et al, 2012).

Tools such as wind tunnels and CFD software are becoming more available to architects during the design process. However, these technologies have required expensive facilities or high expertise or both in the majority of cases. For instance, the conditions to reproduce ABL conditions require large and expensive facilities, including advanced sensor systems (Cermak, 2003). Because of this, the technology is not fully integrated from the early design stage of the architects' work-flow. However, sensing technology is becoming cheaper and more accessible for designers (Badger, 2014; Prohasky and Moya Castro, 2014).

The aim of this research was to develop a wind sensing platform built with low-cost components and provide a highly flexible and adaptable system with the possibility to include multiple types of environmental sensors. The research documented in this paper is an extension of previous work conducted by the authors (Prohasky and Moya Castro, 2014) on the evaluation of a MEMS sensing system within an industrial scale aeronautical wind tunnel (AWT) with ABL conditions.

This paper includes an evaluation of two parts of a proposed low-cost wind sensing platform (1. miniature airflow tunnel (MAT); 2. low-cost sensor platform). The applicability of this analysis platform for the architectural design of building form was evaluated i.e. outdoor pedestrian wind comfort conditions around an example high-rise building with different degrees of twist up the building form.

The twisted buildings were tested in the MAT (see section 2.1 and Figure 1) and in an AWT. The AWT generated very smooth flow (turbulence intensity <0.5% in undisrupted flow) with a flat velocity profile. The test section was octagonal with dimensions: 1.37m by 1.07m (Figure 1). A comparison was made between results from the MAT and AWT. The low-cost sensor re-

sults were verifiable with reference precision wind sensors (Cobra probes (Mousley, 1995; Watkins et al, 2002)).

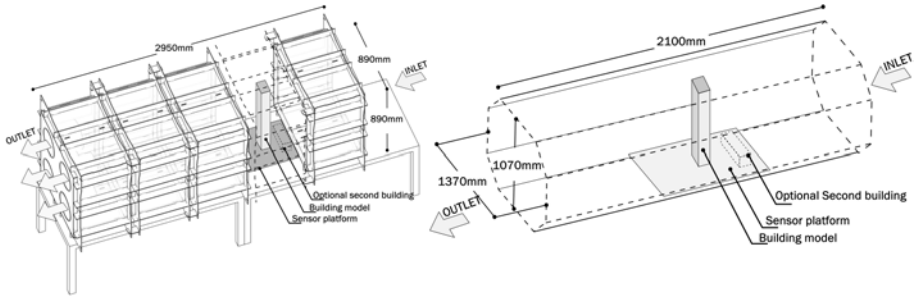



*Figure 1. 'Low-Cost' Miniature Airflow Tunnel (MAT) (left) and the Industrial Scale Aeronautical Wind Tunnel (AWT) test section (right)*

The miniature airflow tunnel and sensing system presented in this paper can be used by architects in the early stage of the design process within a framework which is partly covered within this paper (and will be expanded upon in subsequent papers) (Moya Castro and Prohasky, 2015).

## 2. The flexible wind sensing platform

This wind analysis platform was designed as an accessible and easy to build technology, feasible to be replicated for pedagogical purposes or wind analyses in early design stages within architectural design practice. The platform was envisioned to sense the dynamics in the wind on a basic level using electronic sensing equipment and a graphical interface to visualise the data of wind around buildings in real time.

The flexible wind sensing platform consists of three main components:

1. Miniature airflow tunnel: Open source simulator/generator for the evaluation and investigation of the dynamics in air
2. Wind sensors: Microelectronic wind sensors from ModernDevice (rev-P wind sensors (Badger, 2014))
3. Visual interface: McNeel Rhinoceros 5 and Grasshopper3d/Firefly

Detailed system descriptions of the sensing and visualisation system can be found on the MAT website (Moya Castro and Prohasky, 2015).

### 2.1. OPEN SOURCE MINIATURE AIRFLOW TUNNEL

The miniature airflow tunnel (MAT) is an open circuit wind tunnel (Figure 1). The MAT was constructed with 'low-cost' materials and fabricated using computer numerical control (CNC) methods. The construction of the miniature wind tunnel required: a laser cutter or CNC router; tunnel frame tem-

plates; timber or acrylic sheet material; industrial fans. The total material cost of this MAT was less than AUD$1000.

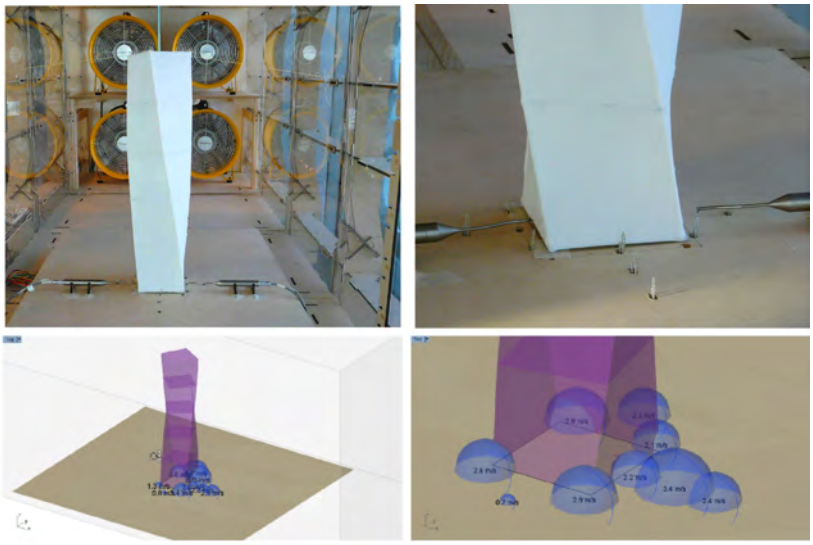


*Figure 2. Low-Cost' Miniature Airflow Tunnel looking down the tunnel from the inlet (left) and an axonometric diagram of the MAT (right)*

The MAT can run both ways (suction or blowing) (depicted as suction in Figure 1). The wind velocity and turbulence intensity were measured within the MAT for both suction and blowing scenarios (Figure 3).

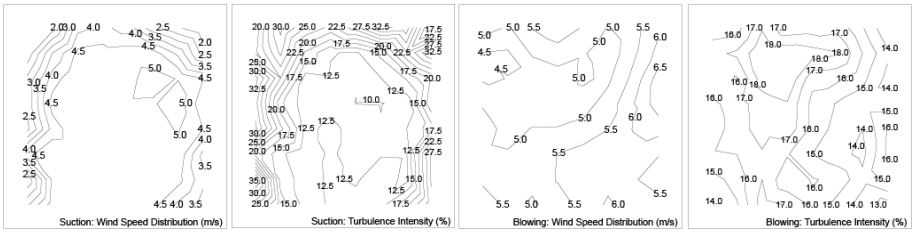



*Figure 3. Velocity contours (m/s) and Turbulence Intensity contours within the Miniature Airflow Tunnel at 2.1m from the fans sucking (left) and blowing (right)*

The characteristics of suction induced flow were: lower wind speed, smoother flow and more homogeneous flow across the tunnel test section (Figure 3). This may be desirable for experiments which involve measurements of boundary layer separation zones, observations of wake regions from bluff bodies or - in the case of porous screens - simulating turbulence characteristics behind a porous screen (Williams et al, 2015).

Flow generated through positive pressure (blowing) was much more turbulent; however the average wind speed was slightly higher (Figure 3). The high turbulence intensities may be desirable for simulations around model buildings where the turbulence characteristics can be trained with obstructions in the flow to simulate atmospheric boundary layer conditions typically experienced in urban environments.

The smoother flow (within the central region of the tunnel (Figure 3)) created through suction was chosen for a more strategic comparison between results in an industrial aeronautical wind tunnel (AWT) (the model buildings were placed 2.1m from the fan inlets within the MAT Figure 1).

### 2.2. MICROELECTRONIC WIND SENSORS

The wind sensors used for the physical wind sensing platform (PWSP) were similar in function to a hot-wire anemometer. The temperature drop of a heated element due to wind flow is transduced. The voltage output is then calibrated against various wind speeds and temperatures. Hence, the wind sensors used are temperature dependent, but this is corrected by a reference temperature measurement on the sensor. The hot-element anemometers are also directionally non-linear - there is no clear correlation between the direction of the wind and the sensor output. However, time-averaged values of wind speed measurements do have a reasonable approximation where the angle of the incident wind flow is less than ~45º (details for which can be found in Prohasky and Watkins, 2014).

The rev-P wind sensors were calibrated en masse and applied to this project. Each sensor required an individual calibration function to create a more reliable sensing system for this study. Though, a general calibration function and simplified calibration method can be found through the ModernDevice website (Badger, 2014).

## 3. Case study and system evaluation

A flat velocity profile was used for the experiments with the model buildings with various degrees of torsional twist (0°; 60°; 120° and 180°) (Figure 4). Reference measurements within the unobstructed wind flow were used to non-dimensionalise the wind speed measurements.

Tests were conducted at three different wind speeds within the AWT (3.5m/s; 5m/s and 6.5m/s) with good repeatability (the distribution of wind speed variation was independent of the incident wind speed). The MAT tests were conducted at only one incident wind speed. The buildings were placed in unobstructed flow and behind a second obstructing building.

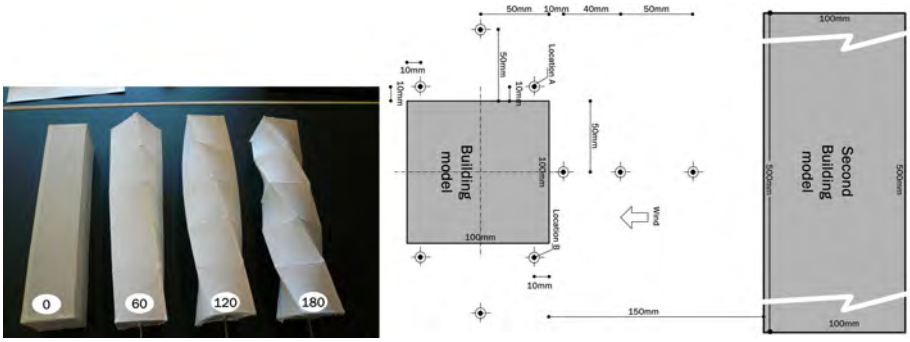



*Figure 4. Sample model buildings with various degrees of torsional twist (left) and sensor locations around the building at pedestrian level (right)*

The atmospheric boundary layer was not simulated in this study, but is important when attempting to replicate the actual conditions in the building's context. The ABL would amplify the vertical wind deflections on the windward façade (Watkins et al., 2015). Thus, without a simulated ABL the main deflection of the airflow was horizontally around the tower - generating low, but reasonably well-structured variations around the building base.

There were 9 rev-P wind sensors located at the points shown in Figure 4. However, the two sensor locations 'A' and 'B' in Figure 4 were used to compare between the results measured by industrial standard wind sensors (Cobra Probes) and the 'low-cost' alternative (rev-P). These measurements were taken in both the MAT and AWT.

Cobra Probes were used for reference measurements to bench mark the sensing system in the turbulent flow condition (in the MAT) and the smooth flow condition (AWT). Since this study involved the evaluation of a measurement system – the errors in the system will also be mentioned. Hence, the first observation to take note of is the very low measurement from 'rev-P sensor B' seen in Figure 4. This value was measured consistently over multiple incident wind speeds, with multiple sensors in-place, yet there was still no explanation – it was expected to match with the Cobra Probe measurement.

The decreasing wind speed with respect to increasing angle of twist at location 'A' has a clear trend in both tunnels with good matching with the reference instruments (Cobra Probes (Mousley, 1995)) (Figure 5). 'Rev-P sensor B' does not agree with reference measures across both tunnels. The turbulence intensities at each point were analysed and were found to have insignificant effects – which may suggest the wind sensor was experiencing directional disturbances that influenced the results.

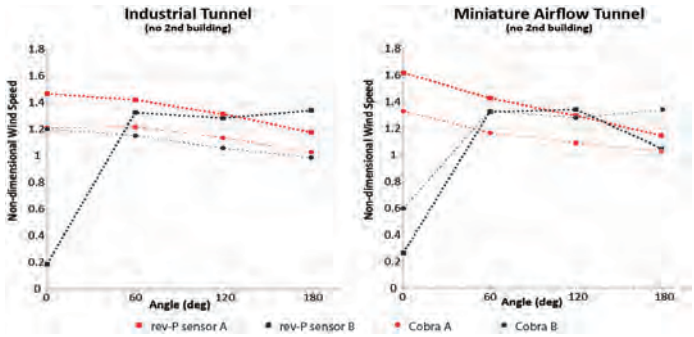



*Figure 5. Non-dimensional wind speeds at locations 'A' and 'B' with unobstructed buildings in the AWT and MAT*

With the obstructing building in place - matching trends are found across both wind tunnels for locations 'A' and 'B' with the Cobra Probe reference measurements (Figure 6). However, only rev-P sensor 'A' had reasonable matching trends with reference measurements – rev-P sensor 'B' showed similar anomalies in the previous example (Figure 6).

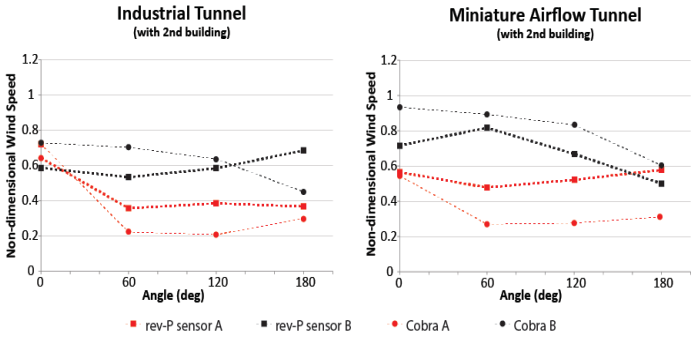



*Figure 6. Non-dimensional wind speeds at locations 'A' and 'B' with an obstructing building (a second building placed in front of the model building in question) in the AWT and MAT*

## 4. PWSP evaluation and design impact

The results between both tools for wind analysis are quite similar and present low variation when the flow is in a trained turbulent condition (with an obstructing building in place) – this may apply well in ABL conditions. This does not mean that the mini airflow tunnel can replace the aero wind tunnel, but it shows the grade of accuracy for this low-cost platform, which can be a reliable tool to visualise wind conditions around conceptual building models with results apt to consider on a conceptual level.

A spiral facade can produce levels of wind discomfort in the corners of the windward side. This effect is clearly visible through both groups of ex-

periments with the AWT and MAT. Both groups of experiments show that this phenomenon of discomfort is produced from the upper area of the facade and secondary buildings do not mitigate it.

However, the observations and comparison of the sensor data shows how the progressive torsion of the building ameliorates the velocity intensity in the sensor locations 'A' and 'B' (near corners). If we discard significant variation of the vertical airflow deflection from the facade to the ground (it is not significant in these experiments with a flat velocity profile), there is one possible cause for this variation of air velocity: the change of the lateral deflection angle of the wind projected from the windward building corners. The separation zone areas are reduced - moving the airflow angle closer to the building façade (Figure 7). Thus, it is possible to state that the better design for less separation of the airstreams from windward corners is a building shape with 180º of torsion.

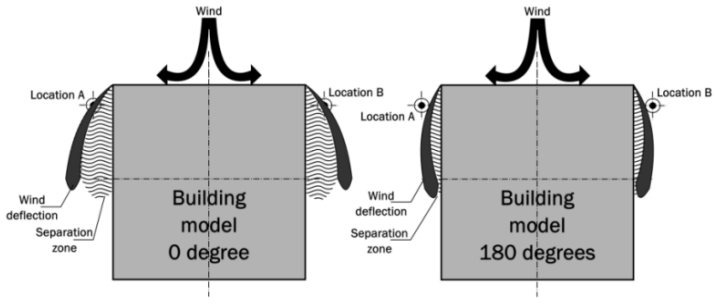



*Figure 7. Effect of building twist on windward corners in flat velocity profile airflow (plan)*

This data showing the change of the airflow direction at the building base allows prediction of possible scenarios and performance of early design actions. For instance, it is possible to estimate a better comfort condition in the areas that are close to this twisted building; so it is possible to propose a better use or program for the surrounding public space. Moreover, the fact that the separation angle of the wind from the corners is less, means the areas at the bottom of the facade could be more uncomfortable (small separation zone); Therefore, it would require a design which includes additional elements such as: windbreaks; gardens with trees or canopies to ameliorate potential pedestrian comfort issues.

The PWSP is a good strategy to compare and evaluate the design (advantages of 180º torsion) with other design alternatives (0º, 60º, 120º) in the early design stage. Also, it provides: more time in the design process to think about how to deal with the potential issues associated with a particular de-

sign option (pedestrian wind comfort); possible implementation at the beginning of the design process.

## Conclusion

A miniature portable airflow tunnel and wind sensing system was evaluated. Several model buildings were placed in wind flow generated within the 'low-cost' miniature airflow tunnel and results were compared with those from precision wind sensors and a wind tunnel with smooth flow. Based on the observations from the 'low cost' sensors (with verification from the precision sensors) it is evident that the building with the 180º torsion is most desirable for pedestrian comfort at locations 'A' and 'B'. However, unexplained phenomena measured by the sensors still caused uncertainties in results that need to be confirmed through qualitative flow visualisation methods (this will be covered in a subsequent publication).

The alternative 'low-cost' wind analysis platform (MAT and microelectronic wind sensors) resulted in a tool with the potential to conduct some preliminary quantitative analysis of wind movement around buildings. The results are promising for a 'low-cost' alternative for physical wind analyses. This method was useful to establish a hypothesis to explain the change in the wind intensity near the corners of the model building concepts. Finally, there is room for more improvements in the MAT and sensing system so the unexpected measurements by the sensors can be avoided.

## Acknowledgements

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# ITERATIVE DESIGN PROCESS BETWEEN PHYSICAL MODELLING AND COMPUTATIONAL SIMULATION FOR PRE-TENSIONED GRID SHELL STRUCTURE

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**Abstract.** Grid shell structures are widely used in many types of buildings. In this paper the author proposes a new grid shell structure, which is pre-tensioned by stretchable membrane. Through iterative process between physical modelling and computational simulation, one pavilion is finally presented as a demonstration of the architectural performance of this structure.

**Keywords.** Material computation; form finding; pavilion; grid shell; active bending.

## 1. Introduction

With the development of computational tools, many natural phenomena can be simulated. In architectural design, it also helps to simulate material behaviour, especially elastic or flexible material, even though these kinds of bending materials were used empirically, even in primitive architecture. This paper shows a new type of grid shell structure, which is created by using the equilibrium of two elastic materials. The grid structure is made out of a bendable material (wire), its deformation made possible by attaching a stretchable fabric smaller than the size of the grid structure. Usually the shape of this grid shell structure is formed by one single material, such as bent wood, and the membrane just covers the shape. But in this case, by controlling local deformations (which comes from the equilibrium of two elastic materials), one can create 3D geometry. Therefore, by changing the 2D grid pattern, the various geometries of a grid shell structure can be generated. In addition, it does not require any supporting formwork for making complex curved geometries, since the system is completely created from a 2D pattern.

In the research of “form finding” by Frei Otto, the German engineer and architect, the form of architecture is developed by way of a series of physical modelling (Otto, 1995). Although it is mainly for structurally optimized forms for tensile structures, the geometries Otto created are so varied and organic, that it is hard to design by a more man-made, top-down idea. This means that the interaction of material and humans still has the primary power as the design driver. Although the main purpose of form finding by Frei Otto is the minimisation of material in construction, this research is focusing on the possibility of form finding as new design tool. Of course, now computational tools can help this process with regard to design speed and quantity of the studies.

Thus, this design process started with finding materials, and with successive, iterative physical modelling using these materials. This physical modelling is always starts with a small model, which can be easily made by one person. Then, after several physical and the computational tests, the model can be scaled up to larger pavilion-scaled structures.

Although these computational tools are widespread in contemporary architectural design practices, the result of the process is only architecturally meaningful if it can be translated into real, physical construction. In reality however, some digitally designed proposals completely lack material performance, and therefore cannot be realised. As opposed to this, the design system proposed in this paper focuses on rational construction, emphasising the material behaviour both for smaller models and larger architecture.

## 2. Iterative design process between physical modelling and computational simulation

The difficulty of this system is that it is hard to precisely control the material behaviour, since both the grid and the membrane are flexible and relatively soft. It therefore needs an iterative design process using both physical modelling and computational simulation.

The computational simulation is done by way of a particle-springs system used in 3D modelling software. By simplifying the material behaviour into the movement of particle and spring, one can simulate the geometry easily and rapidly. It is very helpful to know an appropriate grid pattern for the target geometry. Of course, whenever the used material is changed, the parameter of the simulation settings needs to be changed by comparing the result of the physical modelling and the computational simulation. For example, the simulation with the piano wire for small model and the one with carbon fibre for a mock-up are different. As a result, it is important to have a feedback loop between the physical and the computational. After several mock-ups,

computational simulation, and structural analysis, a pavilion with a 5m by 5m footprint has been built.

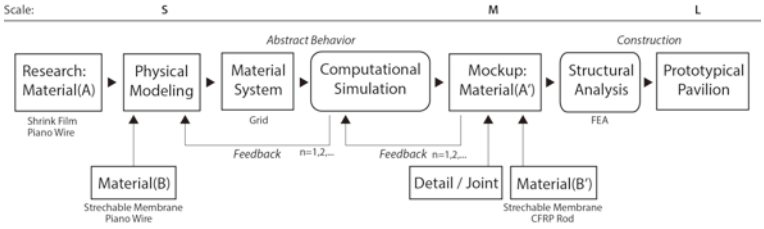



*Figure 1. Iterative design system.*

## 3. Physical modelling from shrink film to stretchable membrane

### 3.1. SHRINK FILM

In the beginning of the research, the physical modelling was tested with shrink film and piano wire. Shrink film is a very thin film made out PVC (polyvinyl chloride) and usually used for wrapping material, shrunken by applying heat. In addition, piano wire is also thin and has elastic behaviour, with very flexible bending properties. By combining these two material characteristics, the specific geometry can be generated. (Kuma, 2014) Piano wires are attached to the flat shrink film by transparent tape in a grid pattern. After applying heat by dryer, the film shrinks, and this tandem system deforms into a three-dimensional, wavy surface. The direction of the bent wire is automatically defined, because it follows the deformation of the surface. However, since the shrink film has limited scalability, a stretchable fabric with more tensile capacity is adopted as alternative material.

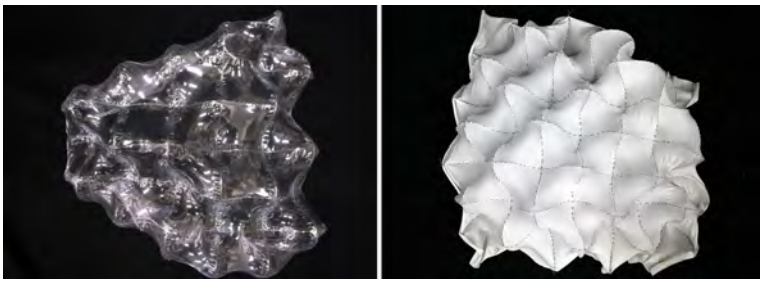


*Figure 2. Model photos of shrink film and stretchable membrane.*

### 3.2. STRETCHABLE MEMBRANE

Stretchable fabric is usually used for clothing such as swimwear or sportswear. It is composed of 88% polyester and 12% polyurethane. By stretching, it can expand to more than double its original area. For the model, the same piano wire is used as with the shrink film. As an initial setup, the stretchable fabric needs to be pulled and held into place by a wooden frame. Then, the piano is directly stitched to the stretchable fabric, rather than with the previous tape. Once all the piano wires are attached in a grid pattern, the resulting surface is released from the frame. As a result, it becomes a 3D wavy surface from 2D. However, if each of the grid spaces is small, it does not create local deformations. On the other hand, when one creates a 2D gradational pattern that has larger spacing in the periphery, and smaller spacing toward the centre, it creates a global dome shape with a wavy surface. This is the result of large local deformations at the periphery, and the much smaller deformations at the centre.

For a larger scale model, the piano wire is too thin, and therefore it is replaced by carbon fibre strand rod, which is light and has high tensile capacity. The mock-up with carbon fibre rod is tested again and again. For example, the several types of joints of the fibre rod and the membrane are tested for structural capacity in this mock-up process. This data also translated into the computational simulation, which is discussed in the following chapter.

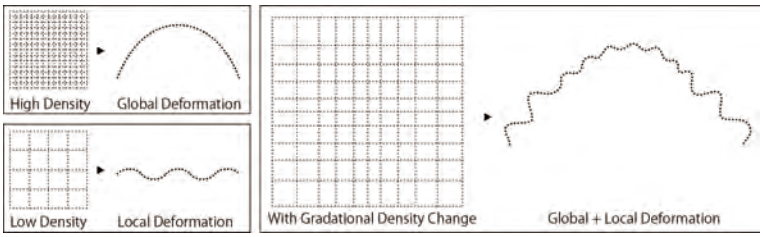



*Figure 3. Patterns for local deformation and global deformation.*

## 4. Computational simulation

For the computational simulation, 3D modelling software with a physics engine approximates a system of particles and springs. (Piker, 2013) The wire is composed of particles and springs in this simulation. It is converted into a polyline, which is the continuous line described by the connecting each of the particles. The membrane is composed of a network of simulated springs, in turn connected to the particles on the polyline. Two features of the wire are represented abstractly. One is the restoring force. The wire tends to become straight by inner stress. The second one is the limitation of bending.

There is a limitation to the curvature of the fibre rod, defined by its material. The first feature, the restoring force, can be simulated in particle and spring system, by a bend function, which controls the angle between three particles. In this situation, the function is set to make those angles to be 180 degrees. Thus, this can be used to simulate the inner stress. With the second feature (limitation of bending), by measuring the curvature of each wire, it is possible to detect any curvature over a determined limit.

The images below show how the 2D grid pattern deforms by changing the shrinkage of the membrane. In the third picture, the shrinkage is 37.5%, which is as same as the setting of the physical modelling. The colour of the wire shows the minimum curvature of the carbon fibre strand rod. Red indicates the limitation of the curvature. If it is smaller than that, the fibre rod can become broken. By comparing with the result of the physical model, the setup of computational simulation is adjusted: the feedback of the computational simulation allows any newly generated pattern to be tested in a physical version, and vice versa. This workflow makes the simulation more accurate.

In addition, for the simulation of pavilion scale prototype, gravity needs to be considered. This is because in reality, the system is too heavy to become a 3D shape from a 2D pattern only by the shrinking force of the membrane. Thus, some anchor points in the periphery are moved to target locations for enabling the tendency to create a 3D shape, in addition to the shrinkage of the membrane.

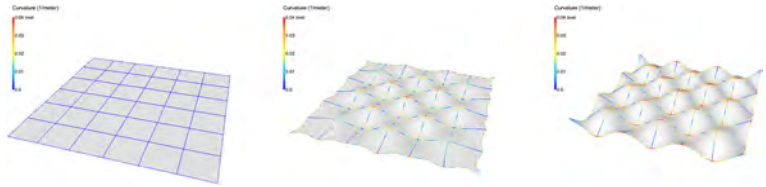


*Figure 4. Computational simulation for local deformation.*

## 5. Structural analysis

The contribution of the membrane is not only for making a deformed grid, but also for reinforcing the global structure by adding pre-tension. In that sense, this structure has a new type of integration between tension and compression forces. In this project, the structural analysis is done by FEM analysis software developed by Prof. Jun Sato from University of Tokyo. It calculates stress and visualizes the safety factor distribution of the model generated from computational simulation mentioned in previous chapters. In that computational simulation, the material property is not considered, but

this structure analysis is based on the structural properties of carbon fibre rod and stretchable membrane. Colour variation represents the safety factor, which is defined as a ratio of calculated stress to allowable stress in each member. For example, blue (less than 0.5) means high safety margin, red (more than 1.0) is over the allowable stress. The structural performance of each model can be compared by the colour distribution. Basically, the new computational models are continually tested in this FEM analysis by changing the form until it attains structural safety as indicated by good colour distribution.

This analysis shows that the structure with a wavy surface is structurally more rigid than one with a smooth surface. The image below shows the comparison between the model without membrane (left) and one with membrane (right). The one with membrane is actually the model of the final prototype. This analysis shows that the one without membrane has red appearing around the bottom. This means that it may not be even self-supporting. The one with membrane has just a few areas of red, and most of the parts are blue, so that it can be self-supporting. In other words, by combining the membrane with the grid wire, the amount of the wire can be minimized. This is because the membrane itself is reinforcing the structure instead of adding the wires.

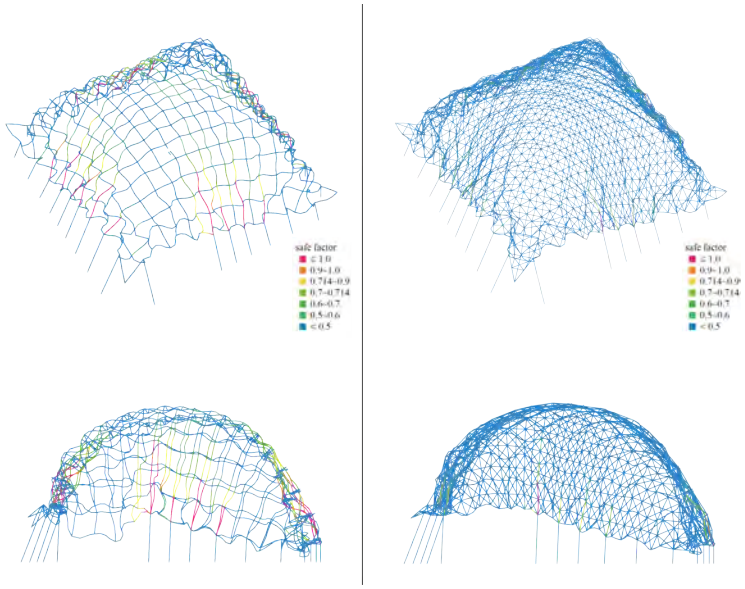



*Figure 5. Structural analysis for the model without membrane and one with membrane.*

## 6. Prototype

To make a pavilion-scale prototype, the stretchable membrane is doubled. Thousands of zip-ties connect the carbon fibre rod to the fabric. First, the carbon fibre rods, cut in specific lengths, are laid down on the ground. Second, connecting the intersection points makes the grid structure. Third, the stretchable membrane is attached to the fibre grid from the centre by zip-ties, while pulling the membrane taut. Fourth, after the attachment of the fibre and the membrane, the stainless pipe for the base is installed. Finally, by moving the fibre and the membrane, some of the fibre edges are fixed into the stainless pipe. This is the procedure of construction of the prototypical pavilion. Following this, by making a 3D scan of this geometry from the series of the photos of the pavilion, the actual model and the computational model are compared, to know if the simulation works precisely.



*Figure 6. Construction process of prototype.*

Although the local wavy surface of the pavilion is not exactly same as the simulation, the global geometry is reasonably close, nearly matching the location of highest point, the size of the entrance, and so on. This pavilion stood for one week in the open air, at the University of Tokyo. It accommodates more than ten people inside.

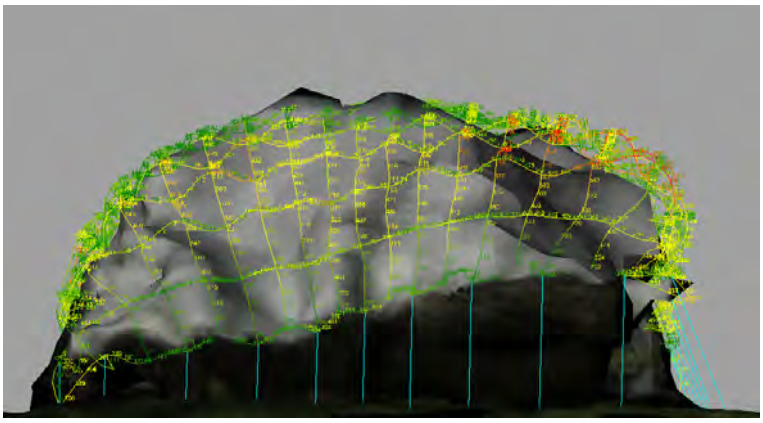


*Figure 7. Comparison between 3D scan data of prototype and computational model.*

## 7. Conclusion

As the prototypical pavilion shows in the chapter before, the combination of two elastic materials can create new architecture in terms of visual effect and spatial quality. In particular, this architecture exhibits lightness without any air-pressure or rigid-structure. This is because the material performances are maximized in terms of structure and design.

In addition, this design process is very adaptive to various types and sizes, since this shows the relationship between 2D patterns and 3D form. It is similar to how origami works with regard to form generation from 2D pattern. But instead of having any folding lines (which are always problematic at a larger scale), this system has a graduation of local deformations in order to create effects on the global structure. Compared to traditional form-finding research, this system has more flexibility in the resulting form. This is because the form is generated by a 2D grid pattern. It means that there are potentials for adapting to given spatial requirements.

Furthermore, the computational process could contribute not only to making faster design studies, but also to integrating multiple factors of architecture, such as the structure analysis in this paper. In analyzing this kind of complex double curved form, the 3D model is necessitates FEM analysis. Potentially other types of analysis can be performed, such as wind load response, or several kinds of environmental analyses.



*Figure 8. Interior view of prototype (Photo by Jun Shimada).*

## 8. Outlook

Although computational tools are used through the entire process, and the geometry of the resulting pavilion is close enough to the simulated target surface, the accuracy is not so high yet. Therefore, in order to get satisfactory results, the iterative process between the physical and the computational models take a long time because of this inaccuracy. Now, the simulated material's behavior is abstracted into a system of particles and springs. This simulation system can be updated by the integration of FEM. In this, the material properties—such as the exact material size, its generated modules, or other structural information—can be included into the calculation, resulting in more accurate results, as well as the full integration of morphological simulation and structural analysis.

Moreover, a future goal is to scale up this pavilion by using the same system. At the moment, the materials of the pavilion—the membrane and the carbon fiber—are not rigid enough for a more permanent structure, and not durable in the outside environment. But by combining a suitable stretchable membrane for architecture and a more rigid bending material, it can be enlarged to the next scale. This is because this system does not require specific material. It uses just the relatively simple two material behaviors: stretching elasticity and bending ability.

Additionally, the system for construction has more room for further development. For example, if at the full scale the membrane is already in ten-

sion and stretched by a rigid frame, people do not need to pull the membrane for the attachment to the wire. By releasing the membrane and the wire after the attachment, it automatically pops up from 2D to 3D in a real scale, much like the smaller physical model. This could improve the speed of the construction process.

## Acknowledgements

This research was primarily conducted in the Obuchi Lab, Kuma Lab, Chiba lab and Sato Lab, at the University of Tokyo. Research sponsor Komatsu Seiren provided carbon fibre strand rods. The authors would like to particularly thank the team of the pavilion project: Jun Shimada, Kantaro Makanae, Masayuki Takiguchi, Aisa Arikawa, Takanori Ishii, Liija Li, Tatsunori Shibuya and Masatoshi Nishizato.

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# ADAPTIVE BUILDING FACADE OPTIMISATION

*An integrated Green-BIM approach*

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**Abstract.** This study focused on the optimal design of adaptive building façade for achieving better energy performance. Iterative façade components design are studied between virtual and physical models with integrated tools of BIM, parametric design and sensor devices. The main objectives of this study are: (1) exploring systematic design process via the analysis of adaptive components in responsive façade design; (2) developing compliance checking system for green building regulations; (3) developing optimization system for adaptive façade design process. This paper demonstrated the integration of various digital design methods and concluded with the energy modelling results of a demo project unit for various façade component designs.

**Keywords.** Building façade design; energy performance; design optimization; parametric design; BIM.

## 1. Introduction

Adaptive building façade provides subtle composition and flexible adjustability of façade elements for optimizing the total effect of heat transfer, daylighting, and solar insolation. From 2004, the IEA (International Energy Agency) has started research efforts for AIF (Advanced Integrated façade, DSF (Double Skin Façades) and RF (Responsive Façade). However, most demo cases are mainly located in the temperate zones, and still no interactive tools are available for complex façade design. Dewi (2013) confirmed that the DSF strategy is possible to use in a subtropical region. Loonen (2011) indicated that building designs with seasonal adaptation strategies can enhance energy and comfort performance compared to the best static situation.

From our review and local project survey, to face the complexity of sustainable building façade design, it requires a holistic and integrated approach to deal with the local situations as follows:

- Façade Design Process - The method for energy survey is now only available for single-layer façade and not for multi-skin and responsive façade yet.
- Green Building Regulations - Most legitimate evaluation rules for multi-skin and kinetic shading are too complicated to be integrated into green building regulations. Therefore, it hinders architects from exploring innovative façade during the design phase. Currently, BIM-based energy design tools provide opportunities in supporting real-time interactive design modification and visualized optimal analysis for the requirements of local green building regulations.

To solve the problems, we aim to develop a design platform that provides smart components and interactive design tools to assist kinetic and complex façade design processes.

## 2. Literature review

Green BIM technology normally focused on simulating the heat performance of different site layouts in order to modify the mass allocation and building orientations in the early design phase. According to Aksamija (2015), façade design in subtropical areas should consider: Solar Control, Reduction of External Heat Gains, Cooling and Daylighting. However, currently many BIM-based energy analysis tools (e.g. Ecotect, Energy Plus, eQuest or Autodesk© Building Performance Analysis) accept only simplified building envelope model and output with general total report of building performance. In order to develop a useful design tool for better simulation of the effects of façade design details, a customized energy analysis platform has to be developed. The key factors of local green building regulations and related research projects are introduced as follows.

### 2.1. RELATED LOCAL REGULATIONS

Based on the local green building regulations in Taiwan, the energy performance of buildings are determined by three factors, i.e. Envelope Loads, Air-Conditioning Loads and Lighting Loads. Building façade is part of Envelope Loads, other than the roof. The energy performance of façade follows the equations of ‘EnvLoad’ calculation. In this study, we will firstly adopt the equation for office buildings (Table 1) as an example for modelling the effects of façade design details. The key parameters in the equation include geometrical data (e.g. area of windows, total envelope area, etc.) and non-

geometrical data (e.g. glass transmission rate, regional data, cooling degree day, etc.). Also some factors such as shading factor are derived from the depth ratio of shading dimensions.

Table 1. Formula and parameter descriptions for the 'EnvLoad' Equation.

$$ENVLOAD = a^* \Sigma Ai * ki * \eta I * IHki / Aen + b \quad \ldots\ldots\ldots (1)$$

| Factor Code | Descriptions | Units |
|---|---|---|
| Ai | Area of Window i | ㎡ |
| i | Shading Factor of Window i | -- |
| η i | Solar Insolation of Window i | -- |
| IHki | Cooling Insolation Hour for Orientation k at site location | Wh/㎡. yr |
| Aen | Total Envelope Area of Office buiding | ㎡ |

| Site Loc. | a | b |
|---|---|---|
| Zone 1 | 0.850 | 40,733 |
| Zone 2 | 0.857 | 42,026 |
| Zone 3 | 0.877 | 58,280 |
| Zone 4 | 0.857 | 54,893 |
| Zone5 | 0.887 | 54,893 |
| Zone 6 | 0.876 | 68,884 |
| Zone 7 | 0.890 | 75,899 |

## 2.2. RELATED WORKS

Recently, self-adaptive building skins have become a major research area in sustainable design because it combines the benefits of active and passive design strategies. According to Rodriguez and Alessandro (2014), these design works creatively reflect the essence of adaptability, transformability and evolution to deal with the fluctuation of natural environment. However, there are still no legitimate evaluation processes to certify the energy performance of the adaptive façades. Except for heat performance, while concerning interior quality, the designer also has to consider the performance of lighting, ventilation, etc. simultaneously. Based on the optimization method of virtual model simulation, Asl et. al, (2015) suggested an "Optimo" system to testify that high performance building design can be achieved if multidisciplinary optimization tools are integrated with the building design platforms to automatically search for the optimal solutions. In this research, we adopted this idea and sought to achieve optimal façade design solutions to meet the requirements of both green regulations and daylighting levels by creating a BIM-based compliance checking platform. However, the adaptability of those optimal results still requires to be proven in the real environment.

Jang et al (2013) present a conceptual framework of "Collaborative Responsive Façade Design Using Sensor and Actuator Network" which depicts the idea of synchronizing the design state of both virtual and physical models on an integrated platform established by Rhino and Grasshopper with Firefly plugins connected to Arduino IDE. The above studies inspired us to

propose a façade design platform by further integrating Revit and Dynamo with Firefly plugins, in order to link the BIM data with dynamic data of lighting levels captured from sensors in physical scaled models. The platform will greatly enhance the complicated process of responsive façade design in designing optimal light-tracking sunshade systems in this study.

## 3. A process framework for adaptive façade design

Under the concept of systematic façade design method, versatile modular-based façade units are pre-fabricated, repeatedly-arrayed or arranged like Lego blocks to compose an adaptive building façade. In order to further explore various design possibilities of kinetic shading and façade units, while defining the adaptive components in Revit, we set up two major criteria for the design platform:

- Kinetics of Dynamic Façade Component: based on the equation in Table 1, various kinetic constraints are defined according to the parameters for the compliance checking of building EnvLoad performance (e.g. REQ - Ratio of Equivalent Transparency, SC - Shading Coefficient, etc.).
- Specifications of Object Relationship for Subtropical Climate: are adopted as genes for façade system development with optimal energy performance.

As depicted in Figure 1, comparing to the traditional design life cycle, the process framework of this study can be divided into two stages. In the former stages of programming, conceptual and schematic design, façade design and energy performance evaluations are mainly processed on the BIM-based design platform. In the latter stages of design development and construction documentation, real model tests are introduced to detect the reaction in the real environment and also verify the feasibilities of structures. The process framework (see Figure 1) introduced the façade unit analysis process into building design life cycle; in the meantime, it ensures that the energy performance of design schemes is ready for the compliance check of green building regulations.

Though the BIM-based tools are currently very straightforward in virtually modelling various quantitative analysis, e.g. conceptual site geometry, energy consumption, lighting etc., it lacks the information which can only be acquired from the traditional physical models, e.g. kinetic component feasibility, material physics, sensor and actuator properties, etc. In order to achieve optimal design results, we established a hybrid framework composed of virtual and physical models. The system framework (in Figure 2) is connected by Arduino IDE for synchronizing virtual and physical model information. The objective of the optimization platform is to provide a double-

checking opportunity for comparing the virtually estimated data with the real environmental data in order to verify the optimal design result.

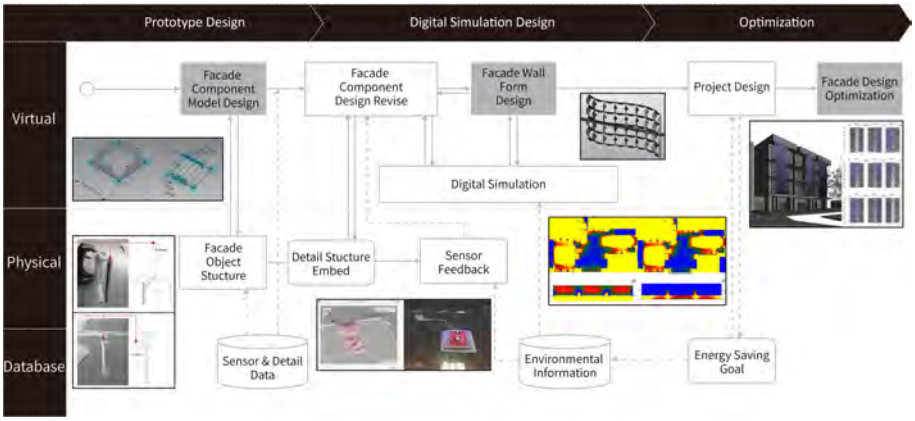



*Figure 1. A process framework for systematic façade design.*

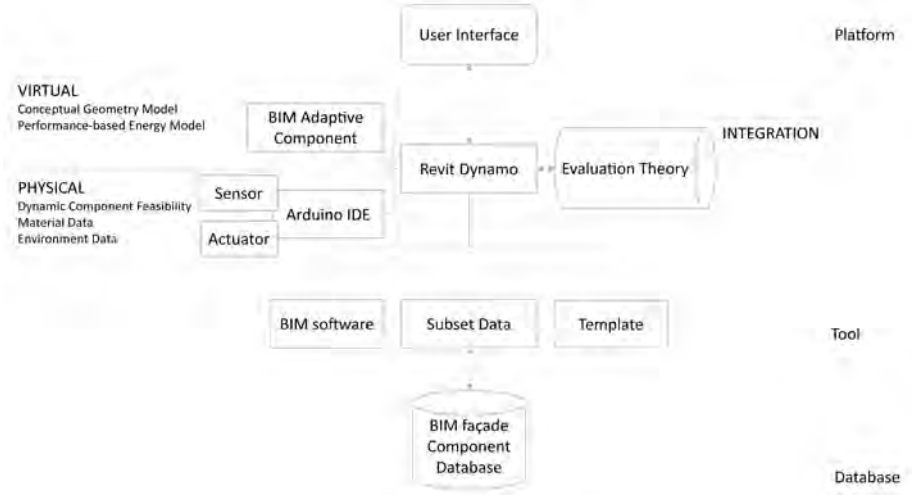



*Figure 2. A system framework for façade element optimization.*

## 4. The implementation

### 4.1. PARAMETRIC FAÇADE COMPONENTS

Based on previous review, we tried to adopt the AIF design prototypes into our study model and investigate their applicability under the local green building regulations. We chose kinetic shading element design as our first experiment and studied their parametric relations using Revit adaptive com-

ponent models with two scenarios of transformation: (A) Opening-shutters, and (B) Tilting-blinds. Table 2 depicts the coding of variables and conditions for Prototype A and Prototype B.

Table 2. Prototype A & Prototype B – BIM component design setting.

| Prototype A | | |
|---|---|---|
| Code Factor | BIM Component Parameters | Expressions |
| Opensize_A | Input_parameter | If (Opensize_A>Width_quarter, Width_quarter, if (Opensize_A<1,1,Opensize_A*1)) |
| Opensize_B | Input_parameter | Opensize_A*0.6 |
| Width | UV_Grid_parameter | |
| Width_quarter | Open_Size_Limit_Value | (width / 4) |
| Rotation_Angle | Blind_Rotation_Angle | If (Rotation_Angle> 90°, 90°, if(Rotation_Angle< 0°, 0°, Rotation_Angle*1)) |
| Prototype B | | |
| Code Factor | BIM Component Parameters | Expressions |
| a | Blind_Open_Size_limit | if(W_Blind>30 cm, 30 cm, if(W_Blind < 20 cm, 20 cm, W_Blind * 1)) |
| W_Blind | Input_parameter | |
| Width | UV_Grid_parameter | |
| Rotation_Angle | Blind_Rotation_Angle | If(Rotation_Angle> 90°, 90°, if(Rotation_Angle< 0°, 0°, Rotation_Angle*1)) |

## 4.2. DEVELOPING COMPLIANCE CHECKING SYSTEM FOR GREEN BUILDING REGULATIONS

In the next step, we seek to interactively capture information from the model to the *EnvLoad* performance checking system developed by *Revit API* and *Dynamo*. According to the equation of *EnvLoad* calculation listed in Table 1, Window Ratio (Ai/Aen), Shading Coefficient (ki) and Glazing U value (η i) are the key factors affecting the energy performance in façade design. As for designing kinetic shading systems, how to effectively define the main parameter ki is the major challenge in creating the adaptive component. In this study, we created *Dynamo Nodes* to extract the projecting area of opening called *'OpenSize'* as a reference for verifying the ki value.

Furthermore, for swiftly calculating total energy effect of façade elements, we developed an API called *'FEcheck'* as a preliminary compliance checking system to parse the results by inputting U values of wall, U values of window and Shading Coefficient. It links the Revit component model (*.rfa) to *Dynamo* to extract the values of wall and window attributes, then

passes the data to Google Excel by Dynamo Package *RAINDROPS* (Nuri Miller, 2015) and connects to compliance checking system in C# language in order to develop the Revit APIs which confirm the component design results and feedback to the designer. If the result is proven as 'yes' or beyond the baseline value specified in building regulations, it means the façade unit is more qualified for the requirements of local green building standards.

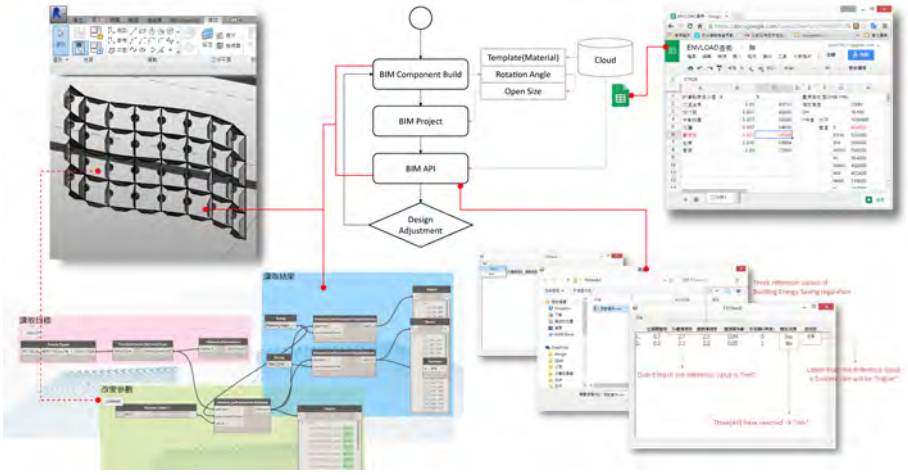



*Figure 3. Energy evaluation platform for façade design.*

As depicted in Figure 3, the material data or green building standards specified in the regulations are separately stored in Excel spreadsheets in the cloud space in order to be easily updated in future revisions. In this study, we use Dynamo Raindrops to connect the Google Excel spreadsheet for the location-corresponded values of IHki, a, b and ki (Table 1) and calculate the results of ENVLOAD by the ki values previously verified by 'OpenSize'.

## 4.3. PHYSICAL TEST PLATFORM

In the physical test platform, we design the façade frame and façade element mobility by a 1/20 scaled model. With motors embedded to emulate the kinetic mechanism of elements, the elements are installed at the front façade of a typical 6m x 6m x 3m space. In this part, we focus on how to transfer the BIM façade component model into physical façade element. We chose two façade component prototypes (A and B) for detail design. As shown in Figure 4, the digital-fabrication stage can be divided into four steps: (1) BIM Component Detail Design, (2) RP Layer Analysis, (3) Physical Model Feedback, and (4) 3D Printing Operation.

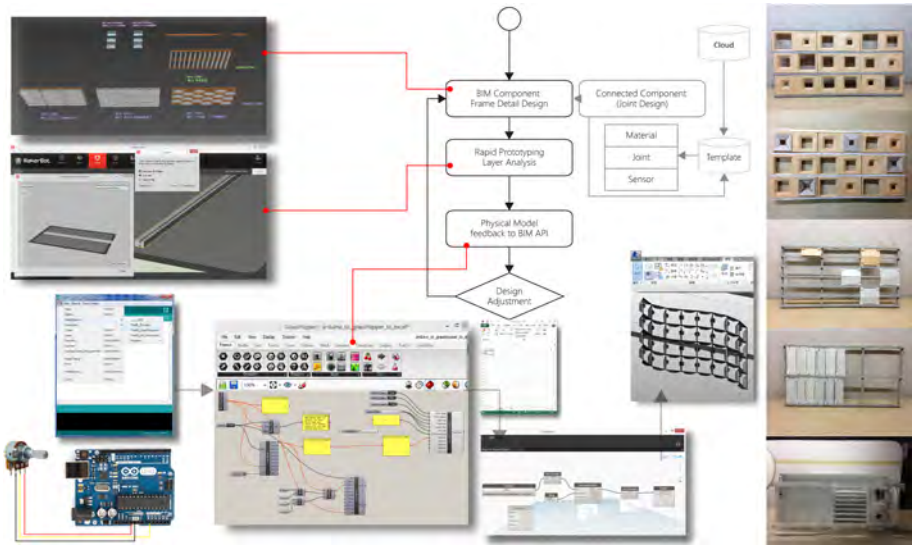



*Figure 4. Façade design in physical system.*

After the connected components were all determined, we then modified the two prototypes and installed them onto the physical model frame. We measured the opening size, rotation angle and distance of blinds in order to feedback to the virtual model. Also, we used Revit Dynamo 'Firefly' (2015) Nodes - 'Arduino.OpenPort' to read the Arduino Uno in C # language, and pass the measurement results of the physical model (i.e. the servo motor rotation angle information) back to Dynamo.

## 5. Test cases and results

Scheme optimization process in design iterations is demonstrated by possible permutations of the two modules. We chose the south-facing glaze curtain of an existing city hall building as the main spot for simulation. As shown in Figure 5, we then applied prototype A and B to the same project and simulated them on the *EnvLoad Evaluation Platform* to compare the EnvLoad values for the two scenarios. The related reference data are acquired from the cloud database (e.g. site IHk), or from the BIM model geometry (e.g. window area Ai) and previously built-in templates (e.g. glazing insolation ηi and shading coefficient ki). According to the local regulations, the design results of EnvLoad values should be divided by the baseline value (i.e. EnvLoads) and to get the final results of EEV ratio as a standard for evaluating energy performance. Currently the EEV value should be lower than 0.8. From the simulation results for the above scenarios, we found that Prototype A (the façade with Opening-Shutters) has lower EEV than Prototype B (the façade

with Tilting-Fins). It means that, in terms of energy performance, controlling the opening rate is a more effective shading design strategy than controlling the ki value.

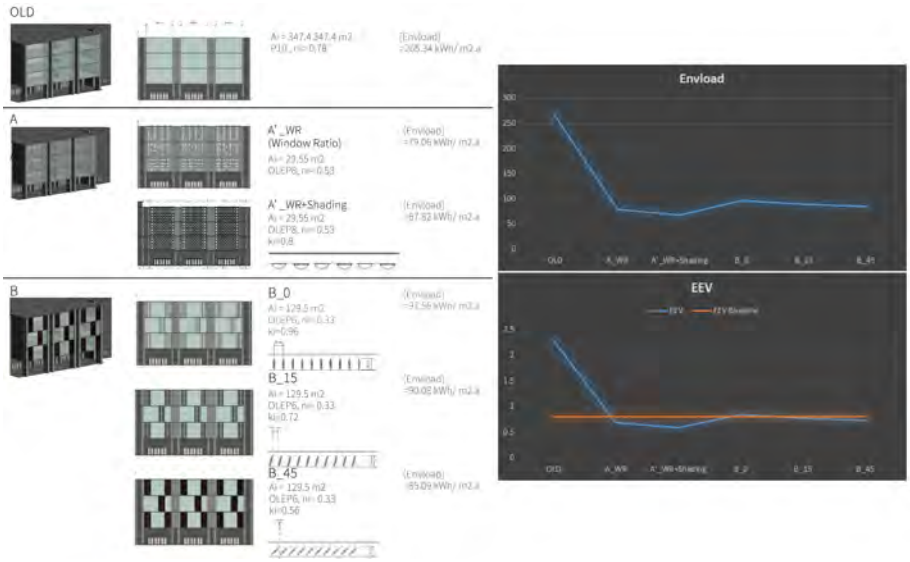



*Figure 5. Project analysis on the 'Evnload' Evaluation Platform.*

## 6. Conclusion

From the implementation results and project-testing process, we developed two systems to test the façade components, both on EnvLoad Simulation Platform and Physical Test Platform. The findings are: (1) BIM tool has the potential in developing powerful platforms for adaptive façade design to achieve a systematic design process. In this study, it is demonstrated with the analysis for adaptive components in shading prototype design development both on virtual and real test platforms; (2) Dynamo plugins enhanced the development of a BIM-based compliance checking system for local green building regulations. It enables the detail design consideration of façade elements and allows parametric simulation in verifying its energy performance; (3) The optimization system for façade design process has initially been explored by integrating various digital design methods, e.g. parametric design, digital fabrication and sensor responsive kinetic control, etc. Nevertheless, it still requires the next-step big data aggregation and analysis both from sensors and kinetic components, in order to feedback to the design solution and achieve the optimal performance.

Therefore, the future works will include: (1) Embedded-components: developing the techniques of sensor- or actuator-embedded façade design elements in digital fabrication process; (2) Multi-skin: developing EnvLoad calculation method through the corrected factor of ki (ki‘=1-(1-ki)* δi) derived from the geometry of multiple layers; (3) Multi-objective optimization: developing more calculation algorithm for more criteria, e.g. daylight or ventilation. On the other hand, when the physical environmental evaluation sensors can be installed everywhere in the real space and pre-fabricated in the façade, it implies that we can optimize the physical environmental factor and virtual simulation results together in the future.

## Acknowledgements

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# PAINTERFACE: AN INTEGRATED RESPONSIVE ARCHITECTURAL INTERFACE

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**Abstract.** Interface design is one of the main research areas in human-computer interaction (HCI). In computer science, many HCI researchers and designers explore novel interface designs with cutting-edge technology, but few investigate alternative interfaces for existing built environments, especially in the area of architecture. In this paper, we investigate alternative interface designs for existing architectural elements—such as walls, floors, and ceilings—that can be created with off-the-shelf materials. Instead of merely serving as discrete sensing and display devices integrated to an existing building's surface, these liquid and thin materials act as interventions that can be 'painted' on a surface, transforming it into an architectural interface. This interface, *Painterface*, is a responsive material intervention that serves as an analogue, wall-type media interface that senses and responds to people's actions. *Painterface* is equipped with three sensing and responsive capacities: touch, sound, and light. While the interface's touch capacity performs tactile sensing, its sound-production and illumination capacities emit notes and light respectively. The outcomes of this research suggest the possibility of a simple, inexpensive, replaceable, and even disposable interface that could serve as an architectural intervention applicable to existing building surfaces.

**Keywords.** Human-computer interaction; integrated interface; sensing and responsive architectural interface.

## 1. Introduction

Recently, ubiquitous computing has become a focus of computer science research. Computing devices can now be installed anywhere and will eventually be practically invisible. This advance changes the way we interact with

computers, mobile devices, and machines. Although ubiquitous computing is not entirely new to architectural design, there is relatively little research that explores the ways in which integrating ubiquitous computing could change how we interact with existing buildings.

Interface design, especially in the area of human-computer interaction (HCI), is a crucial discipline that supports the implementation of ubiquitous computing. Computer interface types such as the graphical user interface (GUI), tangible user interface (TUI), and organic user interface (OUI) facilitate interaction between digital and physical domains, offering different ways of experiencing HCI (Ishii et al, 2012). These interfaces offer small-scale forms of interaction through keyboard, mouse, speech, handwriting, touch, and gestures, as ways of engaging and interacting with a computer through visible actions (Norman, 2010). Larger-scale interfaces have rarely been explored, especially in the context of architecture and the built environment (Pohl and Urs, 2011). Nevertheless, current design innovations give rise to the idea of large-scale haptic interface design involving DIY electronics and alternative materials (Ng, 2013).

Exploration of architectural interface design concepts suggests the new possibility of augmenting existing architectural elements, such as walls and floors, into parts of a human-computer interface. This interface can be considered a calm technology used for low-tech intervention, as it augments an existing built surface by adding interactivity to an existing wall or floor and allows users to experience a novel form of HCI. Projects such as The Fun Theory's *Piano Stairs* set precedents for this approach by making people curious and inviting them to explore further to discover possibilities for social interaction (The Fun Theory, 2009).

In place of conventional media involving digital graphics and information display through light emitting diodes (LEDs) and organic light emitting diodes (OLEDs), in this paper we introduce an alternative, analogue interface that is 'retrofitted' and 'painted' on an existing brick wall. This interface serves as a 'host' that enables pedestrians to interact with the wall through an analogue medium with capabilities including sensing, illumination, and sound production. This painted interface, *Painterface*, intends to stimulate curiosity among pedestrians and encourage robust social interaction through an alternative analogue medium that extends conventional graphic representational methods through use of sound and light. Using sensor fusion and machine-learning techniques, humans' touch gestures over the interface's conductive materials could be detected and learned to allow for more accurate responses and controlled output.

This research was expected to deliver two outcomes. First, exploration aimed to yield a method for designing sensing interfaces by using conductive

and functional materials. Second, we intended to develop a prototype of an alternative interface for HCI in existing buildings and indoor spaces. This interface, when integrated with an existing wall, anticipates a mode of computer-facilitated interaction with architecture that differs substantially from those involving digital media, such as the media façade.

## 2. Interactive architectural surfaces

In computer science, the vision of ubiquitous computing turned computers into everyday objects seamlessly integrated into our daily life. The term, coined by Mark Weiser in the late 1980s, anticipated the development of 'invisible' devices, in many sizes and shapes, which could bring computing to everyone (Weiser, 1991). One of the main ubiquitous computing devices envisioned by Weiser was the wall-sized interactive surface that would potentially replace the office and classroom whiteboard, magnet-covered refrigerator, or bulletin board (Weiser, 1993). Although this kind of interactive surface is not new in the current context, it is still not fully implemented in domestic and commercial settings due to lack of affordability and ease of use. Furthermore, shortcomings in the flexibility and scalability of these interfaces have hindered growth in their popularity over the past few decades.

Weiser's vision has inspired many designers and researchers to explore the HCI possibilities of the wall-sized interface, but few have extended this research to the field of interactive architectural surfaces. In general, current designs of such surfaces involve LED or OLED touch screens or, more often now, digital projection augmented with motion-sensing input devices.

One prominent architectural installation adopting the projection approach is *Augmented Structures: Acoustic Formations*, an augmented architectural surface that performs dynamic aesthetic alterations to the original appearance of its existing building façade. This multidisciplinary, large-scale augmented surface is considered a living canvas that presents the viewer with new media experiences, communicated through sound and movement by way of interactive projection (Augmented Structures, 2012). The *Aegis Hyposurface*, designed by dECOi, takes another approach, using analogue kinetic components to create a dynamic surface capable of physical deformation. This surface served as a dynamic and interactive artwork, allowing a theatre to portray on its exterior a response to stimuli captured from its environment (Goulthorpe, 2008). Although both digital and analogue interactive surfaces have successfully served as large-scale responsive architectural interventions for existing buildings, their 'prosthetic' approach is not fully assimilated into existing building elements, such as walls and façades, to form an integrated architectural interface.

Current advancements in tangible interface design, explored through smart materials, offer new possibilities in the form of 'hybrid' alternatives combining the wall-sized interface and the augmented architectural surface. The concept of "Radical Atoms", developed by Leonardo Bonanni and Hiroshi Ishii of the MIT Media Lab, is a vision for human interaction with dynamic materials that can sense, change shape, and respond to stimuli. In this vision, the material and the interface are one. This concept of human–material interaction envisions that any physical object (atom) could display, embody, and respond to digital information (bits) through its changing material properties and capacities (Ishii et al, 2012).

In the context of architecture, there is a similar opportunity to design materials that react to the touch of a person's hand; to external conditions such as pollution and sunlight; and to a building's ever-changing surroundings (Tibbits et al, 2014).

Partially inspired by the vision of "Radical Atoms," which integrates information and material in interaction design, in this paper we investigate a design approach that explores the possibility of sensing and responsive architectural interfaces made through novel use of day-to-day materials. Instead of developing a high-tech material system that is expensive and intricate, we offer the alternative of developing an interactive architectural surface by more fully exploiting the potential of widely available and affordable off-the-shelf materials, augmented with basic physical computing programs. This simple and inexpensive approach allows the architectural interface to be replaced easily and even to be treated as disposable when newer technology and materials are developed.

## 3. Responsive synthetic material intervention as architectural interface

Two of the main challenges in developing a sensing architectural interface are the limitations of fabrication technology and the high cost of advanced material development. In this paper, we introduce a simple and inexpensive design research process through which to explore the alternative process of designing a responsive material intervention and architectural interface that can be made with off-the-shelf materials. Instead of designing a stand-alone panel-type interface, we investigate a different approach, 'painting' the material intervention as an interface on the existing wall. One of the materials used in this investigation is conductive paint, which can be applied to almost any physical surface to serve as a touch sensor. Other easily accessible and inexpensive materials such as piezoelectric film, translucent silicone rubber, phosphorescent pigment powder, and shape memory alloy are used to create the various sensing and responsive capacities of the painted interface.

These materials are the basic ingredients of a responsive architectural interface that seamlessly retrofits with existing building surfaces such as walls and floor. Most of these materials are manufactured in thin, sheet-based or liquid forms for easy application.

The architectural interface has three sensing and responsive capacities that involve touch, sound, and light (Table 1). Touch serves as input for the interface, enabled by the conductive paint. Sound-producing capacity forms one of the outputs of the interface: in reaction to touch, it produces rhythmic sound notes from thin piezoelectric film. Finally, the light-producing capacity illuminates part of the interface when touch is applied to the existing physical surface.

Three preliminary experiments were conducted to investigate these capacities of the interface when applied to a generic clay brick. These are further discussed in the following subsections.

Table 1. Selected off-the-shelf materials produce different sensing and responsive capacities.

| Sensing and responsive capacities | Off-the-shelf materials | | | | |
|---|---|---|---|---|---|
| | Conductive paint | Polyester film | Transparent silicone rubber | Phosphorescent pigment powder | Shape memory alloy |
| Touch | • | | | | |
| Sound | | • | | | |
| Light | | | • | • | • |

## 3.1. TOUCH

In general, conventional tactile sensors serve as discrete electronic devices that sense physical stimuli such as the touch of a human hand. These sensors are often employed on flat and rigid surfaces that limit their full capability, obscuring the potential inherent in applying them to flexible or undulating surfaces. In this subsection, we explore an alternative technique that uses conductive paint as a tactile sensor we can apply to an existing physical surface. This kind of paint conducts electricity and can be applied or painted on almost any surface or material. Once it dries, the painted surface becomes electrically conductive and can serve as a tactile sensor (Figure 1).

We conducted the simple experiment of applying this conductive paint to the surface of a generic clay brick measuring 230 mm × 110 mm × 76 mm. Once painted and dried, we connected the surface with a capacitive sensing schema through an Arduino microcontroller. Part of the brick then became a tactile sensor that could read input data when touched by another capacitive object (i.e. a finger) (Figure 2).



*Figure 1. Left: The generic clay brick. Middle: Applying conductive paint to the brick's surface. Right: Brick surface covered with dry conductive paint.*

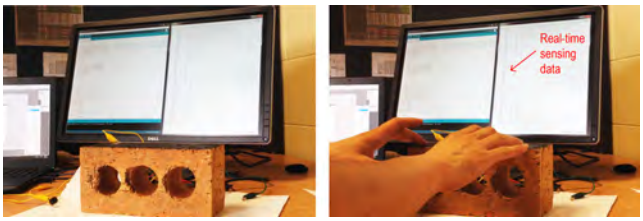



*Figure 2. Left: The painted conductive brick. Right: Brick surface sensing touch data from fingers.*

### 3.2. SOUND

In this subsection, we explore giving sound-producing modality through the use of a thin polyester film with conductive ink and a rare earth magnet. While painted with conductive ink, this polyester film enables us to turn an existing building surface, such as a wall, into a paper-like planar speaker (Figure 3). This simple and low cost speaker provides basic audio tone with minimum energy input. Furthermore, being ultra-thin and lightweight, this kind of speaker has the advantage of being able to be seamlessly integrated with the existing brick's surface.

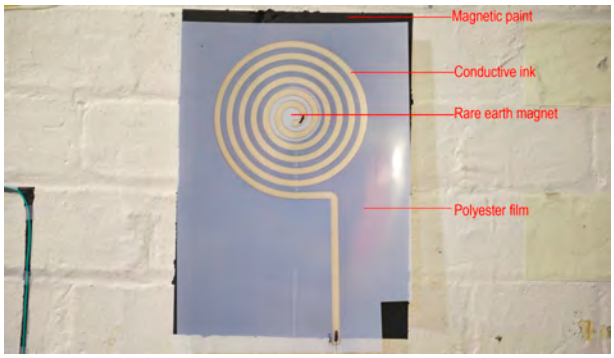



*Figure 3. Paper-like planar speaker retrofitted to the existing brick wall.*

When connected with the conductive paint touch sensor discussed in the previous subsection, the polyester film will produce a simple binary sound

note. This note can be altered by touching different parts of the painted conductive surface: touching the centre or corner, for instance, produces different sounds. By changing the programming of the capacitive sensing schema, the polyester film can be made to produce tones of differing frequency. In this scenario, these simple tones are basic musical notes that anticipate human interaction.

### 3.3. LIGHT

Development of the second responsive capacity, light production, focused on creating the possibility of responsive illumination. Instead of retrofitting discrete lighting devices such as LEDs to a surface, we employed a luminous paint applied to the surface of the brick along with a mixture of transparent silicone rubber, phosphorescent glow pigments, and shape memory alloy (SMA) wires. The goal of this experiment was to come up with a flexible and luminous material that is relatively easy to apply to an existing building surface.

While it will glow in the dark passively, this synthetic material lighting will glow extra bright when heated by embedded SMA wires, complementing the passive lighting. The embedded SMA wires not only serve as a heater: their form-changing capacity also enables the synthetic material to change its form and alter the appearance of the existing brick's surface (Figure 4).



*Figure 4. Left: Luminous paint with embedded SMA wires on the surface of the brick. Middle: Luminous paint glows in the dark. Right: Extra luminosity around the heated SMA wires creates a visible pattern.*

This simple intervention with luminous material is not intended to replace an existing fluorescent or LED lighting system, but rather to create ambient and amorphous light effects to revitalise dark environments. By 'painting' this synthetic luminous material on existing architectural features such as walls or ceilings, these features can be extended beyond their primary function as space dividers to incorporate extra capacities and functions. This approach creates the potential to transform every existing architectural feature into a lighting system.

Application of this luminous material intervention will be further discussed in Section 4.

## 4. Application of the retrofitted interface

Following on from the positive outcome of experiments involving the sensing and responsive brick interface discussed in the previous section, in this section we focus on implementing the interface.

This interface, which we call *Painterface*, creates a haptic experience for pedestrians through its polymorphous appearance. Physical changes in its surface material properties modify the existing brick wall to offer the possibility of a more intuitive physical interaction than does a conventional digital interface. When 'painted' on through application of simple conductive paints and thin films, the existing brick wall becomes a sensing and responsive interface. This augmented interface responds to pedestrian inputs including touch, proximity, and hand gestures. The integrated interface reacts to these inputs by offering feedback in the form of sound and light output.

Where contemporary mobile devices often overwhelm their users and discourage social interaction, this integrated interface, as a responsive architectural intervention, represents a use of computing and architecture that encourages people to communicate and interact with each other in ways physically initiated by alternative analogue media. The approach aims to stimulate curiosity in passers-by to provoke robust social interaction facilitated by analogue representations.

### 4.1. PAINTERFACE

In its full expression, *Painterface* is 'painted' on the existing brick wall of a dark and narrow corridor. The realised project is the design implementation of the retrofitted architectural interface developed through the experiments with synthetic material interventions discussed in the previous section.

The existing brick wall at the implementation site has a stretcher bond pattern that exposes the bricks' long narrow side. Once *Painterface* is applied, the ordinary and inert brick wall becomes an analogue media interface that people can interact with through touch, sound, and light (Figure 5). By 'retrofitted' and 'painting' different capacities to individual bricks, these bricks become input and output devices for *Painterface*, changing the ambient environment of the corridor in response to input from pedestrians.

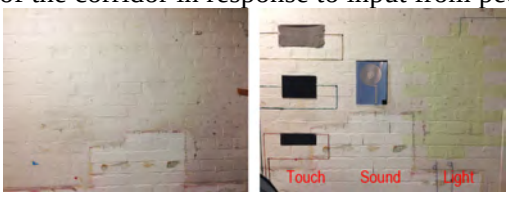



*Figure 5. Left: The existing deserted brick wall. Right: The sensing and responsive capacities of Painterface: touch, sound and light.*

*Painterface* involves three 'retrofitted' zones (Figure 6). Zone 1 is painted with a series of tactile sensors that can sense the touch of a human hand. Zone 2 is the audio area, retrofitted with seamless polyester film speakers that produce sound notes in response to interaction. The 'painted' luminous skin layer of the last zone creates animated glow-in-the-dark visualisations that respond to the touch and sound stimuli of the first and second zones (Figure 7). With additional programming, the three zones will output audio and luminous graphics based on the stretcher bond pattern, in response to pedestrian interaction (Figure 8). Although *Painterface* is the first design iteration of this painted interface, serving as an implementation test on an existing building surface, it represents a promising outcome, providing motivation for further development of similar responsive material interventions that can make any building surface interactive.

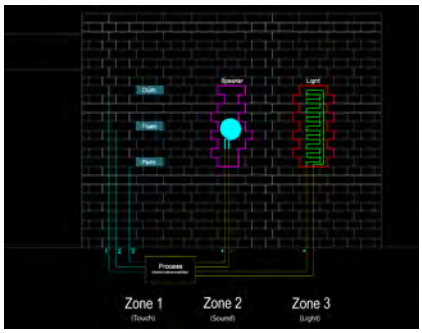



*Figure 6. The three different zones (touch, sound, and light) of Painterface.*

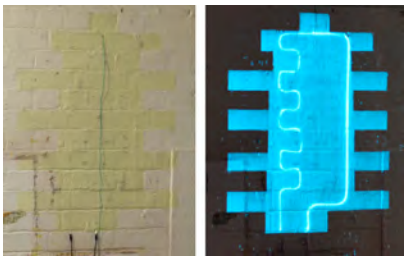


*Figure 7. Left: The 'painted' luminous skin layer on the brick wall. Right: Zone 3 glows in the dark with heated SMA wires that responded to touch stimuli.*

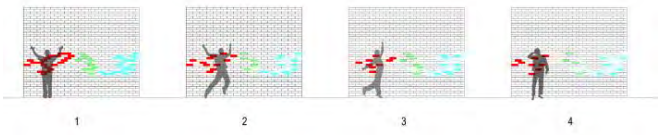



*Figure 8. Programming allows Painterface to output changing audio and luminous patterns in response to pedestrian interaction.*

## 5. Conclusion and future work

The design investigation undertaken in this research demonstrated the potential for of an integrated and 'painted' interface that renders existing architectural surfaces interactive with minimum cost and through a simple process. The preliminary design research acted as the proof of concept for a vision involving 'painting' a thin layer of sensing and responsive solid-state devices such as sensors, lamps, speakers, and display systems on almost any existing building surface. Recent advances in energy-harvesting materials such as painted organic solar cells suggest the additional opportunity to turn such a painted interface into a photovoltaic skin, and even an indicator of energy consumption, with minimum maintenance cost.

The design trajectory of interfaces between architecture and people has entered a new era due to recent material advancements and inventions. New materials not only perform functions such as sensing, actuation, illumination and audio output, but also represent the advent of ubiquitous computing in the existing built environment. The rising popularity of contemporary 3D and conductive inkjet printing technology also suggest novel possibilities for DIY application, involving printing these materials with embedded wireless technology on almost any surface of an existing building. This printed computing approach would allow such existing building surfaces to become multifunctional interfaces that respond and adapt to changing environmental stimuli.

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# MAKING – GESTURES: CONTINUOUS DESIGN THROUGH REAL TIME HUMAN MACHINE INTERACTION

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**Abstract.** Design is "something that we do" that is related to our unique human condition as creative individuals, so as "making" is related to how we manifest and impress that uniqueness into our surrounding environment. As designers, the way we impress our ideas into the material world is tightly connected to a 'continuous creative performance' and with concepts often missing in digital design and fabrication techniques –yet present in analog processes - such as ambiguity, improvisation and imprecision. In this paper, a model of human-machine interaction is proposed, that seeks to transcend the 'hylomorphic' model imperative in today's digital architectural design practice to a more performative and reciprocal form of computational making. By using body gestures and imbuing fabrication machines with behaviour, the research seeks to embrace the concept of 'performance and error' as promoters of creativity and cognition about the things we create, installing human as the bond of the interrelations between designing and making.

**Keywords:** Human machine interaction; computational making; machine learning; digital design and fabrication.

## 1. Introduction

The early CAD implementations during the 1960 were based upon aspirations of using computers as informed, intelligent and cognitive machines. Moreover, influenced by cybernetic theories and artificial intelligence, CAD proponents such as Nicholas Negroponte and Ivan Sutherland, intended to augment the design enterprise in terms of creativity. To do so, they sought the implementation of interactive intelligent systems as 'creative enhancers' that are able to help designers to concentrate on the

creative aspects of the design process by suggesting design options and taking care of tedious tasks such as project documentation, organization and elaboration of quantity takeoffs. Nonetheless, despite the constant efforts of early CAD proponents to frame design into a representational and generic model for production, they soon found themselves in contradiction to aspects of the creative process that cannot be codified as a meta-algorithm capable of grasping designer´s intentions.

According to Sutherland (1975), the major flaw of the early interactive digital tools such as SKETCHPAD, was related to the apparent freedom delivered by the interaction between designer and machine to produce a drawing. To him, a designer should be concerned with the "evolving logic" of the design itself, instead of the structure of the drawing material (p.75). It was clear to Sutherland, and later to Negroponte and Taggart (1975) that a computational approach to design in terms of 'augmentation by automation' was difficult to implement because of the differences between the constant evolving logic of the human brain and the structured logic of the computer that demonstrated its incapability to grasp designer's intentions. In other words, the conclusion of Sutherland was that the 'creativity' part of a design happened outside the machine. Moreover, the design augmentation enterprise through technology somehow failed, orienting the use of digital tools toward areas more related to the documentation, analysis and optimization of designs establishing a clear separation between design-ideation- and representation-making.

In recent years, the issue of enhanced creativity through digital tools has re emerged. As Kolarevic (2003) asserted, "digital technologies are changing architectural practices in ways that few were able to anticipate just a decade ago"(p. 3). This optimistic perspective about the future of Architecture can be related to the aspirations of technological improvement expected by early CAD proponents. The discussion has been oriented toward the emergence, unpredictability and unlimited possibilities of digital tools in terms of algorithmic geometrical experimentation though human - computer interaction. Nonetheless, by looking at CAD-CAM models applied in today's architecture and design practice, it is possible to identify the same problems that Sutherland described in early CAD applications. These problems strengthen the dichotomy between design and execution of an idea. This dichotomy has led to a sort of disembodied design practice in which the architect is permanently performing a set of translations - from idea to 3d model to code to machine to material- that eliminates the performative aspect of improvisation in the design process. This constant translation between representation stages has provoked the emergence of three fundamental problems that are addressed in this paper. The first one is the

problem of the black-boxed processes that are embedded into software and machines. Such processes might bias the design processes into more representational efforts instead of the creative/cognitive aspects of design process. From this black-box concept it is possible to identify the other two. One is related to the use of generic operations - embedded into software and hardware- to impress a specific and non-generic design idea. The final one, is related to the creative gap that occurs as a result of the use of black-boxed generic operations in the mentioned transition from design idea to the fabrication of the prototype.

One can argue that, as physical modelling, gestures, and tools are mechanisms by which designers learn and think. Therefore, this paper discusses the idea that creativity emerges in the very moment of impression of the self onto the material world as an improvised choreography between humans and objects by using body gestures neither as action nor perception, but as the unity of both. If we are to extend our creativity and enhance the design experience through the use of digital fabrication tools, we need to reformulate the way we interact with computers and fabrication machines toward continuous design strategies. It is by the development of new models and strategies that are focused on the integration between human and machine that this could be achieved. In this paper, a cybernetic approach to CAD-CAM is proposed as an alternative model designing and making 'on the go', transcending from a model of 'operation' to a model of 'interaction'.

The hypothesis is that real-time interaction between designers and fabrication machines can augment our creativity and cognition, engaging exploration, speculation, improvisation, and knowledge production about designs through the use of gestures and interactive computation. To do so, 'Making Gestures: a personal fabrication system' is introduced, to explore real-time interaction between mind, body, and tools by using body gestures and imbuing fabrication machines with artificial intelligence. The goal is to propose and interaction model, that seeks to transcend the design-making dichotomy from current CAD-CAM applications to a more reciprocal form of computational making. 'Making Gestures' is proposed as a new paradigm for the use of digital fabrication tools, integrating the designer's 'unique gestures' into the digital design and fabrication process. This paper shows the integration of different technologies that go from machine design and fabrication, to the development of customized software through the application of different gesture recognition techniques base on machine learning. By using body gestures and imbuing fabrication machines with behaviour, adaptive and learning capabilities, the goal is to present a design methodology that embraces ambiguity and the unexpected. This way, the

designer can engage into more improvisational and insightful design processes to freely impress his or her uniqueness in our surrounding environment.

## 2. Digital design and fabrication as a creative endeavor: three problems

From the beginning of CAD, the concerns about the relationship between humans and technology in design were based upon the assumptions of a symmetrical symbiosis between man and machine. Moreover, the development of 'intelligent' tools as "creative enhancers" was an enterprise that failed because of the naive assumptions of the human mind as an 'information processing' machine and the simplistic view of human skill and expertise (Dreyfus, 1986, p.xi) that could be translated to combinatorial and discrete operations of data processing and analysis. Furthermore, it is valid to assert that current use of digital tools somehow maintain this assumption by leaving 'the human' out of important and crucial moments of the process of the physical manifestation of an idea, leaving the "tedious and time consuming tasks" such as drafting or calculating tool paths in a CAM software inside the computer as black-boxed opaque operations to the designer embedded in software.

If we consider that design is "something that we do" which is related to our unique human condition as creative individuals, one can argue that "design and making" is related to how we manifest and impress that uniqueness into our surrounding environment. Hence, its is valid to assert that after more than 50 years of CAD invention, the possibility to impress that uniqueness through the use of software and digital fabrication machines is limited. Furthermore, because the machine is the one that determines the way something will be made according to predetermined structured procedures, the actual process of making, exploring and having feedback through seeing and doing is lost. Furthermore, why should designers accept that the physical manifestation of our ideas should be processed and expressed through this black box using generic operations? Plotting a drawing, 3d printing a model, or milling a piece of wood are processes in which the software calculates the "optimal" or "average" operation to produce the physical manifestation of our ideas. Nonetheless, unlike digital processes that occur inside software, designers don't 'make' according to calculations of optimal data. The creative process is the result of a continuous circulation of ideas and actions, through the interaction between body and its senses -primarily vision and touch- tools -pen, knives, scissors and so on- and matter -clay, paper, ink, wood. To Dreyfus (1986), it is clear that computers are indispensable for some tasks due to their intrinsic

characteristics where they surpass human's capabilities such as precision or exhaustion (p.250). He asserts that computers are specifically useful in CAD applications due to their capacity to compute and process large amounts of information, improving efficiency by optimizing drafting, analysis and processing of tedious optimization, analysis and representational tasks (p.xii).

Nonetheless, What if in the process of designing and making a prototype the designer 'sees something else' and need to reformulate that design in real-time? How does this 'black-boxing' - which rarely happens in analog design processes - affects aspects of creativity and cognition of the design process? The design practice through technology is constrained by the imposition of an hylomorphic model by a constant imposition of predetermined ideas over matter by *"a violent assault on a material prepared 'ad-hoc' to be informed with Stereotypes"* (Flusser, 1991, p.43). Today's digital design technologies work by relying in an operation model that imposes a linearity of events to produce a specific outcome, hence, in the transition from idea to prototype, the designer is forced to pause the creation focusing on the representation of plans to express an idea, neglecting the interaction between action and perception present in continuous analog processes.

How to reconcile Design and Making through technology including the designer into more improvisational processes? How does the interaction between these antithetical worlds - the humans and machines - should happen in order to generate more insightful and creative designs? First, an understanding in the relationship between designers and digital tools must be achieved. According to Idhe (2003, p91), this relationship could be explained through the concept of "intentionality" and what he calls "middle ground" or "area of interaction" or "performance". He asserts that the only way to define or understand the relationship between humans and non-humans is through actionable situations that happen in a specific time and place.

### 3. From tool operation to tool interaction

In the design field, specifically in analog design processes, tools become almost invisible to us and act as mediated objects so the designer focuses in the specific action of 'making something'. Clark's (2004) interpretation about the relationship between humans and technologies according to degrees of transparency (p. 37) might be a useful perspective to understand why the three problems identified are relevant for today's design practice through technology. To Clark (2004) the difference between 'opaque' and

'transparent' technologies, relies on how well technologies fit our individual characteristics as humans (p.37). To Him, the more intricate the technology, the more opaque it is in relation to how it deviates the user from the purpose of its use. Suffice it to say that current model imperative in today's digital design practice is based on pure tool operation, neglecting the idea of real time interaction, leaving important parts of cognitive processes of design aside. Moreover, the many intricacies of digital tools (the black-box), lead the designer to engage and focus in the elaboration of plans for representation (the creative gap), that in many cases lead to rely in the software to solve a specific design problems (the generic) relegating the design experience to a initial effort later rationalized by a fixed structure.

Finally, in order to propose a model of interaction for design, we must explore real-time interaction between mind, body, and tools through a more reciprocal form of 'computational making'. It is by using body gestures and imbuing fabrication machines with behaviour, that we can establish a fluid conversation with machines, embracing ambiguity and the unexpected nature of error to engage the designer into improvisational, insightful and cognitive design processes.

## 4. Making Gestures: an interactive system for continuous improvisation and exploration in design

In this project, the first question to ask is, Why gestures? As it was discussed before in this paper, gestures have the capacity of embracing- beyond mental and intermediate representations- the moment of acting and perceiving. According to Flusser (1991), a gesture could be defined, as *"A movement of the body or of a tool attached with the body, for which there is no satisfactory causal explanation."* (p.3). This definition of gestures talks about how they are defined in relation to motion not only as intention -which refers to a backwards understanding process that require to decode the movement in terms of its results and the causal explanation for it - but with a meaning - which is related to a forward understanding of the unfolding processes of being in a specific moment. One can argue that gestures and the uniqueness of them as manifestation of the self are the result of a constant relationship between Action, Perception and Memory -which emerges from experience and learning. The uniqueness of every gesture can be explained by Schmidt's (1975) schema theory (figure 1) based in two concepts: *The Generalized Motor Program* (GMP) and the *Motor Schema*. While the *GMP* provides a motor pattern deposited in memory that posses different characteristics that are invariant in the desired gesture, the *Motor Schema* adjusts specific selected parameters of that motor response adapted to

situational demands. Maldonato (2014) asserts that because of the relationship of these internal mechanisms, the repetition of a movement - a gesture- will never be identical (p. 61).

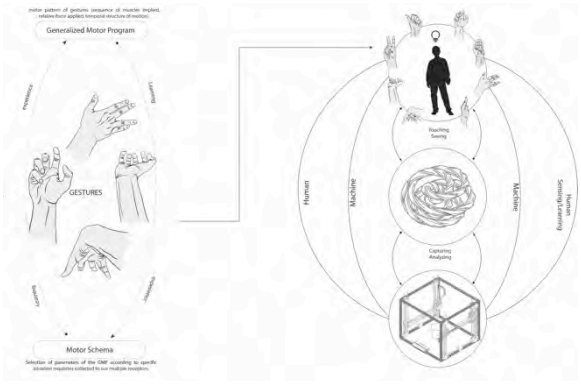



*Figure 1. How action and perception works according to Schmidt's Schema theory and the Making Gestures Project diagram*

Making Gestures is proposed as a specific implementation of a new paradigm for the use of digital fabrication tools integrating these 'unique gestures' as 'tool embodiment' into a cybernetic digital design and fabrication process. Specifically, the project was developed as a 5 axis hot wire cutter CNC machine that takes real time input from body gestures. By using motion tracking sensors it produces architectural designs prototypes through improvisation aided by machine learning algorithms while adapting to 'different ways of designing and making' in real-time.

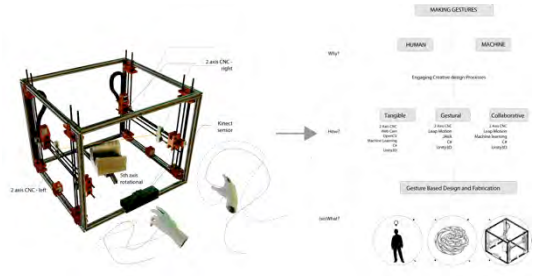



*Figure 2. Hardware and Software working diagrams*

On the hardware side, the machine was built using aluminum profiles and plastic 3D printed parts to integrate the 5 axis structure based on a timing belt motion system. A total of 5 NEMA 17 stepper motors connected to a *TinyG controller* board, which coordinates the motion of the 5 axes. The

system was designed as a double 2 axis system - one for each hand- attached to a nichrome electrified wire. A 5th axis was implemented as a rotary base to hold the Styrofoam blocks to be cut (figure 2), adding one degree of freedom.

On the software side, the main controller was programmed using UNITY3D and C# connected through UDP protocol to the Gesture recognition software (programmed in C++) and also connected to the tiny G controller through serial communication. For the motion tracking, a Microsoft Kinect for windows connected directly to Unity 3D. In order to interact in a more fluid way with the five axes of the machine, the need of capturing a full body skeleton was crucial in the implementation of a more natural interaction with the machine in term of body postures. The interaction with the machine comprises two phases: Training and Making. In the training phase, the designer is encouraged to perform free movements to calibrate the machine in terms of speed, response and accuracy of movements. In this phase of the interaction, the designer performs the training of the symbolic gestures that the machine will perform as fixed operations such as “start motion”, “stop motion”, “go home” or perform specific fixed specific pre programmed geometric operations. (figure 3)

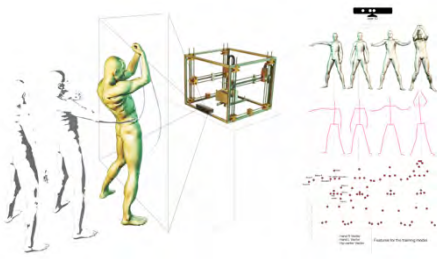


*Figure 3. Training the machine and extracting motion data.*

In the training phase, the software reads the skeleton model from human’s depth map data and blob detection. The skeleton model associated to a user ID, consists of several joints that have a position in space. The vector 3D data from the hands joints is used as features for the creation of the training model with the gesture recognition software. Furthermore, by repeating a specific gesture, the data extracted from the skeleton’s joints is transmitted through OSC to the Gesture recognition software (programmed in C++), which takes it as two 4 dimensional vectors adding them to a trained data file as positions related to a specific class (gesture). The data file is pre processed extracting the features applying a learning algorithm (Adaptive Naive Bayes Classifier). Finally, after the training model is created, the software is ready to perform the real time prediction phase,

which in this case happens in the act of interaction with the machine by the designer. The use of auxiliary fixed movements, allows for a better integration in terms of controlling aspects of the machine that are constant in the act of performing fabrication operations such as “engaging motion” “stopping motion”, “homing” or “rotate 5th axis in x degrees”, or even performing pre defined geometric operations.

In the making phase, the designer is concerned with designing and making through improvisation (figure 4 left). Moreover, is in this stage of the project where the full integration between human and machine happens. Through the use of designer’s gestures, the machine interprets the data and is able to determine from free improvisational and fixed auxiliary movements. The goal of the project implementation as an interactive machine, is to prove that creativity emerges in the very moment of impression of the self onto the material world as an improvised choreography between humans and objects by using body gestures neither as action nor perception, but as the unity of both (figure 4 right).

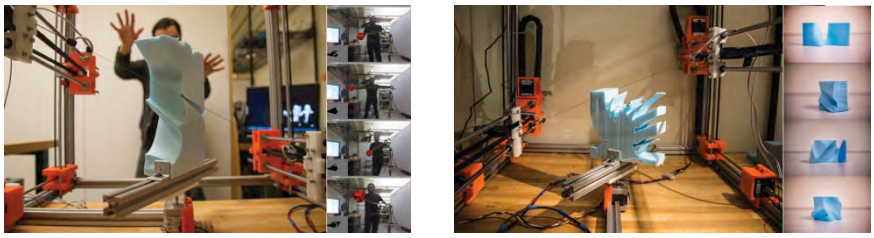


*Figure 4. Different iterations and tests with users (left) and explorations results (right).*

## 5. Conclusions

Is at this point where one can argue that by the development of gestural machines we can solve the three problems identified in the previous chapters - the black box, the creative gap and the generic. Moreover, in order to foster and promote the improvisational aspects of design as exploration, we need not only machines that emulate the movement of the designer but machines that by the use of sensors and actuators can enhance our experience by establishing a constant circulation of action and perception from both sides. Nonetheless by stating this, it’s not the intention of this project to seek the development of neither ‘Intelligent design machines’ nor focus in solving the peculiarities and dead ends that early cad proponents found after a few years of implementing similar systems. The proposal here, is that we can take advantage of current developments on robotics, artificial intelligence, CAD and CAM in order to grasp in a computational way, the very aspects that make design a creative and original enterprise.

In the first place, by using interactive and intelligent design and fabrication machines, the problem of black-boxing can be solved. Moreover, by making tools capable of becoming transparent, the designer can focus and concentrate on the design and making in a similar way analog tools are used. A system that doesn't focus in the manipulation of intermediate artifacts to translate an intention into material but in one that participate seamlessly in a dance of agencies of designer, tools and materials was proposed. As a consequence of this seamless integration between designers and tools, the problem of the 'creative gap' could be avoided. Because the system is interactive and dynamic, capturing and performing according to the specific resistances and contingencies of participants, tools and environment, there is no gap between idea and designed object. The system eliminates the multiple translations -representations- present in digital design and fabrication processes so the designer can focus on the act of creation by seeing and doing-making in real time. Finally, the system solves the problem of the generic outcomes, by allowing the impression of the self onto our material word capturing designer's gestures and translating them as intentions in real time to the material, starting from the argument that the originality and the creativity emerge from the fact that no gesture is same as other, because of the ever-changing properties and characteristics of the participants (material, visual, psychological) of the interaction.

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# THE IMPLEMENTATION OF PROGRAMMABLE ARCHITECTURE

*Wireless interaction with dynamic structure*

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**Abstract.** True adaptability in architecture necessitates both dynamic hardware and software with the potential for continually renewable forms capable of all possible variations necessary for changing demands and conditions, without having to resort to one theoretically optimal solution. PA consists of both autonomous and subservient systems that maintain a constant homeostasis within its contained environment. The information flow between the Genetic Algorithms (GA) and user input prompts this hybrid system to generate the consequent, ever-changing physical form, while continuously optimizing it for environmental stimuli. This paper proposes a smart strategy for a human interactive-cybernetic architecture in the context of K. Hotta's Programmable Architecture (PA), aimed at enhancing GA's capabilities in continuous self-modelling and facilitating human-computer interface.

**Keywords.** Human-computer interaction; user interface.

## 1. Introduction

In recent years, the key word 'adaptability' has increasingly been used in the field of emergent architectural design such as in the late book titled 'Adaptive Ecologies' (Theodore et al, 2013). Also, one of the most established architectural conferences, ACADIA (The Association for Computer Aided Design in Architecture), titled its 2013 symposium 'Adaptive Architecture'. There are many approaches to making architecture (both buildings and sys-

tems) adaptive and sustainable. Most contemporary architecture uses scientific approaches based on mathematics, physics, and computational tools and through experimentation is able to achieve higher levels of adaptability against ever changing circumstances. However, in considering the keyword 'adaptability' in architectural design, it is critical to discuss what adaptability is for. In the previous paper of PA (Hotta, 2013), environmental adaptability is the centre of discussion. The aim is to develop architecture with higher environmental adaptability, and to develop an architectural design methodology that will address issues of shape, systems, and devices that constitute the building.

## 2. State of the art

In the architecture field, there is a seminal book in terms of participatory planning methods; an architect-less architectural system in the vernacular tradition (Rudofsky, 1964). More recent, with reference to temporal design linked with the idea of emergence, it is worth looking at the Fun Palace Plan (Price, 1961) and Plug-in City (Archigram,1964) in the United Kingdom, and the Metabolism Movement in Japan in the 1960s and 70s (Lin, 2010). The idea of emergence in the previously mentioned contexts is that the architect and designer designed 'systems' rather than depicting static images.

On the other hand, there are many precedents in the engineering field. For example, *Cybernetics*, advocated by Norbert Wiener (1961), was a synthetic academic discipline that dealt with the matter of control and correspondence in a system like an organism or a machine. As an extension of this line of thought, *Control Theories* describe the methods in engineering and mathematics, which aim to control dynamic behaviour. The usual objective of control theory is to control a system. It attempts to adjust the system behaviour through the use of feedback via a controller, further developed as P, PI, PID (Proportional, Integral, Derivative) (Minorsky, 1922).

In the robotics field, the 'smart' robotic system has its origins in Social Robot (Walter, 1951), where the first speculation of multiple interacting robots was conceived. Another early trial of 'smart' robot can be referred to in 'Vehicles' (Braitenberg, 1984), in which evolutionary thinking was implemented in the wiring itself. Subsumption Architecture (SA) is the reactive idea used in artificial intelligence (AI), a term and field invented by R. Brooks (1986), which was developed to determine robot behavior. Swarm robotics is a relatively recent methodology for a multiple robot system (Yim et al, 2000), based on swarm intelligence observed in animal behavioral patterns. These past and seminal works ultimately have led to Evolutional Computing (Sims, 1994) and Evolutional Robots (Lipson, 2000).

## 3. Background

As a case study of the PA, flexible kinetic-tensegritic structures are shown in previous thesis (Hotta, 2013). The hardware for this proposal is an accumulation of self-sufficient machines that is dedicated to the actions of sensing, calculating, and actuating. As a case study for this thesis, a kinetic canopy that is organized using tensegrity-based components of variable forms is proposed. This architectural robot is actuated by shape memory alloy (NiTi) instead of tensile wire, and its control is handled electrically by micro controllers Arduino (Banzi et al, 2005~). A physical model of this machine has been built at a one-to-one scale and user-tested via mobile devices such as a smart phone.

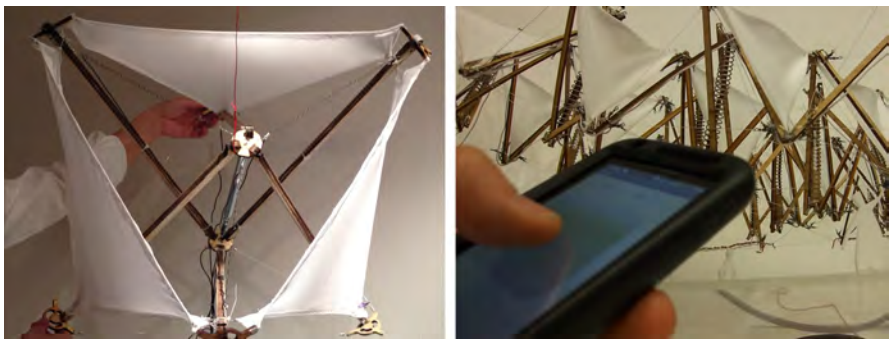


*Figure 1. 4th Generation, Physical Model (referring from PA, Hotta, 2013).*

The software for this proposal consists of a hybrid control system, which attempts to minimize the difference between the desired objective values and the measured values. This is a combination of automatic responses and user manipulations in order to achieve a faster and higher degree of adaptation. Utilizing the versatility of GA, multiple user inputs are proposed to partially substitute for its purely random mutations (usually GA use random digits for mutations).

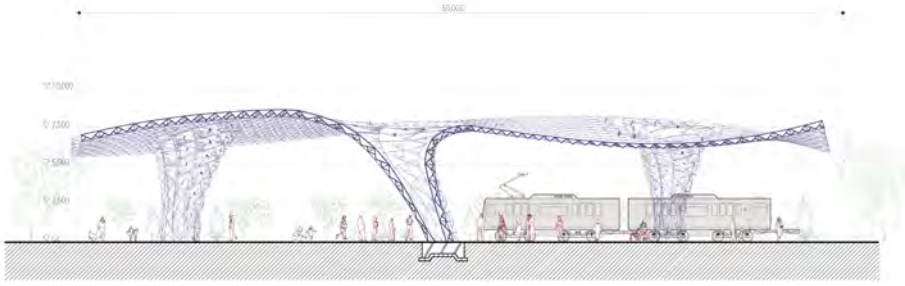


*Figure 2. Drawing of PA (referring from PA, Hotta, 2013).*

This resolves GA's shortcomings, namely protracted calculation time, lack of adaptability to a fluctuating objective function which represents the ideal condition at any given time, and the ability for ad hoc responses when the system experiences usage overload or random environmental fluctuations. Incorporating the user input, the system can respond rationally to actual conditions unanticipated by the GA. Therefore, the user can concurrently control the system locally, to reflect individual preferences, and contribute to the global optimization and increased efficiency of the system as a whole.

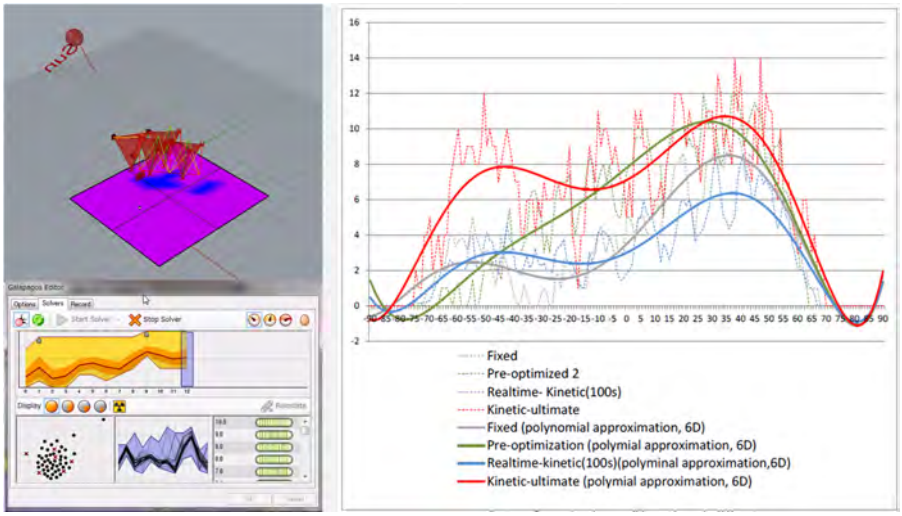



*Figure 3. Experiment-1 and its result (referring from PA, Hotta, 2013).*

The exposure experiment-1 executes with 4 candidates, which consists of Fixed, Pre-optimised (with same algorithm), Realtime-Kinetic (Proposed PA system), Kinetic ultimate (ideal score). The aim of these experiments was to prove that the proposed kinetic roof adapts most effectively to sun exposure over time providing the best result. This set of GA experiments demonstrate the result that normal GA does not work effectively for dynamic situations. The score for the real-time kinetic roof was worse than the pre-optimized roof's score. The following paragraph discusses the possible reason for this and suggests potential solutions. Usually GA is designed and used for static problems. The key issue to focus on in order to improve the score is how to compensate for the lack of initial information in a moving landscape. Two possibilities are: Insert sensor information into the GA's ongoing calculation as an interruption input.

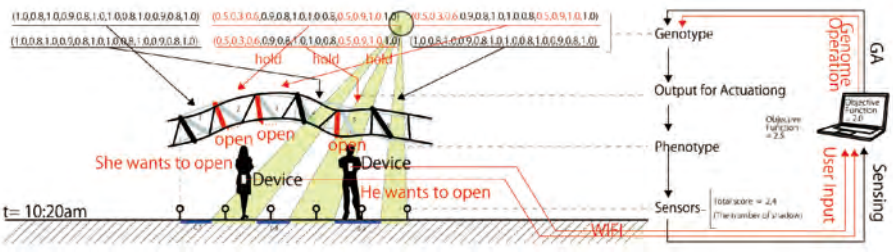



*Figure 4. GA+Human Input Concept Diagram (referring from PA, Hotta, 2013).*

On those contexts, Experiment-2 has examined. While the previous model only allowed one input, namely the environmental input from the sun, this model has 2 inputs, one the top-down environmental input similar to the GA, and the other being a bottom-up user input explained below. Obviously, this is not a pure GA system, but rather a human-interactive evolutionary algorithm. Instead of 'random' mutation, user input is used to seed the next generation. This will help reduce the calculation time.

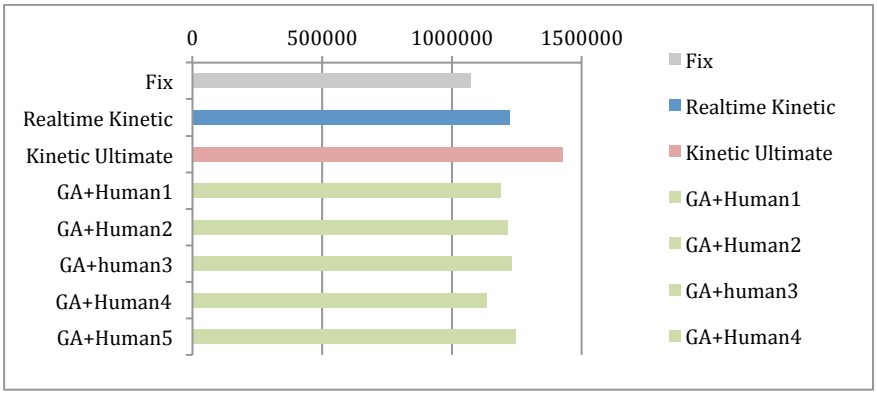



*Figure 5. PA Simulation Result (referring from PA, Hotta, 2013).*

Five different executions are shown as graphs; bigger number is better. Each graph shows a unique 'GA+Human' method, the three candidates: (Fixed, Real-time-Kinetic, Kinetic-Ultimate) are the same. Each 'GA+Human' method's score depends on the proficiency of the human and the timing (number of interventions.). The conclusion of this experiment is 'GA+Human' not always result better than normal GA (Realtime Kinetic) but, sometime could beyond it. This shows if the human manipulations were appropriate, this system can exceed normal GA system. Discrepancy points between the first model and this model are there because those are made by different settings but this is not a main point of this paper. The Grasshopper

experiment raised issues and then it made hypotheses that have been tested in this chapter. In this chapter, the mathematical model (Processing code) confirmed the same minimum set of points; showing that normal GA does not work effectively where dynamic fitness calculations are required. Here a model using Interactive Evolutionary Computation (IEC) was designed and tested. While reaching similar conclusions these chapters could be said to be logically independent.

## 4. Problem statement

Reviewing previous PA research (K.Hotta, 2013), several shortcomings raise up. Here is the problem statement. Human-machine hybridized systems yield relatively better results in the simulation process. However, the large quantity of sliders and lack of intuition in the interface hinders usability and efficiency.

## 5. Physical implementations

In order to get higher score, several systems are tested below.

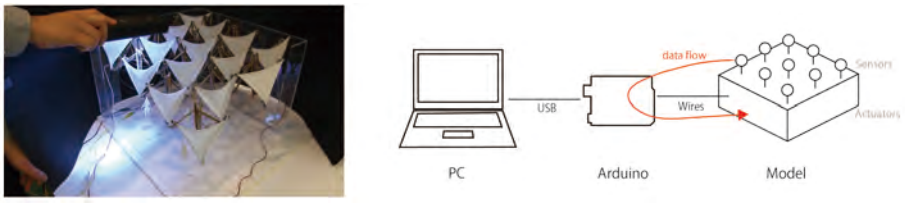



*Figure 6. PA model version-1 and its system.*

The early model of PA, which was made by Arduino in ‘standalone mode’, used the PC strictly as a power source. Though receptive and relatively quick, it was limited to simple responsive or at most branching systems written by the syntax ‘if’, ‘for’, ‘case’ etc. The crucial shortcoming is there is no human interface.

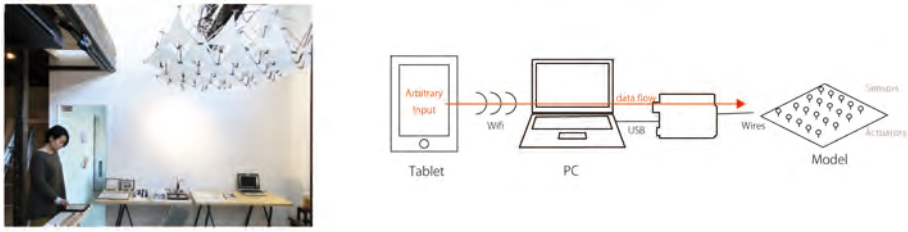



*Figure 7. PA model and its system version 2.*

The wireless system was tested with TouchOSC (hexler.net, 2012), which was originally designed for MIDI controlled surfaces. Yet, its limitations were revealed in its inability to combine two sets of data.

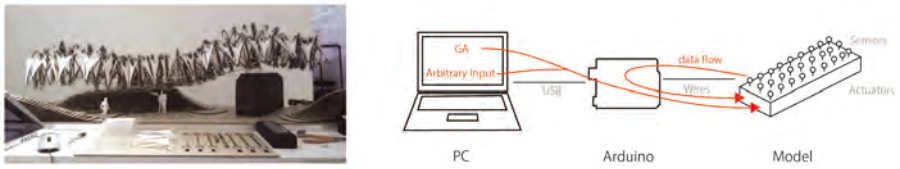



*Figure 8. PA model and its system version 3.*

This implementation is the minimum set for PA, which can afford hybrid data flow, perform automatic calculations and respond to human input. However, the wireless interface with an end device, such as a smartphone, could not be created in reality.

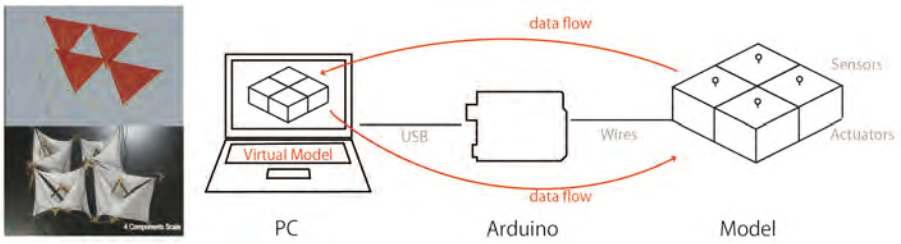



*Figure 9. PA model version 4.*

Referring to Bongard's idea of continuous self-modelling (Bongard, 2006), PA was utilized for simulating precise and physics based virtual models (Fig.10), which was used for previous PA experiments. Ultimately, this will result in the resistance against environmental catastrophic change such as earthquakes, typhoons, etc... Additionally, by selecting outputs instead of expressing every genome could be expected to reduce both energy and cost.

## 6. Experiment and result

Fig. 11 illustrates the comparison between the two different types of user interfaces. The 'simple sliders' (pictured left, Fig. 10) which control each genome independently, yield less performative results, as oppose to the 'smart panel button' (pictured right, Fig. 10), which connects 6 clouds of actuators into a single component, thus demonstrating that the panel control is more intuitive and corresponds accurately with the virtual modelling space.

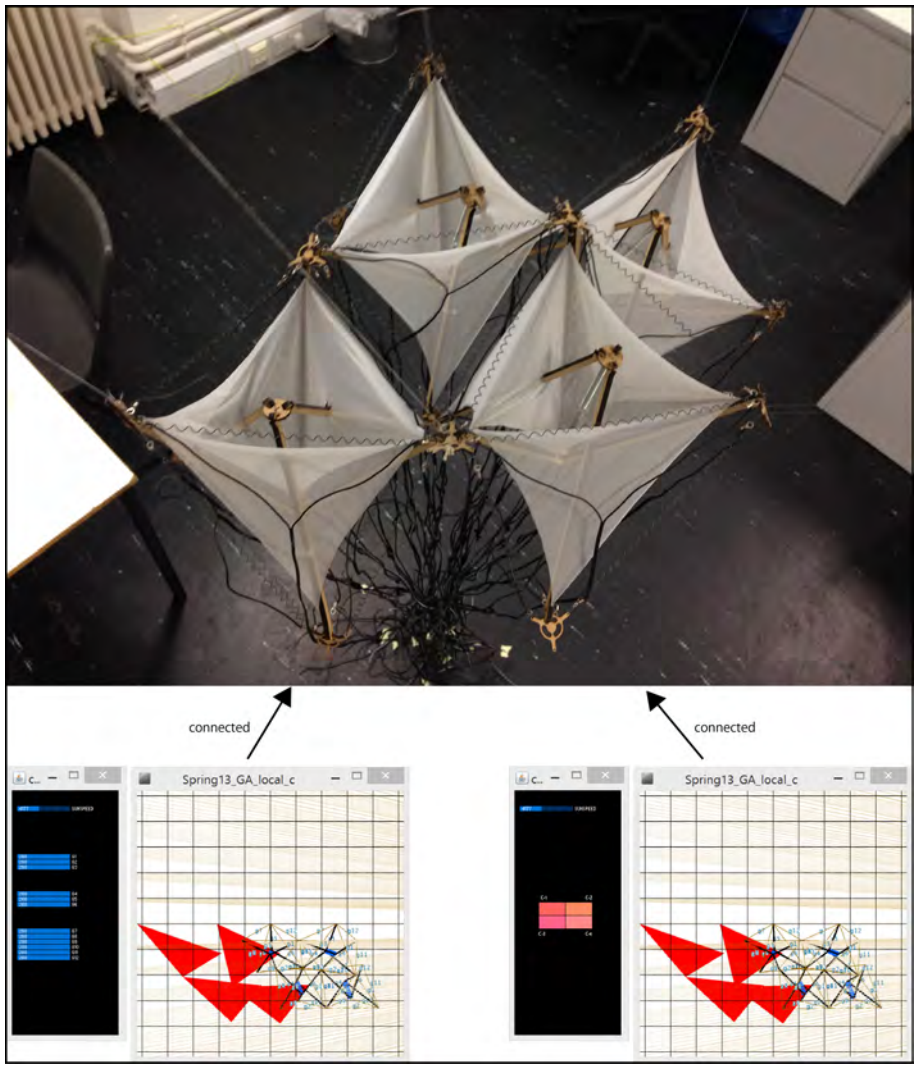



*Figure 10. Two types of Interfaces; Left is sliders, Right is panels.*

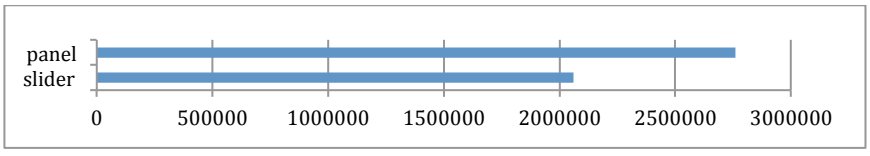



*Figure 11. The result of experiment, bigger is better.*

## 7. Conclusion

Though advances in computational simulations have continuously advanced in recent years, their integration in human-computer interface and dynamic adaptability often lend architectural models to remain as static outputs. The smarter UI strategy is proposed as a step towards an adaptable architecture in two ways. First, by facilitating the computer- human interface in an intuitive modeling process, and second, by favoring a continuous dataflow between the virtual model and physical model, rather than a simple GA setup.

## Acknowledgements

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# CURATING ARCHITECTURAL COLLECTIONS

*Interaction with immersive stereoscopic visualisation*

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**Abstract.** We present our research on the use of immersive stereoscopic visualisation in interaction with collections of architectural representations. We investigate the processing and visualisation of multiple model representations from architectural datasets. We develop two models for locating collections of datasets in spatial contexts, namely a realistic gallery and a synthetic landscape. We evaluate and report the qualitative interactive experience with two forms of contextual interaction within a novel stereoscopic immersive visualisation (cylindrical projection) environment. The use of immersive stereoscopic visualisation conveys aspects and dimensions of the collections that would not be possible without the forms of contextual interaction, the gallery metaphor and the synthetic landscape to interact with the architectural collections. The combination of abstract representations with realistic sense of scale and interaction provide the user with an immersive experience to convey the collective form.

**Keywords.** Digital data acquisition; architectural reconstruction; geometry processing and algorithms; immersive stereoscopic visualisation; human computer interaction.

## 1. Introduction

The built environment domains of architecture, urban design, city and regional planning produce massive visual datasets at multiple spatial scales and modes of representation. Immersive stereoscopic visualisation techniques offer potentially novel ways for representing and navigating such vir-

tual environments. The realistic graphics of building, precinct and city models (real and unrealised) has now reached a point of perfect virtualization of scale, light, materials and context (Hernández et al, 2006). However, the simulation and immersive of abstract datasets poses a number of challenges for the graphics and visualisation pipeline as well as the structuring and serialization of the data. This paper reports on interaction with model collections using an immersive stereoscopic visualisation environment.

## 2. Background

Walter Benjamin's 1936 essay (Benjamin, 1970, edited by Hannah Arendt) on the transformation of cultural experience through photography and film situates the object or experience in space and its dislocation from its context. Malpas (2008, 2009) argues that this loss is also evident in the use of new media in the reproduction of virtual environments. The lack of contextual cues leads to a compression of space and time and is disorienting in the context of virtual reproduction. Recent developments in immersive visualisation using high-resolution large format displays can address these conceptual challenges through combining real and virtual world attributes in a seamless manner. In particular, the examinations of environments that combine realism with abstraction have particular promise in our research.

### 2.1. IMMERSIVE ENVIRONMENTS

The use of desktop Virtual Environments (VEs) to communicate and present design intentions are now commonly used in the spatial disciplines. Immersive environments such as large interactive touch surfaces (Huang and Chang, 2006) head mounted displays (Schnabel and Kvan, 2003), dome projection systems (Melenbrink and King, 2015) and panorama theatres (Oreinstein et al, 2015) provide a new dimension to the ways in which abstract architectural collections can be perceived, studied and analysed. Visual immersion coupled with stereoscopic interaction supplemented with cues such as audio and event based simulation can approximate real, physical environments (Champion et al, 2003). The major benefit of immersive visualisation is the perceptual shift (Bishop and Dave, 2001) in the viewer's experience of the information and the environment. Affleck and Kvan (2005) have observed that the majority of virtual environments attempt to create a realistic representation of their subject. Non-realistic virtual models of artefacts and abstractions have received little attention. In our research we combine the characteristics of virtual environments to explore and interact with a collection of architectural abstractions. Just as close-ups or slow motion in film

permit seeing reality in a deeper way (Manovich, 2002), abstract models provide such a mode in the case of understanding architecture.

## 2.2. INFORMATION ABSTRACTION

Physical artefacts are digitally represented as abstract three-dimensional models through representations comprising geometric entities. The models are composed of geometric primitives comprising point and boundary (edge and surface) representations, wireframe models, surface meshes and solid representations. The multitude of representations and their computational properties reflect the diverse needs of the visualisation, animation, rendering and CAD community. For example, geometric accuracy and modelling precision are emphasised in the CAD community while material properties (e.g. textures) and interactivity are better supported in the visualisation community.

The reconstruction pipeline involves using the digital information generated by acquisition methods to create three dimensional point, surface and solid models (Dave, 2001). Furthermore, the experience of the three dimensional representations are further enhanced with skeletal models of geometry, two dimensional dissections and sectional models that allow the user access to hidden aspects of architecture, not directly experienced through conventional virtual heritage modelling and visualisation (Datta and Beynon, 2014).

## 2.3. RESEARCH OBJECTIVES

The aim of this research is therefore to investigate how immersive stereoscopic visualisation can facilitate interaction with collections of abstract architectural representations. Our objectives in this research are to:

- Investigate the representation, processing and visualisation of multiple architectural datasets (Model Representation); and
- Develop context models for locating collections of datasets (Scenario or Context); and
- Evaluate the immersive experience of these models in a virtual environment (Narrative or Interaction).

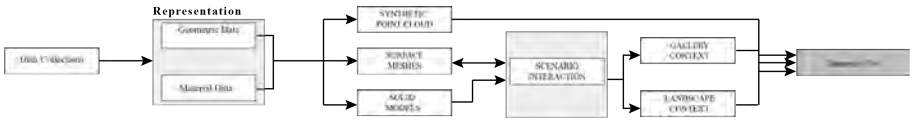



*Figure 1. Immersive Visualisation framework (This figure shows how the information flows from the model to the system e.g. pipeline flow from representations -> scenario context -> interaction)*

Figure 1 shows the framework of our research and in the following sections we will present the representation of models, the development of context and interactive visualisation in an immersive environment.

## 3. Model representation



*Figure 2. Model representations. Point cloud, textured mesh, and voxel models (top) and wireframe geometry, solid models and sectional dissections (bottom).*

We have addressed interoperability by bringing model representations into a single open interface provided by the Unity platform, a gaming engine widely used in immersive visualisation research (Hoon, Jabi and Goldman, 2003). While primarily targeted at gaming and simulation applications, Unity provides a scripting interface suitable for importing and manipulating data from multiple representations. In this section we present architectural collections derived from Asian temple research repository (Datta and Beynon, 2014) models using three abstract representations, point and voxel models, surface models and solid massing models. Each representation and its abstraction properties are described below.

### 3.1. POINT CLOUD

A point cloud is a set of discrete points within a three-dimensional coordinate system. 3D Point clouds in architecture are most commonly obtained from laser scanning and image processing software. Such point clouds typically represent the visible surfaces of a building. Point clouds are useful for capturing architectural surface geometry, particularly the boundary of complex artefacts (e.g. ornamental carvings in historic buildings). Secondly point clouds are naturally multi-resolution and can be controlled using measures of

point density. Finally, each point is able to carry scalar field information for visualisation using colour hues. We exploit each of these properties to visually display point cloud representations.

Unity is an interactive visualisation tool and is not optimised for spatial point processing. We utilise a custom import tool (developed at the HIVE) that reads the PLY file into Unity. The point datasets can be controlled through a process of brute force decimation by reading every $N^{th}$ point in the point set. A custom Unity shader is then used to visualise the resultant point cloud. The results are shown in Figure 2 (top).

### 3.2. VOXEL MODELS

Voxels (3D pixels) can efficiently display dense point cloud data. Octrees provide a hierarchical tree data structure for efficient partitioning, down sampling and search operations on point set data. We have created an import tool that reads point datasets and converts them into an octree representation. A Unity custom script is used to visualise the voxel bounding boxes of each octree node. Figure 2 (top) shows a view of a simplified set of voxels that simplify the dense point cloud data automatically and allows a viewer to interact with the model intuitively.

## 4. Immersive visualisation of model collections

Interaction with model representations is to a large extent designed for desktop or head mounted displays (e.g. Oculus Rift). Using large-scale environments aids the perception of higher fidelity and resolution in details (Hunag and Chang, 2006, Melenbrink and King, 2015). In this section we describe a large format cylindrical panorama system implemented at the HIVE (Figure 3). Two forms of contextual interaction are tested and a qualitative evaluation of stereoscopic 3D for visualisation (cylindrical projection) is presented.

### 4.1. HIVE CLYINDER

The HIVE cylinder permits multiple forms of interaction with virtual environments. This display is composed of a half cylinder screen 8 meters in diameter and 3 meters high. Three 1920x1200 projectors at 120 Hz create a continuous image across the entire screen. Stereoscopic 3D functionality is handled with dual K6000 graphics cards and active shutter glasses. The half-cylindrical interactive projection system accommodates 20 to 30 people. Three hardware warp/blend units operate between the graphics cards and the projectors to rectify the image for cylindrical projection (Woods et al, in preparation).

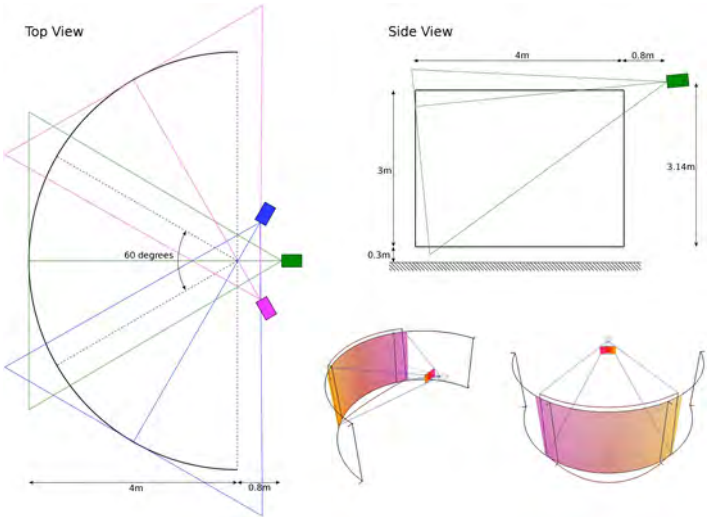



*Figure 3. The HIVE Cylindrical visualisation system shows the various parts of the generic cylinder (right), and the warp-blend projection (left). The display permits infrared marker based interaction between users and the model as well as Kinect-based gestural interaction.*

Unity (www.unity3d.com: Jan 2016) is used both as a content development platform and for the display of immersive experiences. A generic immersive virtual reality plugin called MiddleVR (www.middleVR.com: Jan 2016) handles interaction with trackers, display architectures and stereoscopic projection in conjunction with custom scripts in Unity. For single users head tracking is possible using a set of OptiTrak cameras placed around the screen edge. These infrared cameras are used for tracking motion and gestures based on detection of markers. This allows the perspective of the viewer to be updated as they move around, allowing a natural interaction with the environment.

Larger scale movements are then controlled with one or more of a standard keyboard and mouse setup, a SpaceMouse for 6 degrees of freedom (DOF) movement. A Microsoft Kinect provides marker-less tracking and user interaction through sensing of gestural motions.

## 4.2. VIRTUAL GALLERY CONTEXT

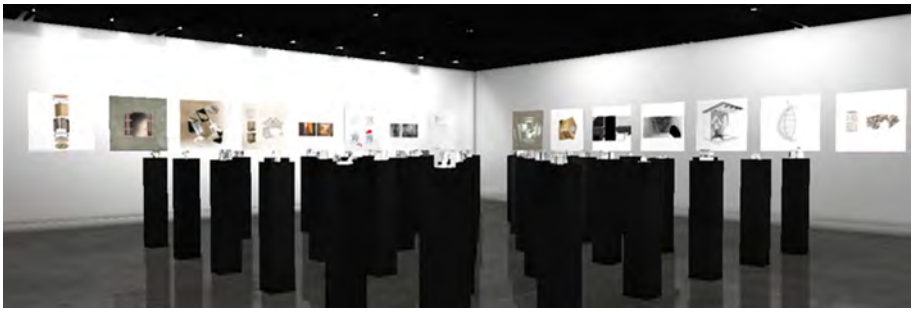


*Figure 4. Virtual Gallery Context. Scale models are displayed in an internal gallery context with a high level of detail in texture, lighting and materiality. The scale model representations are augmented by interactive "wall" displays showing supportive representations.*

The first form of contextual interaction is the display of scaled representations within a gallery model (Figure 4). In this context, architectural model collections are presented within an interior setting. The model collections are organized into a virtual exhibition of scaled models and drawings embedded within a virtual gallery model. To communicate the rich variation of forms as well as the continuities underlying the corpus, the virtual gallery collapses the realism of each instance and presents them in a unified collective context. The scaled models are arrayed in a grid of plinths. The models can be inspected in greater detail using the camera and interaction model. Each model is a singularity representing a particular spatial and temporal context with a formal and compositional structure. Each model belongs to a collection representing a sampling from a family of related forms.

Head tracking provides an intuitive method of interacting with and inspecting the elements in the environment. In this environment many small models are placed on plinths. This allows the user to inspect the model from many different angles simply by waking around within the confines of the Cylinder display.

## 4.3. SYNTHETIC LANDSCAPE CONTEXT

The second form of contextual interaction is the display of full-scale models (Figure 5). In this context, each architectural model is sited within an abstract landscape. The full scale model collections are organized in the synthetic landscape to provide a unified context for model exploration. The models can be explored by walking in or flying through the landscape using the gestural interaction described above (Figure 5).

The exploration of these larger spaces, especially landscapes (Figure 5), often benefits from interaction controls provided in the Microsoft Kinect. A

form of gestural control has been implemented that allows a user to move around in large environments. The user can control pitch and yaw by moving their hands in the desired direction; lifting one hand above the other controls roll. The distance between the hands controls speed, i.e. a faster speed is achieved by holding the hands further apart. This allows large environments to be explored in short periods of time and the layout of an area to be quickly understood.

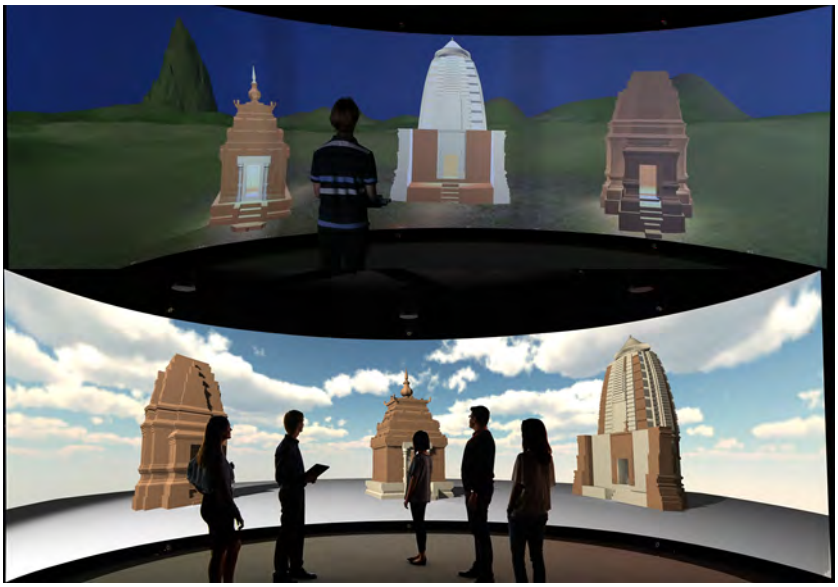


*Figure 5. Immersive interaction with full-scale models in the cylinder and multi-user immersive experience of a synthetic landscape context.*

## 4.4. RESULTS

Immersive environments offer a different mode in which to access and experience places and cultures that may not easily accessible. The advantage of being immersed in the experience and thereby approximating the real experience is a definite advantage. The characteristics, benefits and weaknesses of the interaction parameters are summarised in Table 1. The immersive experiences described above have been tested in the form of guided tours for a collection of people.

TABLE 1. Results matrix based on the framework described in Figure 1

| | Immersive Scenario | Characteristics | Benefits/Weaknesses |
|---|---|---|---|
| **Model Representation** | Virtual Gallery | -3D reconstruction models<br>- 2D surface data<br>- Emphasis on abstraction | Seamless presentation of both raw data from point cloud, surface meshes as well as wireframes, voxels and solids can be imported and displayed. |
| | Synthetic Landscape | - 3D Solid Models<br>- Emphasis on textures, renders, lighting | Presentation of abstract data requires extensive manual preprocessing such as for immersive visualisation |
| **Context** | Virtual Gallery | - Realistic model of gallery<br>- High LOD (4 or 5) | The highly realistic gallery context provides an effective stage within which to view abstract models. |
| | Synthetic Landscape | - Abstract computer generated landscape<br>- Low LOD (1-2) | The synthetic landscape provides an expansive space with a horizon and orientation. |
| **Interaction** | Virtual Gallery | - The primary narrative is walking through a gallery | Models can be viewed and inspected. Models are supported by information on gallery walls such as drawings, site and interactive display. |
| | Synthetic Landscape | - The primary narrative is gliding through a computer generated landscape | Gliding through the landscape based on gestural interaction provides the primary immersive experience of full-scale models. |

Due to this display immersion, adding interactive elements such as head tracking increases the level of immersion and many people suggest that it is just like being there. When larger environments are being displayed the Kinect provides a natural way of navigating around. Interestingly younger people generally find this more intuitive while older people generally require more detail instruction on how to control the interaction. Having said that nearly everyone agrees that this method of control is very effective at navigating around large environments and understanding the wider context of the objects within.

## 5. Discussion

The abstraction of scaled models and materiality (monochrome grey scale) are used to provide the user with a gallery experience to convey the collective form. The purpose of immersive virtual experience is not to challenge or displace the authenticity of the physical object or the faithful accuracy of the photographic record. Instead, the aim is to develop “unobtrusive mediations” that permit connections and interpretations that permit scholars and the public to assess and experience the significance of architecture as a collection.

## Acknowledgements

Nicholas Oliver and the HIVE at Curtin University are acknowledged for providing the basis for the Unity point cloud import scripts and implementation of the gestural gliding interaction with synthetic environments. Rob Cameron and Andrei Smolik, PhD Candidates at Curtin University developed the Virtual Gallery Unity scene used to display the collections.

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# A SMART BRACELET

## *An alternative interfaces between performer and audience*

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**Abstract.** Performing arts has been one of the main recreational activities in people's life. However, most performing arts, performers usually used one direction to express performing contents to the audiences. It means there is no real-time communication channel between the performers and audience in most performance. Hence the challenge of this research is how to provide a better relationship between the performers and audience without disturbing the show? This research we implemented a bio-sensor embedded smart bracelet which is able to transmit the feelings from user's to stage by monitoring biological signal (ex: Galvanic skin response) immediately. When most audiences have the same physiological reaction to a certain level, the stage scene would be changed the colour and pattern to let performers know how the audiences' feeling now. Performers would enhance self-confidence and then incorporate the audiences' feedback to create their future performance. By applying this interactive interface to performing arts, we explored a new vision of performance that can not only enhance the diversity of performance but also provide a comfortable communication channel between performers and audiences, and improve the confidence of the performers.

**Keywords.** Performing arts; computational technology; interactive interface.

## 1. Introduction

The advent of digital technology has provided artists with more diversified media for creativity, and a new concept of "interaction" is integrated into their works of art. These works are presented in a unique manner that constitutes the so-called "digital art." Artists attach much importance to the concept of "interactivity", which is a characteristic of digital technology; this concept has become an approach for creation. As Ascott (1990) said, "Through the medium of art, one can interact with others, leading to communication between a piece of work and a person and engenders a new art value." Digital art has transformed the traditional one-sided way of appreciating and understanding artworks; this implies that art works are not merely meaningful in aesthetics, and their values are derived more from the engagement of the audience. In other words, not only does digital art offer art more diversified media elements and expressions, but it also changes the inherent means of communication between artists and audiences (Lin and Fan, 2004).

At present, digital technology has been applied to performing arts ranging from simple one-sided stage curtain projection (Rakkolainen et al, 2006; Shiba et al, 2010; Soga et al, 2009) or auto-rotating projection technology (Kim and Kim, 2015) to global projection (Anarchy Dance Theatre, 2011). These applications provide more space for artists to thrive. Performing arts, different from static arts, require the collaboration of two groups, that is, collaboration between the performer and audience to complement the works of art, and so two different types of interaction appear. The first one is the interaction between a combination of digital technology and theater space (background, music, props, etc.) and performers, such as the well-known Japanese performing group SIRO-A, who are good at employing projection technology to produce illusions. The second is to invite the audience to perform on stage and use sci-tech media to make some onstage changes, similar to what Seventh Sense performed at Anarchy Dance Theater in 2011. The integration of these performing arts with digital technology delivers fabulous visual feasts to art lovers as well as generates excitement over the future of digital performing arts.

## 2. Problem and objective

The brand new future of art is starting with digital technology. Many performing artists have tried to make use of science and technology to break the barrier between the performer and audience, such as the entertainment system to interact with audiences(Maynes-Aminzade et al, 2002) or the interaction system for impromptu story-telling (Alavesa et al, 2014). The number of

art installations that can facilitate interaction with audiences has been increasing. However, in performing arts, artists rarely use digital technology to interact with the audiences. Digital technology is mostly used for facilitating interaction between performers and theatre space.

Clayton Hamilton, an American critic, once said "The audience plays a significant role in a theater" (Yao, 2004). Anne Ubersfeld, a contemporary French theater scholar, also stated that although no audience is engaged in any part of theater production, the entire drama still exists for them (Chiu, 1997). The theory echoes with the interactivity of digital technology. Performing arts evolve even today nonetheless, but most of them are still caught in the framework of traditional arts. The performance on the stage will impact the emotion of the audience, but the emotional response of the audience cannot be conveyed to the performer. As a result, though audiences play an important role, they cannot engage themselves in the performance.

The interactive relationship between the performer and audience is still in a phase where audiences watch performances through the performers' eyes. In this one-sided communication style, a performer is satisfied by his/her own performance but he/she is not able to determine the audiences' thoughts. If suppose an audience reacts radically towards a performer (claps hands or shouts suddenly during a performance), the performer would get disturbed. Therefore, the main subject in this study is to explore a special interactive approach that can improve the relationship between a performer and his/her audiences without influencing the performance. This study seeks to utilize digital technology to improve the interactive relationship between the performer and audience. The approach involved a smart bracelet system prototype. More specifically, the physiological signals of the audience could be gained through biological signal sensing devices (mainly based on electric skin response). As the performance proceeds, the background projection on the stage slowly changes to minimize the possibility of influence from the audience on the performer. Simultaneously, performers could find out whether their performance was appreciated by the audience, through watching the changes on the stage, as indicated by the bracelet in real time. Thus, they could be encouraged and gain confidence that a better and more intuitive interactive system could be built.

## 3. Methodology and steps

In this study, we aim to change the interactive mode between the performer and audience in performing arts; an interactive system was proposed that uses people's emotion as an intuitive response via the physiological signals of audiences. This arrangement sought to control the change in the image back-

ground on the stage so that the interactive response could be directly offered to performers. This study was mainly based on electric skin response and included the following two steps:

**Step 1. System Concept**

Even though digital technology has been widely applied to performing arts, there have been no studies for sensing physiological signals as a means of interaction. Therefore, the emotional changes in audiences who appreciate performing arts would be analyzed first in the study. Tsai (2013) discovered that the intensity of emotion changes in "The Emotional Expressions and Structure in Beijing Opera *Pong-Yin*: Combining Performance Analysis with Audience's Physiological Measures" was the best physiological response to be sensed, and so we selected skin electric response as a sensing standard through the electric conductivity of fingers to detect emotions, and combined the above results to establish a framework of this interactive system.

**Step 2. System Implementation**

In order to prove the practicability and reliability of the smart bracelet interactive system in this study, a model of the smart bracelet system was established. First, the main program of the interactive system was installed to ensure it cascades image changes on the background projection in response to the audience's physiological changes. At the same time, the assembly and testing of the wearable devices was carried out. Finally, the subjects were invited to have a scenario demonstration.

## 4. Result

### 4.1. SYSTEM CONCEPT

In order to improve the one-sided interactive relationship between the performer and audience, we built a good and intuitive interactive bridge between these two groups via a smart bracelet system (Figure 1). The study focused on the background projection in digital performing arts with a large audience with the same reaction to an increase in the image changes in the background. The more the people felt excited, the more evident the image transparency was. The demonstration of the image not only offered the audience a sense of satisfaction in participation, but also allowed performers on stage to know the feelings of audiences through the background changes on the stage.

The system included two major parts: one was the physiological sensing of a smart bracelet and the other was the image changes on the background

projection. The system must be built while on performance in a way that the audience can engage themselves with the performance on the stage in the prescribed periods via the setup of the performing party. The smart bracelet mentioned in the study is still in its development stage, so there had been no cooperation from any performing group yet. At present, the development of the system is the key part in the entire study.

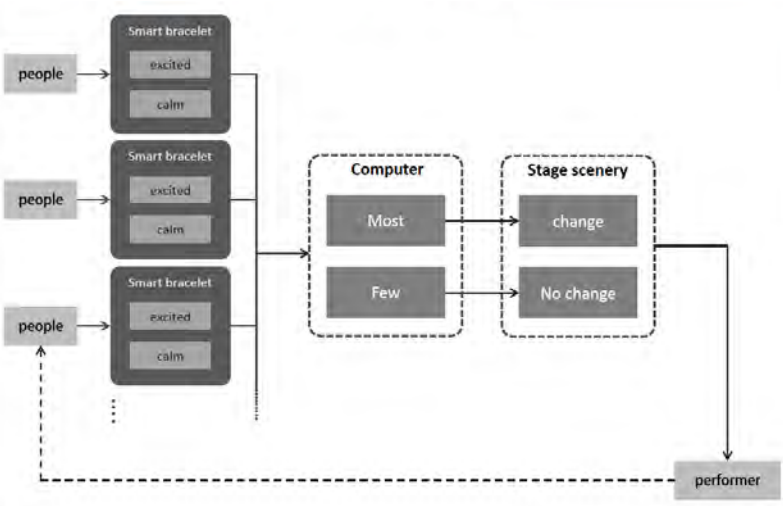



*Figure 1. System concept*

## 4.2. IMPLEMENTATION OF SMART BRACELET SYSTEM

In this paper, we proposed a new architecture for interfacing the performer and audience. The audience, who has worn our smart bracelet, plays the role of source generator. This bracelet can measure galvanic skin response, establish a channel with a backend server, and transmit the data. Then, the performer can react to these sensing data, which show up as different colors depending on the feedback of the audience (Figure 2).

The first problem we have to solve is the connectivity between all the smart bracelets and back-end server. Fortunately, with the growth of Internet of Things (IoT), the bridge module between a microcontroller and Internet has been widely developed. Therefore, we choose the NodeMCU as our platform for the smart bracelet due to its low-power consumption and Wi-Fi connectivity. The following section will cover the details of our implementation of hardware and software, respectively.

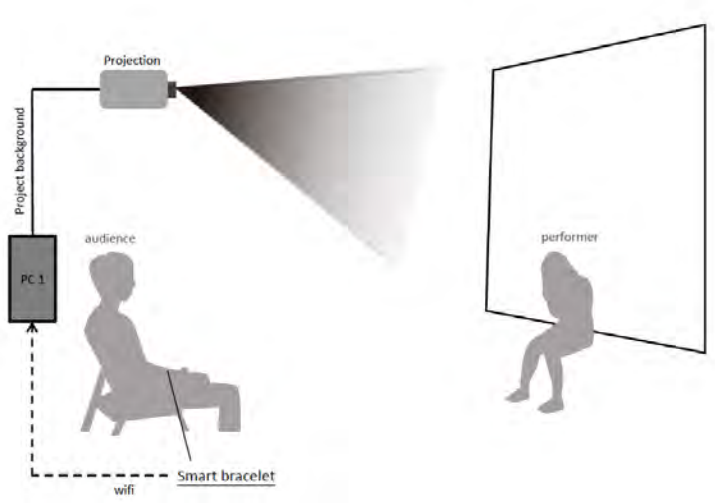



*Figure 2. System framework*

### *4.2.1. Smart bracelet*

The NodeMCU offers a complete and self-contained Wi-Fi networking solution. It provides a system-on-chip with integrated TCP/IP protocol on a microcontroller with a bunch of peripherals, such as UART, ADC and GPIO. Additionally, NodeMCU uses an on-board programmer, which makes the solution more portable and easy to use.

To measure the conductivity on the skin, we use a high precision comparator to compare the voltage difference between two fingers. Note that the ADC on NodeMCU is then applied to sample the analog signal on the comparator output. In this experiment, we select TI LM393 as our comparator. A voltage divider was needed to limit the ADC input to a maximum of 1 V, since LM393 has an output voltage of 3.3 V. The DC bias for TI LM393 is provided from NodeMCU.

The power solution on our smart bracelet is a small power bank with a mini USB cable plug into NodeMCU.

Finally, the program in NodeMCU keeps sampling the conductivity and sending it to the back-end server.

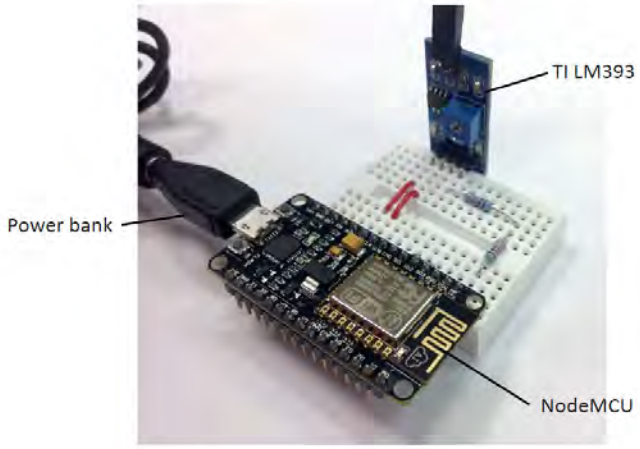



*Figure 3. Smart bracelet components*

### *4.2.2. Back-end server*

To handle hundreds of connections from the smart bracelet and render a responsive colour block, we need a computer running as a server. In this experiment, we choose Nodejs as our framework because of its event-driven and non-blocking advantages. During the reactive performance, the responsive colour reaction is accomplished by computing the average conductivity continuously and mapping to a colour. Note that the average process can be equal to a low-pass filter when the audience becomes larger. Therefore, the colour can change gradually and the index of the audience excitation can then be observed.

### *4.2.3. Scenario simulation*

Maggie has just finished work and wants to relax by watching a show. When she enters the theatre (Figure 4-A), the staff helps her to wear a bracelet (Figure 4-B). She is not sure why she needs to wear it, but she takes her seat. During the show, she finds that when everybody laughs, the background becomes bright (Figure 4-C). In contrast, when nobody is responding, the background becomes dark. Actor looks poor (Figure 4-D). She thinks it is amazing and enjoys this show.

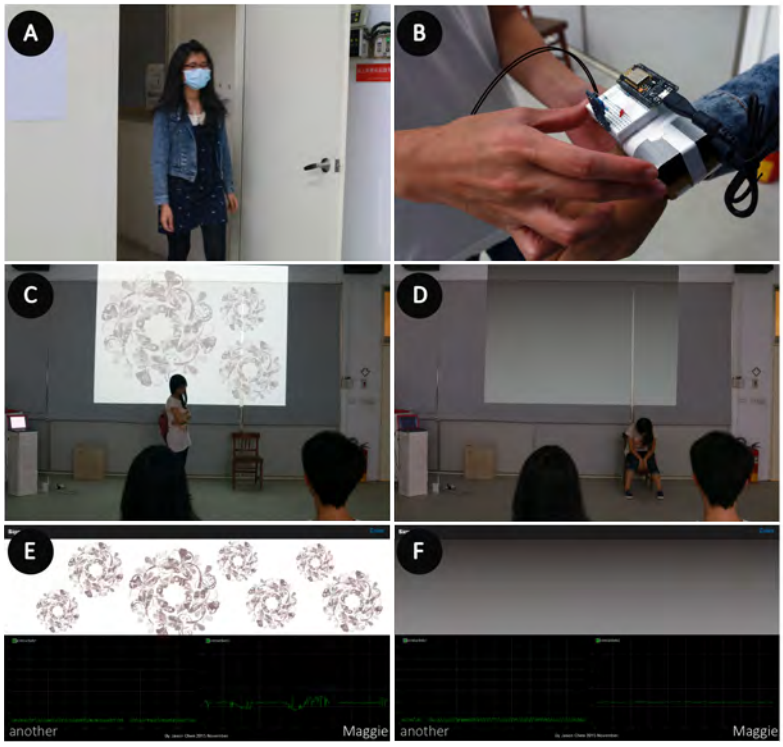



*Figure 4. Scenario demonstration:* ***A*** *audience member enters the theater;* ***B*** *staff helps her wear the bracelet;* ***C*** *when the audience exhibits large changes in emotion, the background becomes bright;* ***D*** *when the audience does not exhibit any change in emotion, the background becomes dark;* ***E*** *the interface of GSR (left: another audience; right: Maggie) and bright background;* ***F*** *the interface of GSR and dark background*

## 5. Conclusion and contribution

The future of performing arts is full of possibilities. In this paper, a smart bracelet has been proposed to measure the skin electrical resistance and report to performers. It not only provides a quantitative biological response to performers, but also enables real-time feedback from audience. The implementation of the smart bracelet system has proved the feasibility that physiological signals and interactive devices can be integrated, with the audience and performer satisfied. Since the system in the study is in its early stages, it still offers scope for development, such as the use and efficiency of wearable bracelets, the endurance of batteries, or the richness of image projection. The system can be applied to other spaces, such as the remote monitoring of home healthcare, to deliver the benefits of this intuitive and excellent interactive interface to users. Finally, the proposed smart bracelet system com-

bines biological signal processing, Internet of Things and performing arts as a modern performing system.

## Acknowledgements

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# REFLECTING SELF: AN INTERACTIVE MIRROR STUDY

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**Abstract.** Immersive environment provides a virtual environment immersion experience for the user, and allow users in-depth experience. In this study through research "self- reflecting" and "self-reflecting during interaction with the space environment" by entity makeup table for discussion. Makeup table reflect the role of people and the surrounding environment. We found the style selected by the user, often conform to the user's external style, and does not because of the age limit the user to interact with curiosity. We also found that in addition to the female user, make up table will also trigger young men of curiosity, they will close to observation and interaction with the table. Finally, we have statistical distribution of general user preferences. We also in accordance with the user's behavior, revised interactive processes, make recommendations when designing immersive environments.

**Keywords.** Immersive environment; virtual environments; reflecting self; avatar; virtual make up table.

## 1. Introduction

Creating the immersive space, usually by the surrounding environment, allowing users in-depth experience, such as to play a virtual role in a particular environment (an avatar). They will not be subject to static restrictions, like cameras, recording, the user can see their own virtual manifestation by dynamic changes (Kuijk et al, 2015); and under the environment of things that people can work, participate in the activities of field experience, social and

sharing experience. Because people are not in real life, so there is no time and space burdens and limitations.

The spatial environment of interaction with virtual information has three different problems: information can be effectively presented; user can effective operate; and consequence of operation can be effective represented. The above problems affect users in different level of immersion. Through research *self-reflecting* and *self-reflecting during interaction with the space environment*, a makeup system with table/mirror to reflect the role of people and the surrounding environment is implemented. With first-person perspective to space, augmented reality and virtual reality technologies are used, and self-reflection provides users with an immersive experience.

## 2. From immersive environments to self-reflecting

### 2.1. IMMERSIVE ENVIRONMENT

Immersive environment provides a virtual environment immersion experience for the user, effectively cross between the virtual and the real world (Boussemart et al, 2004). Prabhakaran (2009) who ask questions, in immersive environments which user's interaction, users and the environment, users and other objects or users and computers. Three items will provide increased degree of user experience, and another research area of human gesture recognition combined (Prabhakaran 2009).

Boussemart et al (2004) proposed a visualization three-dimensional virtual environment and control mode, users do not use the traditional keyboard and mouse, they can avoid the embarrassment of operation interaction glossary; (Law et al, 2009) who developed the interactive system allows users to go on virtual natural materials, to provide users with tactile, auditory and visual feedback, allowing users to have immersive experience. Additionally, diverse different computer platforms and increasingly rich multimedia are two main factors can further enrich the user's experience. New generation of users requires not only the functional requirements and entertainment, but also a variety of media for aesthetics and experience.

Therefore the user's interaction includes users and the environment and the relationship between users and objects, and immersive environments should provide diverse added values to user. A daily life "makeup table" is used the media, and "makeup" to reflect their user own behaviour. Through interviews and questionnaires in a group of 20-30 year-old women, analysis and preliminary interactive design is conducted to testify the result.

## 2.2. NONVERBAL BEHAVIOUR OF SELF-REFLECTING

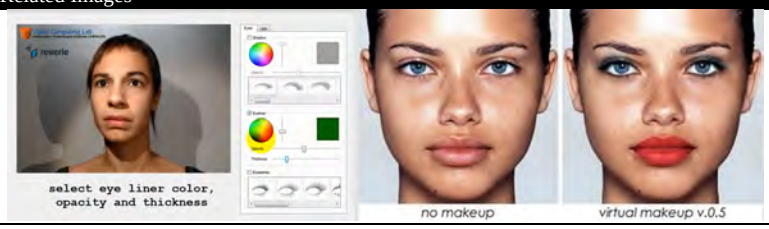
Through real human body acquired data, virtual characters simulate the interaction between real and imaginary including facial expressions, looks and gestures. (Schröder, 2010) proposed facial expressions and vamp gestures in virtual architecture referred to in real life, people interaction with a single character; while the other is shared virtual space with more than one virtual role players. Both will have different levels of immersion and interaction of different feeling. Therefore, self-reflecting is the key and the expression must be in line with reality, and ultimately nonverbal behaviours.

Related cases about self-reflecting are: Yoshida et al (1995) let the ATR combined with hand gestures and verbal description, the graphics object is the key for interaction; Capin et al (1997) developed VLNET (Virtual Life Network) system that is using a motor function, and with the role of a real environment combined with each other; Garau et al (2003) found that the use of matches man and semi-real avatar that will affect the quality of the user's immersive. Therefore, we need to increase the effectiveness of avatar.

Virtual Vanity with digital LCD screen displays the image to encourage customers to try to use makeup. With the tips customers select their favourite look, and print a list of all products used in the end (Sephora, 2009). Estee Lauder launched a virtual makeup services in the official website, customers can upload their own photos; try the latest merchandise and colour. After trying, customers can decide whether to buy according to the customer's own wishes (Lauder, 2010); Visual Computing Lab uses face automatic tracking and colour system development Virtual Makeup, for face tracking, they use complete algorithm, and comparing, guiding active shape models (Active Shape Models, ASMs). ASM 115 select feature points on the face, then the researchers train 12,300 data in manual mode, and imported 135 female faces into the model library, when using the 135 will be derived from the face, making facial expressions and posture can fit (Louizis and Daras 2014). The universality of mobile phones and tablet also bring out the real-time makeup used in mobile phones, virtual reality makeup used on the iPad (Ever, 2014) and ModiFace is a mobile phone application that has been downloaded more than 300,000 times (Aarabi, 2014) (Table 1).

According to reviews above, self-reflecting focus on semi-real projection or true projection, and it will affect the degree of user immersion in the interactive process. Thus, through facial shape and sharpness of the face makeup, the appropriate range is found. The level of immersion affects the self-reflecting, thus the real and gentle makeup will be proposed.

Table 1. Virtual Makeup case.

| Case | Related Images | Case | Related Images |
|---|---|---|---|
| Virtual Vanity |   | ModiFace |  |
| Virtual Makeup Tool |   | My Studio |  |
| Case | Related Images | | |
| Virtual Makeup |   | | |

## 2.3. SELF-REFLECTING ENVIRONMENT CREATE AND INTERACTION DESIGN

To make users from the complete, natural interaction process, and users in the process can immerse into the space, to feel the complete atmosphere. Thus, the study allows the user to interact with the entity makeup table, use the mirror of medium, and explore “self-reflecting” and “self-reflecting during interaction with the space environment”, to further verification of immersive space’s information.

Through self-reflecting interface and interactive process design, with amplification reality technology, this study developed a complete set of interactive processes (Figure 1). When the user enters the sensing range, the interaction is activated. Through the cube and round brushes on the table, the either expert or custom mode is selected, When the user decides the makeup outlook, the camera mode is decided. Through scanning QR on coupons, the user can download makeup photos. The following will be described in detail

interface and interaction processes design, and how to match augmented reality technology, allowing users to achieve a natural use.

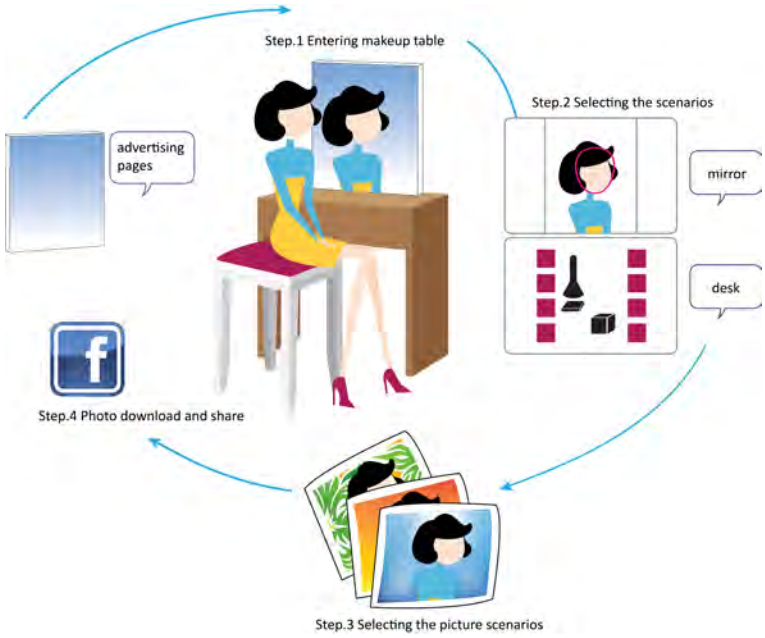



*Figure 1. Immersive makeup interaction of use scenario planning.*

## 3. Software technical and implementation of self-reflecting

Conducted by questionnaire in face shape data collection and analysis, as well as interviews with users and make-up expert. According to the results of interviews, to summarize Taiwanese women major face shape and classification: long face, diamond-shaped face, oval face, square face and round face; makeup basic categories: makeup base, facial, lip and face. Finally, situational makeups are decided in different context (Figure 2).

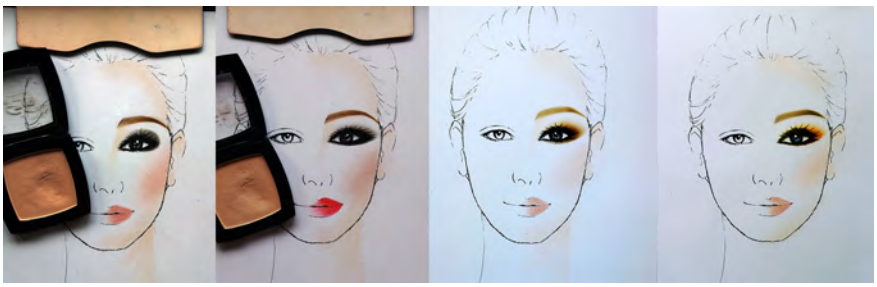


*Figure 2. Situational makeup by the expert.*

### 3.1. USER FACIAL FEATURES AND DYNAMIC IDENTIFICATION

Self-reflection and facial expressions, face shape have a great relationship, facial expressions and the true extent of face will affect the degree of immersion of the user. Thus, the study tested through facial shape and sharpness of the face makeup to find the appropriate range. We found that users still prefer the real and gentle makeup, in subsequent research, peripheral contour of makeup, details will be processed.

Because face shape may affect women in the makeup of the way, the facial expression will affect the authenticity of identification. This study uses a method that split face into a triangular, unlike traditional face recognition technology, a slight changes only affect regional triangle, for the entire image, it will not have much impact. Using this triangulation to determine facial features, if there is a change in a small range on the face, it can still be identified, and will not affect other triangles. The five faces are selected, and collection target multiple angles of the face are recorded. For the geometric characteristics of the face: eye, nose, mouth, eyebrow and head type, hairline relative position, and brought together into face repository.

### 3.2. AUGMENTED REALITY TECHNOLOGY AND SELECT INTERFACE

Interactive mode contains expert mode (situated makeup) and custom mode (interactive makeup). User uses turn, rotation and drag-n-drop operation (Figure 3) over a controller (cube) for the interaction. The cube with five sides responds to five scenarios and one for custom mode (Figure 4). User selects scenarios through flip the cube: work, travel, weddings, shopping and nightclubs, and through rotation to select adjective: elegant, sweet, sexy, bold and stylish. Custom mode icon is a round brush. The user chooses the product through rotating brushes: liquid foundation, eyebrow pencil, eye shadow, eyeliner, mascara, blush cake, trimming cake and lip gloss. Extra factors can be selected through rotation (Figure 3).

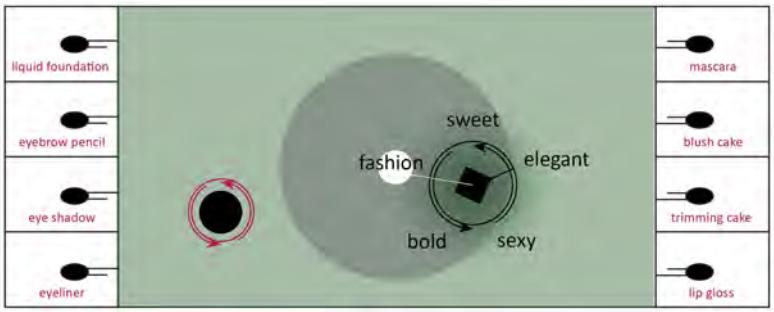



*Figure 3. Instructions for use the augmented reality items.*




*Figure 4. Augmented reality items and icon.*

## 4. Interface and interaction processes design of self-reflecting

With focus groups studies on self-reflecting, the recommendations of makeup interactive experience systems along with the user interface and interactive processes are refined. Combing two components: “mirror” and “table”, the user is prompted with greeting on interaction process. User can act according to their needs, either expert or custom mode. Camera mode is reached after the determined makeup is done.

Custom mode allows users select a commodity, such when the user selects the lipstick on the table, the mirror will immediately fit lipstick effect on the user; or the choice of liquid foundation, the mirror will have beautiful skin and lighting. Up to eight types of merchandise, there will be immersive effect and each commodity at most three colours, users can choose according to personal needs. If the user wants to cancel the selected commodities, they can turn round brushes to cancel icon (X) position (Figure 5).




*Figure 5. Custom mode interface.*

Expert mode is a recommendation that applies professional knowledge to mix and match each scenario. Expert mode is divided into five scenarios as described. When user selects expert mode of the wedding scenarios, table will change the interface into the wedding style to correspondence. User se-

lects “stylish”, then the eyebrows, eyelashes, eye shadow, lip gloss, and repair capacity will put the effect immediately on the self in mirror (Figure 6).




*Figure 6. Wedding scenarios interface of expert mode.*

When the user moves the square cube to camera icon, camera mode is reached. In the camera mode, users can choose different magazine covers to increase the durability of table. After the cover, three continuous shooting is activated (Figure 7). By selecting a favourite photo and through scanning QR code on coupons, the user can download makeup photos for sharing.




*Figure 7. Selection and continuous in camera mode.*




*Figure 8. (top) Selection and continuous in camera mode (bottom) User test.*

## 5. Conclusion

Through the user self-reflecting simulation and testing, we found the style selected by the user often conform to the user's external style, and regardless of the age (Figure 8 bottom). Curiosity is higher if the immersive level is high. In addition to the female, make up table will also trigger young male of curiosity, they will close to observation and interaction with the table.

After statistical distribution of general user preferences found that users prefer to select Expert Mode, they like the makeup products combination according to the popular. The five kinds of situations rankings: shopping is most people choose, wedding and travel the same as the second, third work, fourth nightclubs. The choice of adjectives, whatever the situation, fashion as the first choice of the majority; the second choice for the travel situation is sexy; elegant and sweet is the second choice for wedding situations; shopping and nightclub situational second choice is elegant; in the work situation, users preferences sexy and sweet, and users does not like the bold as the first consideration.

Finally, we have statistical distribution of general user preferences. We also in accordance with the user's behaviour, revised interactive processes, make recommendations when designing immersive environments. The interactive criteria: must be intuitive, user can to interactive without going through teaching; everyone can participate; the interaction is diverse, but it is easy to modify. Then the finally interactive interface and initial interactive interface, the design will be adjusted, comprising: 1.augmented reality objects simplified modification; 2. augmented reality icon simplified modification; 3. custom mode cancel icon (X) adjustment the position; 4. modify the disk interface in expert mode; 5. in order to comply with "interaction is diverse, but it is easy to modify", Thus consider planning the background, can be easily updated. Additionally there are still a few details would affect the degree of user immersion, the study will continue amendments, include: surrounding environment without cluttered background; in addition to individual users without other people beside; and interactive range size (here refers to the desktop).

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# TANGIBLE MIXED REALTY

*Interactive augmented visualisation of digital simulation in physical working models*

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**Abstract.** The implications of architectural design decisions are in many cases hard to predict and envisage. As architectural tasks grow more complex and the design of architecture shifts away from the design of end products towards the steering of dynamic processes, new ways of coping with complexity in the design and planning process are needed. Taking this as its starting point, as well as the need for architects to use familiar, established design tools, the CDP research group is working on new ways of supporting the design decision-making process with objective information so that designers are better able to manage these complexities. The focus of the group lies on directly coupling interactive simulations and analyses with established design tools. This paper discusses a central problem in this context: how to present complex calculation results directly within a physical 3D-model. The approach described, as evidenced by the realized prototype, shows clearly that directly coupling real and digital information using interactive augmented visualization presents immense possibilities for managing the complexity of planning processes.

**Keywords.** Design support, simulations, computational design, urban planning, augmented reality.

## 1. Introduction

The larger the construction project, the more complex the interactions between its technical, social, planning and design aspects. As large construction projects become more widespread, the building sector is confronted with increasingly difficult challenges. Planners are faced not only with deal-

ing with a multiplicity of static conditions but also with changing situations resulting from dynamic processes. Today's designers, as Wood (2007) has remarked, need to "become the facilitators of flow, rather than the originators of maintainable 'things' such as discrete products or images". In this context, we need to find new ways of planning that help us to visualise and understand complex interactions, implications, interdependencies and processes. Given that the designer's influence in the early design stage is high and decisions made in these stages have a significant impact on later design stages, the building cost and its lifecycle (Paulson, 1976), it is important to take into account such factors from a very early stage in the design process.

A key approach to dealing with these new challenges is the use of Design Decision Support systems that assist architects and planners by providing objective design criteria at appropriate points in the design development process. They allow designers to see the impact of complex, dynamic concepts in the form of objective information. The earlier this information can be made available in the design process, the greater the impact it can have – if taken into account – on the planning outcome. The main question here is: how can digital content be incorporated into existing established ways of working in a form that is useful and does not interrupt the working process? The intention here is not to replace established ways of working, such as models and hand-drawn sketches, with computerised methods, but instead to find ways of combining the two worlds in a single system.

## 2. Approach

Starting from this position and the requirements of Design Decision Support in the early creative phases, the "CDP // Collaborative Design Platform" research project examines ways of seamlessly integrating interactive simulations and analyses in the creative architectural design process (Schubert, 2014). The approach taken here is to explore how established design tools, such as physical working models and hand-drawn sketches, can function as tangible interfaces within a digital environment. Over the past few years, several approaches to integrated human-computer interfaces have been researched and implemented as prototypes for solving urban design problems at a scale of 1:500 e.g. in (Schubert et al, 2011; 2012; 2014). The seamless integration of established design tools into a digital system makes it possible for designers or planners to continue working with familiar design tools while simultaneously making available interactive simulations and analyses within the physical model. Designers can then see the implications and effects of design decisions in the early creative planning phases, and respond to them accordingly. A key aspect of this is the use of information visualisa-

tion as a direct means of feedback directly within the actual physical model. Such information needs to be presented in a way that is simple to understand and that does not interrupt or detract from the process of visual thinking but enriches it with underlying objective criteria. This must be considered at both a technological as well as a conceptual level. The fact that not just the physical model but also the resulting digital computation model as well as the results of the calculation are all three-dimensional leads to the question of how best to display 3D simulation results in the physical model?

This paper describes an interactive mixed-augmented reality (AR) application that was developed and implemented – based on the prior system design – to improve the integrity of the digital authenticity in the physical model. By means of a tablet or see-through glasses, the new extended setup allows users to view interactive simulation results such as shadows cast over the course of the year, wind currents or even statutory regulations (inter-building distances and areas or construction volumes) in three-dimensions that augment the physical working model in real time.

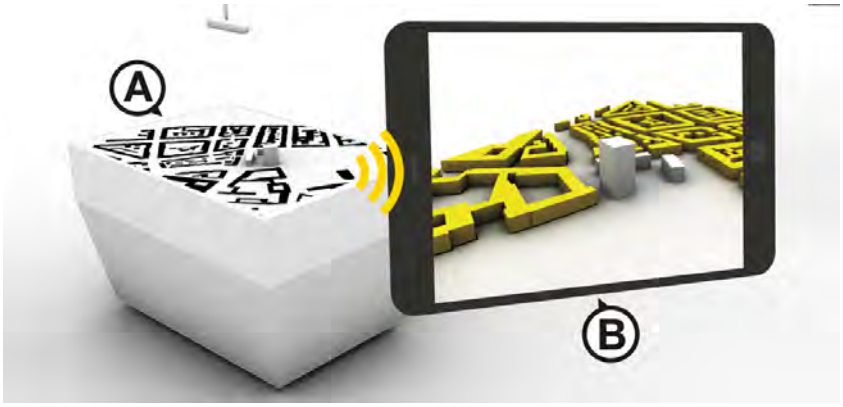



*Figure 1. System setup showing both parts of the system: the design platform and the AR application. A network protocol links the physical model placed on a display of the design environment (A) with the display on the AR-device (see-through glasses or tablet) (B) in real time. The physical model placed on the table in combination with a digital map is augmented with a 3D visualisation of the surrounding architecture and interactive analyses and simulations.*

The seamless coupling of physical model and simulation means that this method is not limited to the static representation of results. Changes in the working model (shape, position, orientation...) have a direct impact on the computational base and therefore also on the simulations and their display in the AR application: design and analysis merge into a single creative cycle.

## 2.1. USER SCENARIO

The chosen user scenario is an urban design planning project for an urban quarter extending over several hectares. The project manager, planning team and members of the planning authority meet up to discuss possible approaches. Instead of sitting down facing a beamer projection, they stand around a large multi-touch table. The surface of the table shows a digital plan of the surrounding urban grain. Various Styrofoam blocks have been placed on the site in the map on the table showing a possible urban arrangement for the quarter. The project manager explains the architectural concept and shows how care has been taken to avoid buildings shading each other. To illustrate this, he activates a solar-envelope analysis and the results of the calculations are shown directly as shaded areas on the plan on the table. For an improved impression of the shading, the participants put on transparent glasses. Immediately, the participants see the solar envelope as a 3D projection embedded within the view they are seeing. They can move around and view the scene from different perspectives and see how this will change with the successive phases of the project. One of the participants has an idea and removes a block from the model, trims it to a new shape with a cutter knife, and places it back in the model. The results of the solar-envelope simulation adjust in real time to match the new situation, and the augmented image seen through the glasses changes accordingly. It is immediately apparent to all that the change represents an improvement. The project manager changes the simulation to show wind flow patterns in the new situation. The glasses now overlay the scene with a 3D vector simulation of the wind flow. It's immediately clear where the effects of wind will be felt most. Over the course of the meeting, the participants discuss various aspects and adjust the concept, taking into account the objective feedback provided by the simulations.

## 2.2. RELATED WORK

Various teams have investigated ways of presenting digital information in physical contexts or physical models and various different approaches can be identified. The URP (Underkoffler and Ishii, 1999) is a further project which uses a multi-touch table in combination with marker tracking to present interactive simulations and to control these with models. The presentation on the multi-touch table shows the results only in two dimensions. Three-dimensional information can only be represented in an abstract form. Another approach, this time from the field of geography, is taken by the Sandscape project (Ishii et al, 2004). The concept makes it possible to model landscapes using sand. The resulting surfaces are scanned in three dimensions, providing the basis for calculating relevant information for the planning process.

The resulting information is projected directly onto the model from above. This process permits a degree of interactive feedback with the model, or the model's surface. One problem with this approach is shadows cast by the user or the user's hands. In addition, it is not possible to present information in three-dimensional space. The "Sketchand+" project (Seichter, 2003), for example, employs an AR application to display digital design variants embedded in a physical model of the urban environment. Different variants can be examined using Fiducial marker tracking. The evaluation of the relative advantages or disadvantages is purely subjective. Simulations and analyses are not shown in the context of the project. A similar approach, this time at the scale of a building, is taken by "MxR" (Belcher and Johnson, 2008). Using AR, a physical model of a building is augmented with digital information such as architectural elements as well as simulations. A further approach can also be seen in the "Magic Meeting" project (Regenbrecht et al, 2002). Here the system setup makes it possible to collaboratively view and interact with a mixed-reality environment using a centrally-placed marker. Additional functional markers are used to control the clipping and illumination of the model. With the exception of notes, however, it is not possible to directly change the model, or to make use of analyses and simulations. "ARTHUR" is a further mixed-reality system that makes it possible to display digital models on a table top using a head-mounted display (Penn et al, 2004). This makes it possible for people to collectively see the results of a pedestrian simulation according to certain objective criteria. Compared with a physical model, the ability to interact with such entirely virtual scenarios are considerably more limited.

## 3. System Setup

To implement the extended approach outlined above, the existing system setup is extended to include an AR application. The existing system comprising a large multi-touch table with integrated 3D object recognition forms the technological basis of the implemented design platform (Schubert et al, 2011). The table surface serves as the planning base and incorporates a digitized city map. In combination with 3D object recognition in real time, the system allows the user to design interactively within the digital map by means of physical models and sketches. The reconstruction is achieved by combining two connected systems using a 3D on-top depth camera and the object footprint. Tracking markers are not required. Two algorithms have currently been developed that support the use of both rectangular blocks as well as freeform bodies (Schubert et al, 2013). All design ideas in the form of a physical model placed on the table are reconstructed in three-

dimensions in real time, and serve as the basis for computing decision support simulation and analysis. To meet the various needs of design tasks and design ideas, the software setup cannot be a fixed system but must provide a flexible, individually extensible structure. The software framework therefore employs a plug-in architecture comprising two sub-systems: Firstly, the host application that provides all system-relevant functions, including the semantic GIS data basis, the interaction possibilities and output of the results on the different devices. And secondly, the plug-ins which can be used in different combinations as required, providing a flexible toolkit of different design-supporting tools such as complex and dynamic calculations, analyses and simulations (e.g. wind simulations, shadow projections, process simulation, route analyses, etc.).

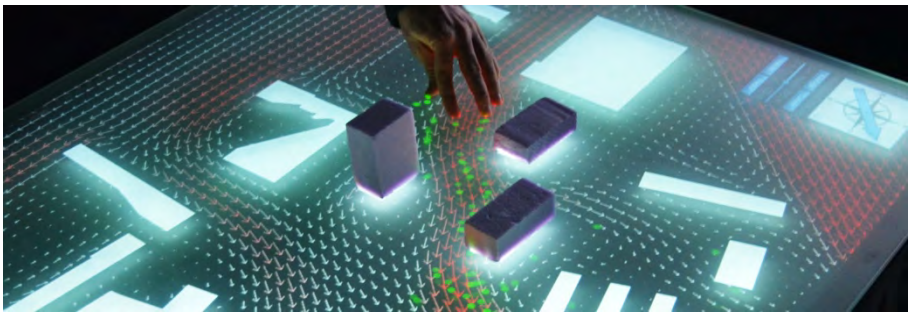


*Figure 2. 2D presentation of simulation results on the table surface – seamlessly connected to the physical working models.*

The system setup makes it possible to display the results of a simulation directly on the surface of the table in the plan presentation. This form of presentation on a planar surface is, however, necessarily only a 2D visualisation of the information. Studies have shown that this pure 2D feedback is, in many cases, not sufficient to convey the complexity of information contained in the simulations. Given that the basis for the computation and the computation itself is based on 3D- data, this artificially constrains the information simulation possibilities. To alleviate this discrepancy, additional methods for visualising 3D information in a physical context were examined and implemented as part of a sub-project, that is presented here. The approach is based on an AR application that allows one to see design decision support information using see-through glasses or a tablet device. The three-dimensional representation of the digitally computed three-dimensional information is presented superimposed over the view of the model with the result that it appears embedded within the physical model. The requirements for realising the concept can be defined as follows:

- Display of the simulation results in real time
- Tracking without markers in response to a dynamically changing scenario
- A simple means of extending the system for use by multiple users
- Flexible use of clients to show different simulations and analyses

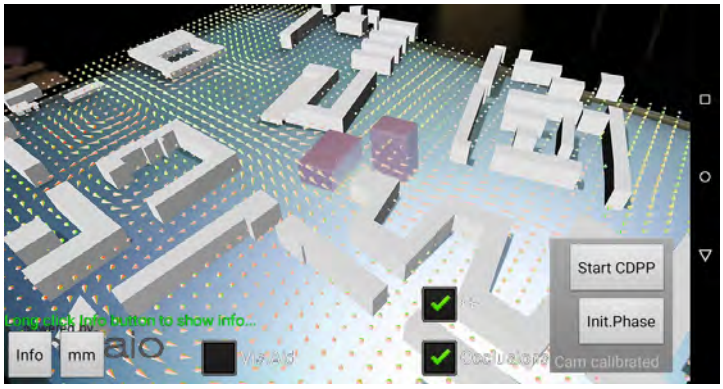



*Figure 3. 3D presentation of simulation results and urban context via augmented visualisation directly in the physical model. Physical model (purple), digital model (grey) and digital simulations (wind) are merged interactively (first prototype).*

## 3.1. IMPLEMENTATION

The prototypical implementation of the software side of the system is based on a server-client architecture. It comprises the design platform consisting of a multi-touch table and info panel that serves simultaneously as the server. To view the results in the physical model via an AR application, a separate application for mobile devices that has been developed in a previous subproject has been improved (Schubert et al, 2015). The metaio SDK was used to create the application (Metaio GmbH, 2015). The priority here was to ensure the display of simulation results in real time and the ability to respond to and display changes in the design scenario. The most important components here are the tracking and the custom-developed TCP/UDP protocol for transferring simulation results to the AR client.

## 3.2. TRACKING

Given the requirement for a flexible, markerless tracking system, we employ a feature tracking approach. This works by tracking prominent edges in the stream of images. The plan drawing shown on the table's surface serves as a good reference for basing the tracking system on. Because we can ascertain the position of the camera from the plan, we can calculate the position and perspective of augmented objects. This makes it possible to track an overall scenario even as the scene changes as a result of changes to the physical

model. The system also affords a degree of tolerance in recognising features, even when they are not all visible.

### 3.3. SIMULATIONS

Using the server-client architecture, the design platform itself functions as the server. The individual AR applications for presenting the different kinds of simulation results are linked to the system as clients via a network connection. The basis of this is a specially developed TCP/UDP network protocol for the transmission of data between both partners (Goldschwendt et al, 2014). The AR application receives simulation results as well as digitized object geometries in real time from the design platform. Both the design platform as well as the mobile application employ the TCP/UDP protocol to communicate with each other, facilitating real-time communication between server and client. This also makes it possible to extend the system to accommodate multi-user scenarios without having to change the internal system – new clients simply connect to the server application. The different presentation perspectives and contents are computed individually and displayed by the respective client. This setup also makes it possible to communicate simulations centrally. The results are then streamed to the clients, which significantly reduces the computational demand on the client application. To establish and maintain communication between two system peers, several so-called control messages are defined within the protocol. After the successful connection of two peers, the collaboration starts.

To communicate the results of the calculation taking into account the flexible connection of different simulations, a corresponding concept was developed for the TCP/UDP protocol. The data communication between table and app works as follows: the physical and virtual buildings on the table setup are processed and represented in a binary format to send them as a TCP/UDP message to the application. These messages are in JSON format with corresponding predefined elements and properties which affords greater flexibility as JSON messages provide a convenient way to send arbitrary data via the protocol. This makes it possible to send new data without having to adapt the protocol. It is only necessary to parse the new data on the sender/receiver side. By way of example: the table creates a JSON message for different primitive objects, such as spheres or arrows and then sends the JSON message to the application. The protocol is unaware of the content of the message. The app receives the JSON message and parses it to reveal the content. Finally, the app visualises the received primitive objects.

## 4. Discussion

The previously developed concept in combination with the new implemented prototype of the AR application permits the interactive and direct three-dimensional representation of computed simulations and analyses in physical models. The integrated approach of using physical models along with an AR application on a tablet device or see-through glasses makes it possible to interact with established design tools while concurrently displaying digital models of the surrounding buildings as well as digital supporting information directly in the physical model. The physical and digital realms are closely connected with one another. As such, the designer can incorporate objective information in his or her design explorations in the early design phases. The server-client software architecture also allows the prototypical implementation to be easily extended to cater for multi-user scenarios, so that several participants can work interactively with the model to discuss a design scenario and use the simulations to assess the implications of design decisions. The use of the JSON format for data communication also makes it possible to flexibly extend the system to accommodate future design-supporting plug-ins with simultaneous display on the table and in the AR view. The use of feature-based tracking using the plan drawing on the table enables markerless tracking. Tracking problems only occur if the display quality is not good (for example low contrast or poor or skewed visibility of the plan on the table), and are most noticeable when changing the direction of view. In addition, the need for an AR device is not ideal. Holding a tablet for example, limits one's ability to simultaneously interact freely with the physical model. The use of see-through glasses is better in this respects, as it leaves one's hands free, but the ability to interact with the GUI of the AR-view is more limited than when using a tablet.

## 5. Summary and outlook

The expanded setup and prototype described in this paper enables simulations to be presented no longer purely in 2D but also to portray complex 3D-content, which expands the usefulness of analyses and simulations considerably. The system helps the user to see and understand complex, 3D-relationships and their implications. This is especially relevant in the context of ever more complex construction tasks, and the nature of architectural projects as dynamic processes rather than the production of final products. Future work will concentrate in particular on how to present separate content to specific users, for example different degrees of information for specialist planners or laypersons. In addition, different ways of interacting with the GUI using see-through glasses will be examined and implemented.

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S. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, S. Roudavski (eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2016*, 343–352. © 2016, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

# MAKING SENSE OF AGENT-BASED SIMULATION

*Developing design strategy for pedestrian-centric urban space*

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**Abstract.** This study investigates the relationships of field observation, multi-agent simulation and space-syntax theory in spatial configuration for developing design strategy for a case study, a tourist hub area in Musi Riverside, Palembang. Having such potential advantage and to tackle existing social and urban issues, our study developed a design approach based on multi-agent simulation enhanced by space syntax theory. The goal of this study is a deep understanding of multi agent simulation through mechanism of validation using field observation and by taking into account the existing urban features. The purpose is to develop design strategy of pedestrian-centric urban space to be functioned as a tourist hub based on computational modelling. Following the paths result of pedestrian flow by multi-agents simulation, we elaborated the analysis of facility programming by means of Space Syntax theory. It shows the ranking of facility programs based on their relative connectivity and integration. By merging this result, it assembles programs and their circulation spaces by means of computational simulation. Experimenting in both fields show a novel approach for pedestrian-centric design in urban scale, particularly since behavioural models rarely used in early stage of design process. It shows that multi-agent simulation should be coupled with field observation.

**Keywords.** Multi-agents simulation; network analysis; Space Syntax theory; design strategy; urban space.

## 1. Introduction

Multi-agent based simulation has been developed in years for pedestrian flows modelling in related fields such as urban planning, transportation planning, evacuation studies and social studies. Generally, in this simulation,

the model of agents are equipped with personal and interpersonal traits for social interaction and augmented with basic locomotive parameters such as seek, collision avoidance, wander (Reynolds, 1999) and other goal-directed abilities (Chen and Chiu, 2006). The core idea of agent-based simulation is to describe particular phenomena that generated from the actions and interactions of multi agents system (Klügl and Bazzan, 2012).

Implementation of agents simulation in theory open an opportunity for designers and architects both in building scale and in city scale for various purposes in the process of design. For particular urban design process, ability to test the people behaviour in an urban area given some existing urban features such as parking space, urban park, sitting area, transportation hub is important for solving problem that may not seem obvious in early phase of design.

The case study is part of the design process of urban tourist hub. The site is located at the waterfront area of Musi Riverside, Palembang, capital city of South Sumatra and one of the largest rivers in Sumatra Island, Indonesia. In current condition, the designated area is a vacant urban park that being utilized as parking lot, street vendors and an interface for the local dock for the riverboat. The local government plan to rejuvenate this area, utilizing the potential of domestic destination, encourage local economy, and build city-park for people attraction.

## 2. Characteristic of the case study

The main characteristic of the site is that it is located under the iconic Ampera Bridge, one of the largest river bridges in Indonesia. It has been historically known for its waterfront area for leisure in addition to be one of the local ports for water-based transportation. The area of the site is approximately 3.37 ha and bordered by Musi River on the South East, heritage district up to the North side and it is actually in the middle of commercial district of Palembang city, the capital city of South Sumatera. Having an open space in such strategic location made this spot is favourable for domestic tourist destination and transportation hub to other places by boat.

This existing condition is growing uncontrolled without proper planning and design and yet, the site already becomes part of urban nodes that support public needs and activities. The observation of the site is depicted in Figure 1 and Figure 2.



*Figure 1. (Left) Existing condition and surrounding urban features; (Right) existing condition inside the case study*



*Figure 2. (Left) Delineation of case study; (Right) Section of the case study*

As indicated in Figure 1 and Figure 2 the case study area is a waterfront site that has several point of pedestrian connections such as:

- Shelter dock/ small passenger terminal; the point of departure and arrival from riverboat.
- Minibus terminal; terminal for city minibus.
- Car parking area; parking facility for occasional events.

Field observation on site resulted in patterns of pedestrian movements as depicted in Figure 3 below:




*Figure 3. Pedestrian movement patterns based-on field observation*

### 2.1. THE NEED FOR AGENT-BASED MODELLING FOR PEDESTRIAN

In the theory of urban design, the urban features often experienced through several elements such as landmark, district, nodes, edges and paths (Lynch, 1960). However, the sprawling of urban informalities, *spatio*-temporal activities and other issues that usually occurred in the city of the developing countries, lead to the consideration that focus on the pedestrian spatial flow movements. The top-down approach is sometimes unable to predict potential use of the site by pedestrian and the pattern of pedestrians' spatial movements. Particularly if the design of this urban park needs to encourage people to use its features, implement walking friendly urban environment, there is need of new model to help understanding existing pedestrian behaviours, analysing the patterns and determine the programs that adapt to the patterns. The agent-based modelling system to be developed is to provide prediction of pedestrian movements and distribution on existing condition and the impact of the new proposed design on pedestrian behaviour. Given the significant aspect of prediction model based on pedestrian movements, the need for its study for urban design is growing in recent years (Chen, 2012).

### 2.2. SCOPE OF STUDY AND STAGES OF PLANNING AND DESIGN

The scope of the study comes into two stages that incorporated within the planning and design process. In the first stage, the agent-based modelling was developed to describe pedestrian movements on the existing site considering existing urban features and conditions. This model is to be validated using field observation data where pedestrian movements and behaviours were recorded. Through comparison between field observation and pedestrian modelling, we identify and determine the parameters and attributes for next simulation involving new program facilities on site.

Furthermore, based on the pattern of pedestrian movements, we began analysing the site and facilities that will be included in the site. Upon receiving pedestrian patterns and facility programs, in the second stage we developed a method that incorporated these patterns with Space-Syntax model to analyse the accessibility and visibility of the program design. The Space Syntax based model identifies and determines accessibility and visibility based on the spatial network and constraints.

## 3. Overview of recent development

Agent-based simulations is not only represent existing configurations, but also can be used to analyse possible interventions and amendment. Movement patterns of pedestrians are a topic in many related fields like transpor-

tation planning, computer graphics and sociology (Aschwanden, 2012). Some previous study have experimented and researched about pedestrian behaviour modelling in architectural design, urban planning and with different simulation tools. Kitazawa on his research on using Genetic Algorithm (GA) to recreate retail movement of shoppers in a large shopping centre to examine the applicability of the basic assumptions in existing models of spatial behaviour; the route with the shortest distance maximizes the utility of each pedestrian's travel (Batty et al, 2004). Sharma and Tabak researched on using 3D Network and SMART Move to analyse of flow using a detailed agent based simulation that also incorporates dynamic route-choice modelling, agent behaviours and interaction, and stochastic variations (Sharma and Tabak, 2008). Aschwanden (2012) generated 3D environment and GIS to analyse urban planning configurations and to give designers and decision makers a tool to measure the amount of people walking and therefore define the health of a society, finding places of social interaction and improving social coherence in neighbourhoods.

## 4. Methodology

This study employs two methods as a design strategy for pedestrian-centric urban space. The first method is multi-agent system based on the evaluation and validation by field observation; the second method is facilities and spatial planning using Space Syntax-based modelling. The result of visibility and accessibility index by the later method then confronted by multi-agent system. The result is obtained by optimising and tweaking solution provided by two methods. By this stage, the designer takes the role to synthesize an optimum solution for further design processes.

### 4.1. MECHANISM OF SIMULATION

The following is the mechanism of simulation using multi-agent system. Based on observation, there are three types of pedestrian originators: water based transportation point, arrival park point-public transport shelter point, and traffic point. The agent settings are summarized in the Table 1 below.

There are four types of movement controls used in this simulation that are goal seeking, obstacle avoidance, separation, cohesion, and alignment. Those controls worked on the two types of agents: waypoint agents and way-finding agents.

Table 1. Simulation Set-Up

| | |
|---|---|
| Agent (normal setting) | |
| Lifespan (L) | Number of time steps<br>Setting agent step around 150-200 steps, depends on the condition of the site. This observation in Palembang, tropical season without shading, normally walking ability around 150-200 steps. |
| Mass (M) | Affects how strongly the agents reacts to forces.<br>The higher mass setting number, the stronger forces will affect the trajectory of pedestrian, normally setting mass index = 1 |
| Max Speed (S) | The agent move incrementally by this speed towards targets that it seeks.<br>Normally, max speed setting index = 1 |
| Max Force (F) | Steering ability can be controlled by limiting the magnitude of the steering force.<br>Normally, max force setting index = 1 |
| History Length (N) | The number of past position to remember for each agent.<br>Normally, history length = 50 |
| Engine simulation | |
| System | Represent a self-contained system of agents and emitters |
| Engine | Engines that runs the simulation |
| Agent sources | |
| Agents transfer from land – water transportation, and vice versa is assumed around 40 agents | |
| Agents from arrival points is assumed 40 agents | |
| Agents from congestion points is assumed 40 agents | |
| Boundary Constraint | |
| The boundary observation site | |
| Goal points | |
| Environmental and physical attractors | Musi Promenade, Musi riverside, activities riverside, 16 Ilir market, SMB Museum, Monpera, BKB |

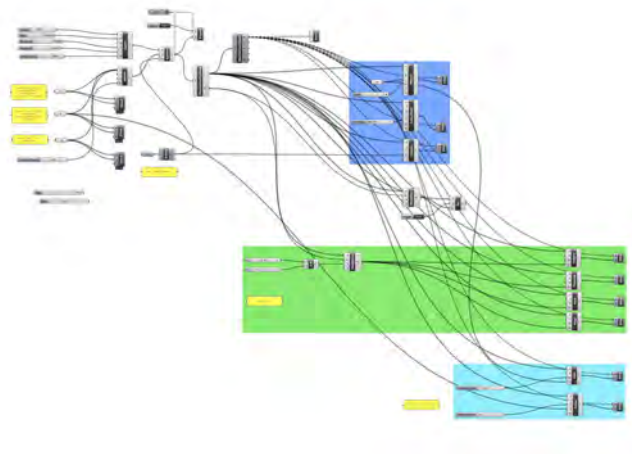


*Figure 4. Movement Controls of Agents*

## 4.2. SPATIAL PLANNING BASED ON PEDESTRIAN PATTERNS

Following the paths result of pedestrian flow by multi-agents simulation, we elaborated the analysis of facility programming by means of Space Syntax

theory to generate alternative space configuration simulation that will represent accessibility space optimization for pedestrian. The model based on the theory that calculates relationships of spatial requirements represented by programs through analysing their network using four analysis parameters: integration (Hillier and Hanson, 1984), entropy, control (Hillier et al, 1987), and choice (Freeman, 1977). These four parameters worked by analysing all proposed facility programs of the case study that is comprised of three major facilities: tourism facility, hub facility and public leisure facility. Since the spatial planning is site-dependent, the Space-Syntax modelling is exercised within site's boundary. Table 2 below sum-up the Space Syntax model while Figure 5 shows the mechanism (Nourian et al, 2013) and result into spatial map.

Table 2 Space syntax set-up

| Facility Program | |
|---|---|
| Node Link Graph | Representation and connecting of nodes and links |
| P (Points) | Representation of nodes (points) space |
| L (Link) | Representations of links (lines) space |
| T (Labels) | Representations names of space |
| A (Areas) | Areas of spaces, an average area relative to the size of connectivity diagram will be assumed |
| S (Total Area) | Total area of the whole configuration, area values will be normalized to satisfy this amount exactly |
| Analysis simulation | |
| Entropy analysis | Identify the higher the entropy value, the more difficult it is to reach other space and vice versa |
| Integration analysis | Identify the higher the integration value, the more likely for a space to be communal and the lower the integration value, the more private that space |
| Control analysis | Identify how strongly a vertex in graph (a space in a configuration) is link to others points in a superior manner |
| Choice analysis | Identify how often a node (space) happens to be on a shortest path between other space; it measures 'the degree of choice each space represents (how likely it is to be passed through) on all shortest routes from all spaces to all other spaces in the system |

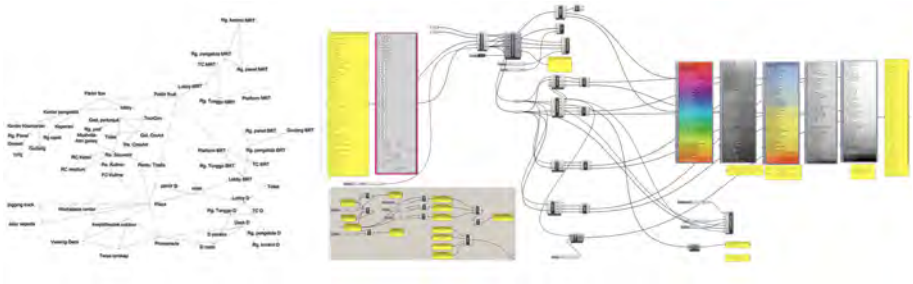


*Figure 5. (Left) Network configuration graph overlaid proposed by user on site, (Right) Space Syntax program for spatial planning*

## 5. Result and Discussion

### 5.1. PEDESTRIAN PATTERN

The pedestrian patterns on the existing site showed density and accessibility of the movements considering site boundaries and features. We used three parameters: urban features, type of pedestrians: wayfinding pedestrian and waypoint pedestrian (Kontovourkis, 2011), and movement controls: agent to agent and agent to environment. After series of simulations, the pedestrian patterns of existing simulation are depicted in Figure 6 below.




*Figure 6. Simulation result*

Based on results, there are three types of density and accessibility of pedestrian movements in the area (Figure 7). The last simulation results (Scene 10-11) were the closest result similar to the pattern by field observation. We further used this result as the basis for design guideline for node activities patterns (Alexander et al, 1977).

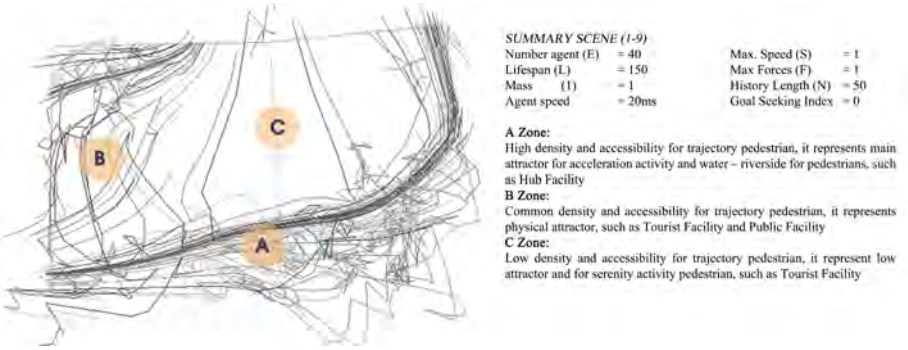



*Figure 7. Overlay patterns by simulations*

The result of network analysis is navigation graph showing the ranking of facility programs based on their relative connectivity and integration (Figure

8). By merging this result to the paths and boundary area, we are able to assemble programs and their circulation spaces by means of computational simulation.



*Figure 8. Result of space syntax modelling, (left) interactive vertices for bubble drawing of a graph; (right) justified graph depth analysis*

This below describes tourist facility, hub facility and public city in the value index of maximum and minimum of entropy analysis, integration analysis, control analysis, and choice analysis based on the Space Syntax modelling (Figure 9).




*Figure 9. The result of network navigation by space syntax analysis*

## 6. Discussion

Experimenting in both multi-agents simulation and network analysis shows a novel approach for pedestrian-centric design in urban scale, particularly since behavioural models rarely used in early stage of design process. However, our study shows that multi-agent simulation should be coupled with field observation and runs iteratively through series of parameter traits in order to achieve appropriate level of validity. The co-existence of multi-agent system and Space-Syntax model in early stage of spatial planning offers strategic approach for designer considering the possibility to generate pedestrian-centric spatial mapping along the process. The multi-agent system can

serve as a validator for Space-Syntax model in finding optimum spatial configuration in urban area. Accordingly, it simplifies the mechanism to evaluate the impact of design proposal into social context (i.e. pedestrian movements) by generating immediate feedback.

The limitation of this model for design strategy in urban scale remain on the limited preference traits of interactions both to other agent(s) and/or to the environment in addition to the maximum number agents can be simulated in real time.

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# PHYSICAL AND NUMERICAL SIMULATION AS A GENERATIVE DESIGN TOOL

*Formation of a high-rise typology using wind tunnel testing and CFD simulation*

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**Abstract.** Environmentally sound and high-performance buildings are contributing towards a sustainable future. With increased density of contemporary urban space and the urgent desire to promote building performance, a better understanding of wind behaviour will positively influence future design explorations. In the traditional sequential architectural practice, there is a gap between design and performance simulation. This paper presents an experimental and systematic study of the performance-oriented design tools, strategies and workflows utilized in the concept prototyping of a high-rise building. It describes a new approach to incorporate wind tunnel testing, computational fluid dynamics simulation as well as parametric software, sensors and open-source electronics platform into an accessible, interactive and low-cost form generation kit, rapidly evaluating the performance of potential design options in the early design stage. As indicated in this research, environmental simulation can be a decision-making tool, integrating the concept of continuity into the design process.

**Keywords.** Environmental performance; building aerodynamics; wind tunnel testing; computational fluid dynamics.

## 1. Introduction

High-density urban development has generated increasingly serious environmental problems, challenging the notion of continuity and sustainability. Air movement in relation to the built environment is particularly taken as crucial factors for pedestrian comfort, building ventilation, air quality and energy use (Erell et al, 2010). Wind shapes natural forms throughout thou-

sands of years, dunes of desert in the Yadan landform and smooth granite rocks in Capo Testa are all masterpieces of wind. Although high-rise buildings are more susceptible to winds, issues pertaining to environmental performance are generally conducted during the later design phase, after the overall geometry has been well articulated, which is limited to after-the-fact validation rather than design exploration, leading directly or indirectly to solutions with mediocre performance and increased energy demands (Kaijima and Bouffanais, 2013; Menicovich et al, 2012; Gane and Haymaker, 2010). The current inability to effectively integrate dynamic performance expectations into building design strategies is partly due to the deficiency of applicable simulation tools, known as "performance sketch tools", which can conduct rapid, qualitative and rough quantitative simulation of concept design alternatives (Passe and Battaglia, 2014; Naboni, 2013). As building morphology largely determines the resulting wind response, assessments to wind effects in early design stage will assist architects in making responsible and reality-based instead of intuitive and experiential design decisions.

## 2. Literature review

Performance-driven design has generated new modes of practice. There are commonly two different ways to assess wind environment: the numerical one, also known as computational fluid dynamics (CFD) methods; and the physical one, i.e. wind tunnel testing. Among them, CFD is limited in complexity, time-consuming and depends on high computing power. Wind tunnel testing is expensive, uses sophisticated instruments, and relies on expert assistance (McAlpine, 2004; Salim and Moya, 2012). As a result, traditional methods are laborious to be incorporated meaningfully into the early design stage when iterative design options are generated, requiring rapid evaluation. In response to above dilemma, a third possibility, namely custom-made wind tunnel, is under research. Ramkissoon and Manohar (2014) discussed general considerations and principles for the design, construction and calibration of an open-circuit, low-speed wind tunnel under specific cost, time and space constraints. Meanwhile, some pioneering custom-made wind tunnel projects are emerging in Rensselaer Polytechnic Institute, RMIT University and Cardiff University in the last several years, verifying their advantages of simple visualization, quick feedback and effective data collection (Menicovich et al, 2012; Salim and Moya, 2012; Alexander et al, 1997).

## 3. Tools development

The investigation tools consist of physical and numerical ones which work together to assess wind effects, optimize the overall design process and facilitate the development of high-performance, energy-efficient buildings.

### 3.1. CUSTOM-MADE WIND TUNNEL

Based on solid theory and demonstrated experience, we fabricated two different-scale wind tunnels as is shown in the schematic (Figure 1). The proposed mini wind tunnel is an open-circuit section one constructed with laser-cut plywood and Plexiglas. It consists of five parts: inlet section (including a flow straightener and two anti-turbulence screens at the front), contraction cone, test section (including a rotary disk and an access hatch), diffuser and fan section. The mini wind tunnel is 3 meters long with the test section measures 0.6m in width and 0.45m in height. Air flow is controlled by an axial suction fan, reaching a maximum speed of 5m/s.

The mini wind tunnel is low-cost, easily fabricated though limited in its ability to reproduce large-scale urban environment and provide detailed performance data. To realize complementary advantages, a hermetically sealed, adjustable-speed laboratory wind tunnel is constructed later, featuring air flow visualization with a helium bubble generator and surface pressure measurements using sensitive pressure sensors. The test section measures 1.8 wide by 1.2m high, which has a stable, uniform flow condition and reaches a maximum speed of 25m/s.

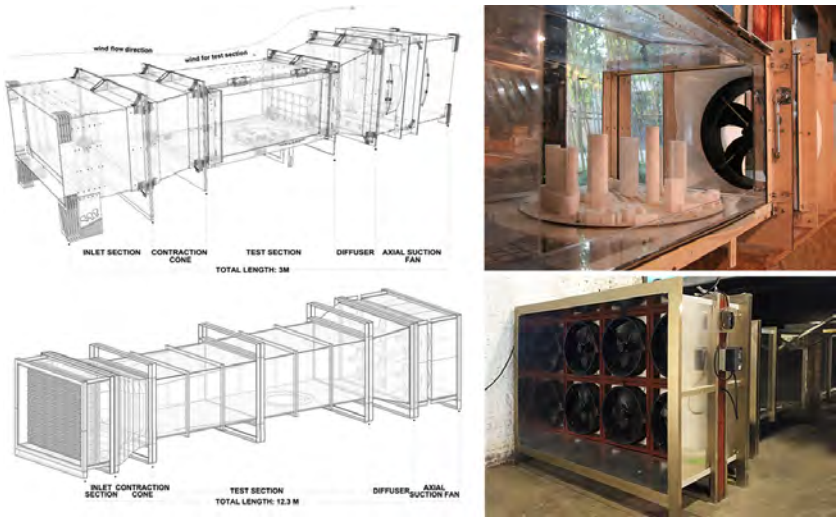



*Figure 1. Composition diagram of the custom-made wind tunnel and the completed projects*

### 3.2. COMPUTATIONAL FLUID DYNAMICS SIMUALTION

CFD simulations can be applied to assess external wind flows, internal HVAC or natural ventilation design. In this process, CAD package was used to create geometries, which were then imported into STAR-CCM+ to do simulations. The meshing and automation capabilities of STAR-CCM+ enable high working efficiency. Vector and scalar diagrams generated can demonstrate the influence of buildings on local microclimate.

## 4. Methodology and research process

Performance-driven design is profoundly reshaping the overall workflow and is reinventing the design orientation, pushing the boundaries of the design space. In this interactive and iterative workflow (Figure 2), physical and numerical simulations are used to complement and validate the results from each other. Site analysis and initial studies contribute to sensible decision making which supports the prototype generation with parametric tools. The initial prototypes are tested, filtered and optimized under specific criteria. Collaboration and calibration between the generative and analytical tools allow for the interaction of formal and environmental design considerations.

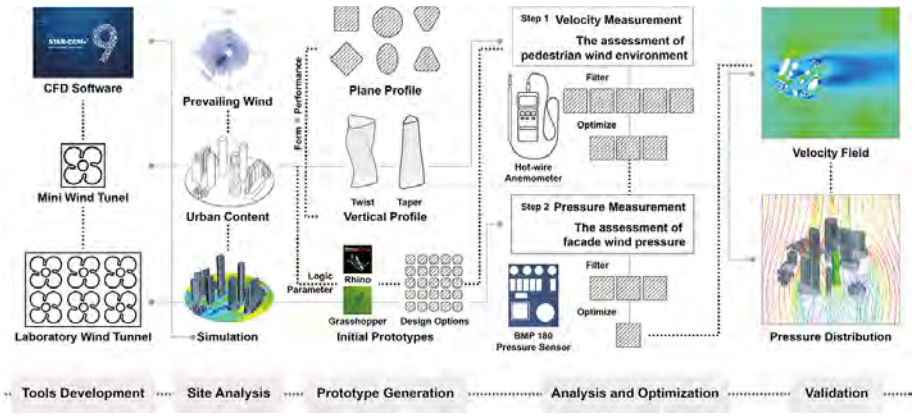



*Figure 2. Overall workflow diagram*

### 4.1. SITE ANALYSIS

The selected site is in the central business district, one of the excessively windy areas in Hefei, Anhui province, China. As a fundamental step, environmental analysis, e.g. wind speed and direction, were drawn to provide a basic understanding of this site condition (Figure 3). The annual wind direction is fairly constant, with the southeast wind prevailing in summer and the east wind prevailing in winter. Average temperature and humidity in both

summer and winter far exceed our expectations of comfort. Based on local climate condition, the sustainable design strategy was to create a comfortable urban microclimate, ameliorating the negative impact of wind on pedestrians in winter and balancing surface wind pressure distributions in summer.

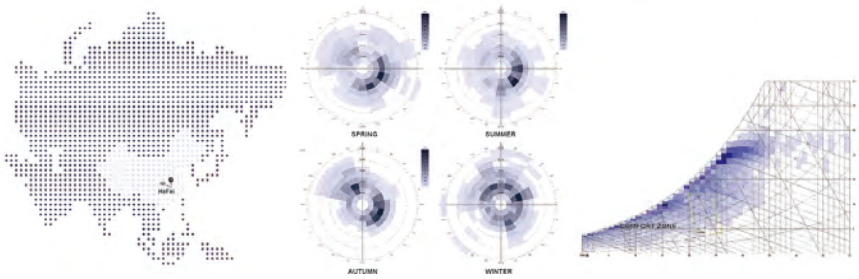



*Figure 3. Site context and environmental analysis from Ecotect Weather Tool*

## 4.2. INITIAL STUDIES

As airflow patterns are considerably influenced by building's geometry, architects are propelled to conduct a series of numerical simulations to explore how the geometrically-driven morphological variants of building form impacts the resulting wind-induced aerodynamic effects.

Blocks with various cross-sections were analysed to decipher which can cause reduced turbulence flows. Basic studies indicated that wind velocity fluctuation decreases with increasing number of edges. Meanwhile, geometric manipulations along the height, e.g. tapering and twisting, were assessed to test the resulting aerodynamic performance, proved to be useful to assist wind deflection and maintain the pedestrian comfort.

## 4.3. PROTOTYPE GENERATION

Rapid prototyping of a parametrically defined geometry was conducted based on the foregoing simulation. Grasshopper, which permits the modification and optimization of models according to the simulation results, becomes the preferred medium for the early iterative design exploration.

Started with a 40-story ellipse tower, the preconditioning of the 3D model included translation, scaling and rotation transformation. Control points of the original ellipse could amplify along the Y-axis or move along the X-axis, enabling the construction of a new, elongated or squashed NURBS curve. The curve was then scaled to maintain the equal area before and after transformation. The newly generated plane curve gradually twisted or tapered following the specific control profile along the height, lofting to a series of high-rise typologies (Figure 4).

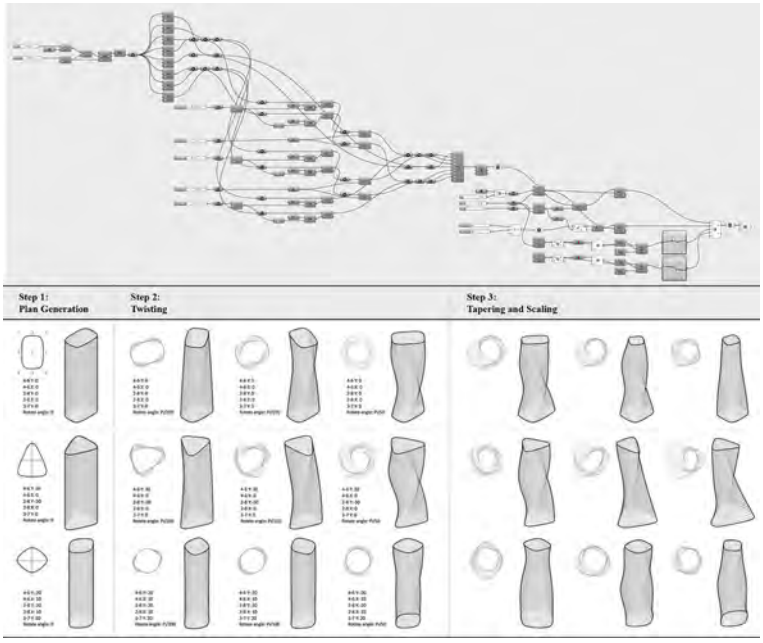



*Figure 4. Generative program in Grasshopper and schematic diagram of possible solutions*

## 4.4. ANALYSIS AND OPTIMIZATION

A multi-objective screening method of design options was employed for the optimization of pedestrian comfort and surface wind pressure distributions.

### *4.4.1. Velocity measurement using mini wind tunnel*

Mini wind tunnel was used to test pedestrian level microclimate around the target high-rise building. As evidenced by a large amount of in-site measurements and relative standard, the threshold value of acceptable wind velocity for human activity in an outdoor environment was concluded (Table 1). Mini wind tunnel simulation was conducted for a winter month using a 1:1200 scale model. About 50 removable measuring points were set within a 150-meter radius of the target building where a hot-wire anemometer can record a database of wind velocities.

Table 1. Comfort criteria in different seasons.

| Season | Acceptable 1.5m-wave-height wind speed (m/s) |
|---|---|
| Summer | 1 m/s < v < 5 m/s |
| Spring/ Autumn | 0.6 m/s < v < 5 m/s |
| Winter | v < 3 m/s |

Wind speed is used as the criterion for evaluating the wind-induced influence on pedestrian comfort. The design option with a higher ratio of outdoor comfortable wind zone, i.e. owns more areas which offers people comfortable feeling, was identified better. Simulations were performed for various high-rise typologies following the steps below.

- Change the values of margin control points along two coordinates to generate different cross-section blocks. Select typical ones for 3D printing.
- First-round testing. Compare the simulation results to draw a general direction of building typology. Do some modulations for second-round simulation.
- Fix the margin control points. Move the central control points to generate more alternatives for further simulations.
- Iterations were terminated when the simulation results showed little improvements. Fix the plan shape for further manipulation.

For each typology, the wind velocity data were transferred into Grasshopper to allow an easy-to-understand graphical visualization. Detailed aerodynamic information can be obtained through CFD simulations to calculate the ratio of comfortable zones. The iterations indicated that chamfered trapezoid shape turned out to perform better.

### *4.4.2. Pressure measurement using laboratory wind tunnel*

In order to obtain an optimal perception of the aerodynamic phenomenon, including wind deflections and turbulence areas, a helium bubble generator was used in the laboratory wind tunnel to intuitively visualize airflow patterns in an urban context. Those patterns were recorded with a digital camera at 10 frames per second, showing the traces of airflow (Figure 5).



*Figure 5. The experimental environment in laboratory wind tunnel*

Wind tunnel testing tends to be effective and trustworthy merely as the dynamic similarity and geometric similarity principles along with the roughness elements meet the requirements. The simulation was conducted in 1/400 scale for summer time with an average wind speed of 3.2 m/s. Pressure sensors were placed on both windward and leeward facades at intervals to measure wind pressures. Firefly, a Grasshopper plug-in for Rhino, can read data from sensors connected to an Arduino board, and represent the data in Grasshopper. Sensors were hooked up to the digital I/O port of the Arduino board which was then connected to the computer.

To explore potential optimal solutions, typologies with variable rotating angles derived from previous experiments were tested. The simulation results indicated that the 140° twist from base to top performed relatively better which can reduce the wind load with a percentage of 15%. For the last step, profile variations along the height controlled by a Bezier curve was used to taper the rotating geometry. Those typologies were tested again to pick up the most effective one of optimal wind load distribution. The optimization process (Figure 6) enabled us to look into the prospect of aerodynamic high-rise typology generation and optimization from a new perspective.

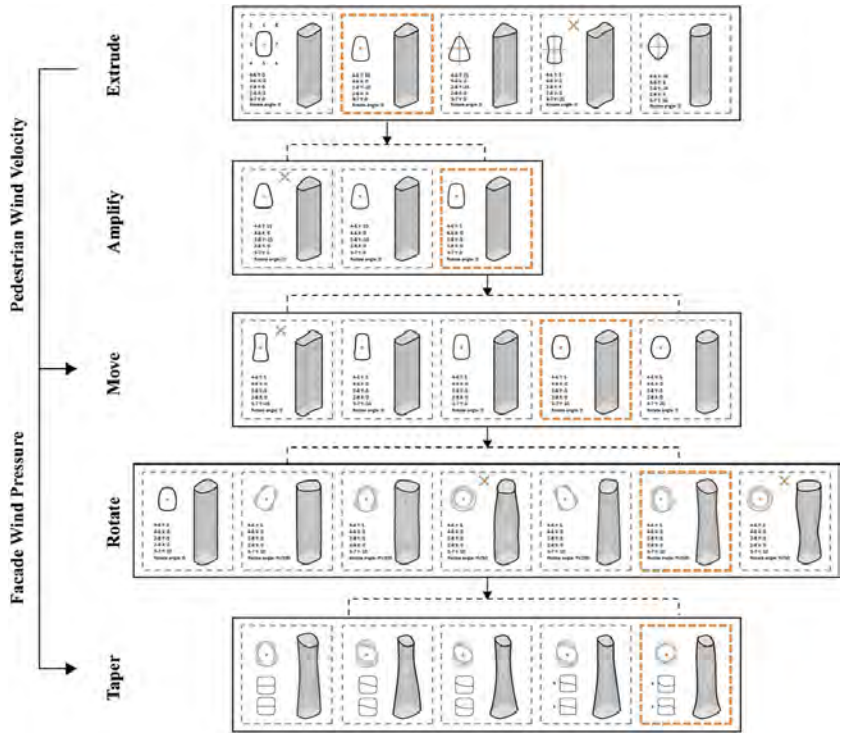



*Figure 6. The process of design iteration and optimization*

### 4.5. COMPUTATIONAL VALIDATION

As for validation, the final typology was simulated in CFD software to see its influence on turbulence areas, wind pressure and velocity (Figure 7). The image shows velocity streamlines from a prevailing wind interacting with the local surrounding buildings with the subject building coloured by surface pressure. The aerodynamic form enables wind to flow smoothly around the high-rise building, minimizing wind loads on the structure. The spiralling form can generate pressure differences that greatly assist the natural airflow.

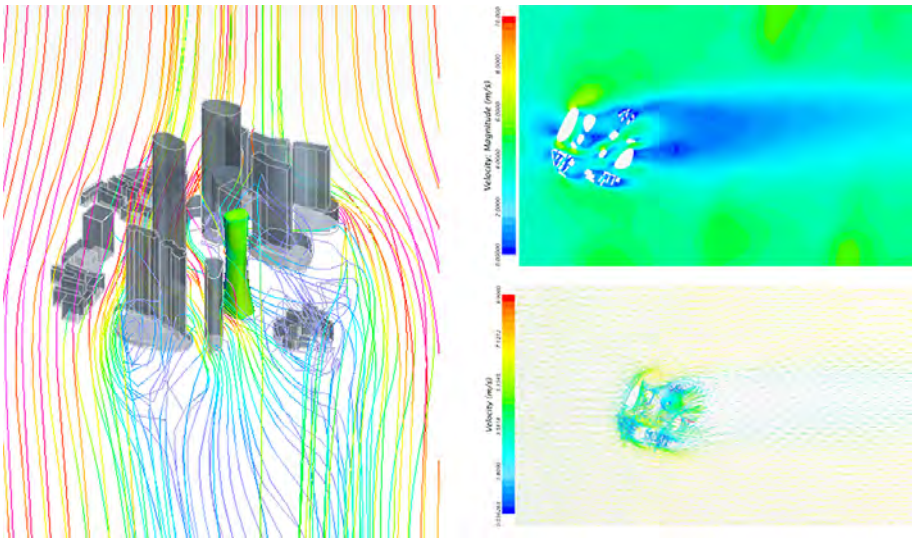


*Figure 7. Flow streamlines in the urban environment and the pressure distribution of the high-rise facade (left).Velocity scalar field and vector field diagram (right).*

## 5. Conclusion

This paper elaborates an interactive approach that integrates wind tunnel testing, CFD simulation and digital software for the formation of a high-rise typology. We anticipate that the methods presented here would be a highly efficient tool and an essential aid for architects to do reliable concept prototyping and explore novel data-driven design options.

In an era of cutting-edge digital technology, the future lies in reassessing the discipline as a dynamic system of complex relations. From the environmental simulation to the building formation, the building morphology is no longer subjective definitions from designers, but objective outcomes of environmental performance data (Yuan et al, 2015). Thus, building morphology

serves as a modifier to improve the urban environment in turn, facilitating ecological and liveable civic environments.

Though lacking accuracy, advantages of the miniature sensors and processors in terms of cost, accessibility and application are bound to prompt more possibilities of digital design in the near future. Meanwhile, pure aerodynamic optimization may be at the cost of increased construction difficulties or reduced usable space. But as long as such bold moves beyond the "comfort zone" could make things easier, we will march towards the unknown, full of hope.

## Acknowledgements

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# DEVELOPING A WORKFLOW FOR DAYLIGHT SIMULATION

*Daylight requirements simulation in early design stages to address the Green Star ratings within local regulations.*

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**Abstract.** Daylight simulations are occasionally used as active tools in regards to local governing regulations, which are necessary for providing documentation. Simulation tools have been avoided in the past due to their barriers. Daylight simulation tools are used within documentation design stages as 'passive tools', however they do not have a direct impact on the architecture design decisions, as passive tools are used by engineers usually to derive material and glass specifications. Recent developments within an online community have provided designers with access to daylight simulation tools within a design platform accessible data can be modified and represented with local governing codes to provide designers with relevant information. The paper aimed to develop an active daylight simulation tool within a design platform. Data is filtered with the Green Star benchmarks to export visual information as well as a voxel matrix instead of 2D luminance maps. This paper outlines a workflow of the simulation tool used to evaluate daylight performance of a selected building as a case study in real time. The paper also details potential problems and justified suggestions derived from the analysis for the building to reach the requirements within the Green Star Multi Unit Residential

**Keywords.** Data-driven design; computation environmental design; daylight simulation; Green Star.

## 1. Introduction and motivation

Early design stages of building development use energy simulation techniques to analyse a building's performance in accordance to local governing regulations (Elghazi 2014). Daylight simulation is often applied during design process prior to submitting the design concept to the planning authorities, however due to the inconsistency of 3D programs used, the simulation becomes passive and redundant through the development stage. Yet, simulation tools can provide data as evidence to help assist in generating and understanding the consequences of design decisions (Lam et al, 1999), helping the user make informed decisions. Therefore, adjusting the functionality of simulation tools within the workflow can help transform daylight simulations into a data driven project.

Daylight simulations prove, through applying physic rules within a mathematical framework, if a design meets the criteria set by local regulations, however they are not currently used consistently as drivers of data driven design. The Flemish government analysed the results of a questionnaire targeting Flemish architects and revealed "less than 30% of the respondents mentioned simulations…" (Verdonck et al, 2011). Alternatively, another survey on Singaporean design firms supports the use of simulation tools in design (Lam et al, 1999). Simulation outputs enable data driven design to play an impactful role in early design stages. Hence the question persists: Why are daylight simulations not used regularly to achieve local regulations within preliminary design decisions? Government agencies have become more aware with the effects of building construction relating to the surrounding environment. The U.S. Green Building Council and Green Building Council of Australia have acknowledged the need for building design changes and compiled voluntary regulation tools to outline the future of the built environment.

## 2. Research observations and question

Software is available for New South Wales and Australian regulations including 'State Environmental Planning Policy 65 – Design Quality of Residential Apartment Development' (SEPP 65) and 'Leadership in Energy and Environmental Design' (LEED), however Green Star rating requirements have no tools to test designs against its benchmarks. Simulation software has become necessary for proving a proposed design that meets the minimum criteria for emerging compulsory and voluntary regulations. The lack of design support tools for Green Star generates friction within design from achieving the requirements by using simulations and analysis methods. As a result architects may not be encouraged to aim towards the Australian stand-

ard of sustainable design. Daylight simulations currently play impactful roles in design with initiating and performance improvement (Frazer, 2014). Plug-ins within Grasshopper can import EnergyPlus Weather Files (.EPW) to generate environmental information for the preliminary design stage including shadow study diagrams and solar radiation (Roudsari and Pak 2013).

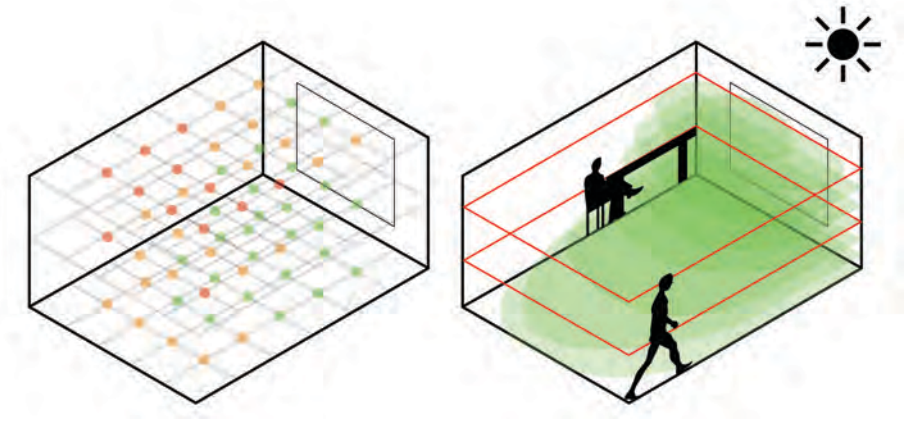


*Figure 1. Concept diagrams of 3D daylight simulations. (1) Voxel based simulation, grid representation (2) Mesh representation of lux value contour lines.*

3D based simulations are not traditionally used within design stages, however they have the ability to identify design effects in which traditional software would not be able to show (Gianni Botsford Architects 2008). Volume based simulation can identify the levels of daylight in a specific point, allowing designers to understand the consequences of façade and roof openings (Frazer 2014) to further improve and understand the design. The project will experiment with volume simulation within a matrix to improve traditional simulation tool which outputs 2D graphical representations such as Ecotect and Autodesk Green Studio, and assisting in providing a greater understanding of a projected model's relationship with its envelope and interior.

The project aims to create a daylight simulation tool to assist with reaching Green Star Multi Unit Residential benchmark requirements. The decision support workflow is intended for the early design stages, when the building's form has been designed and an elementary layout is generated. Most industry standard tools require multiple resources, requiring both the cost of the software and user training (Verdonck et al, 2011). The project will use accessible technology available through open-source software to develop a workflow aimed at assisting in reaching the Green Star daylight requirements.

Daylight requirements from the Green Star Multi Unit Residential require computer simulations to prove an evaluated building meets the minimum requirements (Green Building Council of Australia 2015). The project needs to provide useful information to designers; raw data will confuse rather than inform designers. Data from the daylight simulation will be compared with Green Star daylighting requirements and projected visually into the model giving a detailed analysis.

Based on these observations the paper aims to develop an active daylight simulation tool, acknowledging Green Star requirements by: presenting a workflow intended to help designers address daylight requirements defined by Green Star Multi Unit Residential to identify design concerns in an early design stage within a voxel based daylight simulation.

## 3. Background research

Verdonck (2011) argues that, the majority of architectural practices had negatively portrayed simulations. Justifications for not using simulations dominated the benefits of applying simulations and simulations tools were also resisted due to the complexity and cost for running simulations.

Velux and Ecotect are existing daylight simulation tools that can help assist in the developments of buildings. The tools export the necessary information in 2D images to help impact the developed design stages and provide adequate information for documentation of regulations but do not apply the regulation layer. Data within the software cannot be extracted without the help of a third party application, making it difficult to manipulate the generated data into visual information by designers.

Geco is a plug-in recently designed for Grasshopper and Ecotect linking the 3D modelling tool and energy simulations in a reduced feedback loop, assisting in reducing the missing gap between simulation and modelling (Grabner and Frick 2013). This solution helps achieve a fluid workflow between modelling and simulation, actively reducing the time needed for design improvements. Preliminary daylight simulations are used to assess the initial framework of the design, to the surrounding environment, however they are currently not addressing regulations. Light House by Gianni Botsford Architects (2008) used a daylight simulation to analyse horizontal planes at different elevations to visualise the daylight and solar data in the building. The simulation data influenced a reversed traditional housing layout, granting daylight priority to the living rooms and open private areas on the higher level. The unique layout of the house was a result of positive data driven design through the use of 3D daylight simulations.

Green Star requires either daylight factor or annual dynamic model simulations in the documentation application. Daylight factor models are considered a subpar measuring method, because they do not consider building orientation, sky options and operating schedules (Welle 2009). An annual dydynamic daylight model will be preferred due to the consideration of the sites geographic location and more control over simulation data. This brings the research to the topic of compliance and validation tools currently used. In Australia, the New South Wales regulation 'State Environmental Planning Policy 65 – Design Quality of Residential Apartment Development' (SEPP 65) is compulsory for all new multi residential buildings. Sefaria is a performance design plug-in used for the modelling tools to generate reports identifying the design consequences in comparison to SEPP 65 requirements (Sefaria 2015). Sefaria is used to help achieve an improved workflow to assist the designer in achieving the SEPP 65 requirements. Existing tools in design programs perform early stage assessments of their rating systems including LEED. The paper wants to conclude the background research by briefly discussing topic of feedback loops.

Due to constraints including cost and time in the design stages, outsourcing simulations for building analysis is costly and takes time to develop, urging the need for immediate feedback tools (Morbitzer et al, 2001). Decreasing time consumed in the feedback loop will help assist designers by drastically reducing time constraints. Without the access to a reduced and customised feedback daylight simulation tool, designers attempting Green Star requirements need to use experience and rule of thumb techniques.

## 4. Research methodology

Drawing from existing knowledge in literature in sustainable design, design tools, compliance and validation; the research develops a workflow that aims to increase the accessibility of daylight simulation techniques through Grasshopper plug-ins *Ladybug* (Roudsari and Pak 2013) to import .EPW / EnergyPlus Weather Files into *Honeybee* that runs an energy analysis simulation.




*Figure 2. Projected simulation tool flowchart.*

The data from the simulation will be compared to a benchmark tool developed in this research with requirements from the Green Star daylight requirements to produce a report to check if requirements are fulfilled. In the workflow, the model is first prepared for daylight simulation by the user applying specific material properties to the surfaces of the building. Test points are generated on the surfaces, representing the room's floor and multiplied vertically to generate the one-meter voxels matrix. The data are used to calculate statics when compared to the Green Star daylight requirements. The user is given the choice to improve the simulation by adjusting the model inside Rhinoceros. Further, the simulation will not only show compliance with local regulations, but also represent the data extracted to highlight strengths and weaknesses in the design, providing an analysis for improvement in the early design stages in an improved workflow.

## 5. Case study

Summer Hill Flower Mills Apartments is a proposed multiple residential building in the inner west suburbs of Sydney, Australia. The buildings designed by HASSELL Studio are inspired by the site's previous flourmill architecture, an adaptive-reuse of concrete silo into multi-residential building. Within stage 3 of Flower Mill development, building 3C was chosen to test daylight simulations. The building has problems with natural light entering the building. The daylight lighting problems associated with Building 3C will generate the greatest conflicting results, outlining the possible benefits of the workflow developed in this research. Building 3C is currently not aiming for Green Star certification.

Multiple problems relating to daylight are inherited from the existing site conditions; making it difficult to improve the volume of daylight. Areas pertinent to Green Star within building 3C have difficulty reaching the minimum daylight requirements as prescribed in the Green Star Multi Unit Residential. Multiple simulations are used to compare and evaluate the efficiency in the placement of rooms. Simulations were run using a) only structural and external walls and b) the building as it is currently designed. Comparing the data identifies the effects of the different design elements on daylighting.

### 5.1. RESULTS

The daylight simulation has shown that Building 3C has poor access to natural daylight. Rooms adjacent to windows occupy a small percentage of the area in which successfully passes and contribute to the Green Star requirements. While the internal walls restrict the movement of daylight, the design of the buildings core foundations has created natural resistance to receive

natural lighting. The limitations on the structural walls and windows create great difficulty to increase the levels of daylight to achieve the benchmark requirements. The initial simulation shows large red areas (low daylight levels) in the middle, demonstrating an efficient placement of space when judged from a Green Star compliance perspective. The Green Star daylight requirements only require nominated areas to be measured. Nominated areas exclude bedrooms, sleeping areas and bathrooms and include internal habitable areas including kitchens and living rooms. In building 3C, the western apartment has problems with daylight reaching the nominated areas, however the bedrooms receive a large amount of daylight and would achieving the criteria if they were nominated.

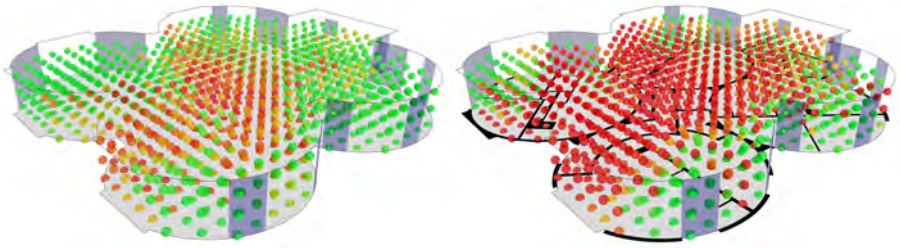


*Figure 3. Level 8 of Building 3C. Left: Voxel daylight simulation results before internal walls are accounted; Right: Voxel daylight simulation results after internal walls are accounted.*

Restructuring the apartment room layout would increase the amount of daylight entering the nominated areas, the kitchen and living room, by using the existing window's exposure in the bedroom. The suggested restructuring is unlikely to proceed due to the bedrooms having no access to windows and natural light.

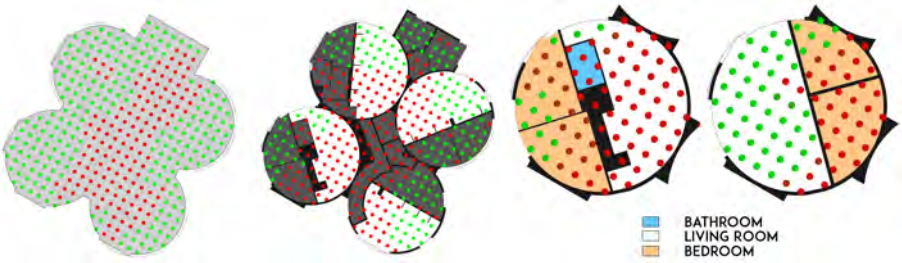



*Figure 4. Level 8 of Building 3C. Daylight simulation of the level before and after the internal walls are accounted. Building 3C level 8 west apartment. Designed layout again proposed layout, giving larger priority to Green Star nominated areas.*

## 5. Limitations

The simulation increases in time based on the number of points. This is a function of distance between each point the area being tested and the floor to ceiling height i.e. $O(n^3)$. A balance between density of points per volume and consumed time is required to create the most effective use of the tool. Voxel simulation consumes a greater amount of calculation time than 2D daylight simulations. An experiment method to decrease calculation time was derived from generating lower density voxel to select the targeted areas and creating a targeted point cloud, decreasing the amount of calculated points by approximately 20%. Reducing points through this method is directly related to the volume of targeted points.

The workflow heavily relies on the input geometry to be created within Grasshopper and Rhino. Imported geometry from other modelling software including Revit, can create errors with the simulation workflow. Incompatible geometry needs to be recreated manually to allow the user to run the successfully simulation. The model transfer from Revit to Rhino created geometry that gave the simulation difficulties. The bathroom in the west apartment initially revealed incorrect of daylight within the area enclosed because surrounding walls were incorrect. This decreased the overall accuracy of the analysis. When the geometry was recreated in Rhino and Grasshopper, the simulation was successful in providing accurate results. Simple geometry generated within the modelling software is more likely to be successful than imported geometry from Revit.

## 6. Evaluation

The daylight simulation tool successfully analyses the space and building within a voxel matrix. While the information generated on several level can help in the early design stage to find design impacts, the simulation is unnecessary towards the documentation process, Green Star only requires measurements on the finished floor level. Results from the simulation formatted into a voxel grid provide daylight information within a 3D space. The workflow needs further evaluation on the potential impact within the early design stages by testing on a building in preliminary development. Building 3C is well within the documentation stages, therefore changes to the buildings structure cannot greatly impact the design. Proposed suggestions are recommended derived from the information gained from the daylight simulation data. The method in which Honeybee runs the simulation does not enable a continuous data stream. Comparing the designed tool against existing software is hard to determine the effectiveness due to the different designs stages. Considering the programs in use accessibility, the simulation was

successful in providing an alternative to existing market programs for daylighting analysis.

Intermediate skill knowledge of Grasshopper and Rhinoceros is required to use this tool to create the proposed geometry. The use of layering systems in practice will increase the time efficiency of the workflow. While the majority of the work is automatically processed, different level of user inputs are required to complete a daylight simulation and analysis. The number of geometries also created some inconsistencies within the simulation results, rare occasions include not picking up surfaces. The numbers of inputs are lower than traditional energy simulations due to the pre-defined nature of Green Star requirements, making it quicker for experienced users. An evaluation though practice will help redefine the complicated stages of the workflow to increase the usability. The proposed tool only commits an analysis on daylight requirements within the Green Star. Local regulations have multiple criteria that are necessary to receive certification. Adjusting the levels of daylight interacting with a building can affect other building properties including energy performance and natural ventilation. Existing projects and software compare the different regulations categories, allowing the designer to identify the non-daylight consequences in their designs. The software may negatively affect other aspects of design due to a tunnel-vision effect, not increasing the designs overall value.

## 7. Significance of project

The research team concludes that this research is significant as it: (1) Provides an accessible daylight analysis tool that can influence design decisions to achieve the minimum requirements Green Star Multi Unit Residential benchmarks. (2) Investigates the openings of façades/roof and the relationship between the interior volume and the façade within early design stages. This is relevant as most other scripts that are developed computationally are superficial and the process of this research address this issue and enable designers to create informative design decisions and being more aware of green design and building performance.

## 8. Conclusion

The tool is successful in providing an accessible daylight simulation and comparing the results to the Green Star daylight requirements. The importance of a Voxel daylight simulation was not enhanced with Building 3C due to the overall design. With further developments, the project will evaluate the accuracy and effectiveness with existing tools accessing the industry standard tools to the developed workflow. Additional further developments

include investigate in different methods to reduce time needed to generate the voxel results including selective point cloud simulation testing.

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# FOR TIME-CONTINUOUS OPTIMISATION

*Replacing automation with interactive visualisation in multi-objective behavioural design*

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**Abstract.** Strategies for optimisation in design normatively assume an artefact end-point, disallowing continuous architecture that engages living systems, dynamic behaviour, and complex systems. In our Flora Robotica investigations of symbiotic plant-robot bio-hybrids, we require computational tools and strategies that help us evaluate designed behaviours, rather than discrete 'things'. In this paper, we present our strategy of using embodied interaction to facilitate engagement with a scenario's full scope of possible states and their continuous changes over time. We detail the ways in which this approach to time-continuous optimisation can be broadly impactful for decision-making, especially in architectural systems that aspire to effective dealings with control flows and lifecycle management.

**Keywords.** Multi-objective; dynamic; visualisation; interaction; optimisation.

## 1. Introduction

As architectural projects have become more complex and begun to engage more numerous complex systems, the computational task of assessing a design's performance according to many disparate objectives has become more prominent. Computational design teams frequently search for performative solutions with optimisation algorithms or metaheuristic approaches such as evolutionary search methods. The prerequisites for utilising these methods, while well-suited to engineering, are less productive for the full scope of architectural design tasks. They require comprehensive numeric formalization of objectives and their relative priorities (Deb, 2001). Pre-defined fitness

functions may be a poor companion to exploring design nuance, discovering commonalities between quantitative objectives and those without metrics, and leveraging designer understanding of emergent relationships between various real-world systems. Therefore, rather than seek a more perfect method of automated optimisation, we propose the investigation of Human-Computer Interaction methods (as an augmentation or extension of automated search methods) for situations when a designer does not already know the correct fitness function, and needs to explore the commonalities between objectives in order to design appropriate fitness functions. Our approach intends to enhance understanding of objectives and fitness through embodied interaction (Dourish, 2001). This requires that improvements of visualisations, as tools from which designers can make reliable inference, become a priority.

It is well established that solution sets with more than three dimensions cannot readily be understood visually, and that the problem of visual representation becomes increasingly difficult with increased dimensionality (Coello et al, 2007). Therefore, in the research conducted, we intentionally construct a case study scenario with more than three dimensions not only in the objectives, but also in the parameter set.

## 2. An approach for the problem of multidimensional visualisation

As pointed out by Coello et al (2007), it is readily accepted that legible visualisation of optimisation results is typically limited to three dimensions. It is with this problem that the key underlying algorithm of our approach deals. One way to visualise three dimensions is with xyz plots. We assume here that plots will be used for the parameter space, leaving colour as the visualisation medium for objectives. Gradients are commonly used in optimisation visualisations, to visualise a single set of values (Figure 1). Our underlying algorithm therefore deals with visualising more than one set of values, by combining multiple gradients in a single parameter space. In the examples of in this section, the combination is first shown with full gradients (distributed across the value set). It is then also shown with a threshold at the median, creating a binary colourisation.

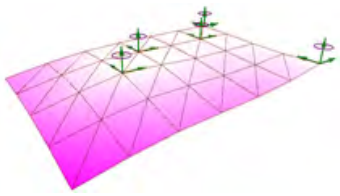


*Figure 1. KARAMBA3D. An example of one value set visualised with gradient.*

First, we look at the problem of gradient combination with two gradients (representing value sets) (Figure 2). Both the method of averaging RGB and of assigning each value set to an individual RGB channel are visually clear.

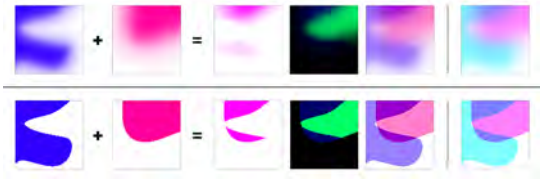


*Figure 2. From left to right, first gradient, second gradient, adding RGB, subtracting RGB, averaging RGB, assigning value sets to individual RGB channels.*

Assigning value sets to RGB channels gives visually clear results not just with two sets, but with three (Figure 3). It is an approach often used, and is for example used by the Grasshopper add-on Octopus. However, its limit is reached at three value sets, when the R, G, and B channels are all occupied.



*Figure 3. Assigning three value sets to the R, G, and B channels.*

Next, we look at the strategy of averaging the RGB values of multiple gradients representing value sets. Averaging two gradients (Figure 2) was visually clear. Averaging three gradients (Figure 4) is still mostly visually clear, but as we continue to add more gradients, the legibility declines significantly. Averaging six gradients becomes quite illegible when using binary colourisation, and completely illegible when using full gradients (Figure 4).

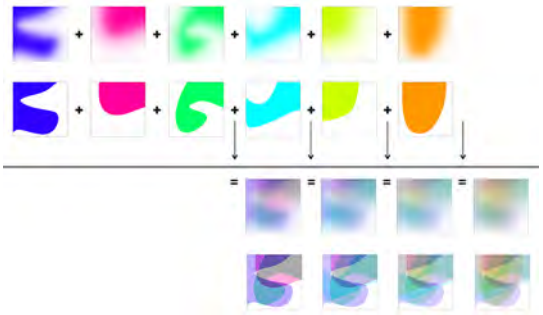


*Figure 4. Averaging the RGB values of up to six gradients.*

By contrast, when we use our algorithm for gradient interspersion (refer to Section 4) combining six gradients remains quite legible using full gradients, and highly legible using binary colourisations (Figure 5).



*Figure 5. Left to right, averaging RGB, our approach of interspersing full gradients, our approach of interspersing binary colourisations.*

When using our strategy of combining many gradients representing value sets for objectives, on one parameter space, one can visually identify areas of density. These areas of density occur when there is the most overlap of gradients, and therefore the most commonality between many objectives on specific individual solutions in the parameter space (Figure 6). In other words, the simple task of visually identifying density allows the viewer to intuitively identify optimal solutions.

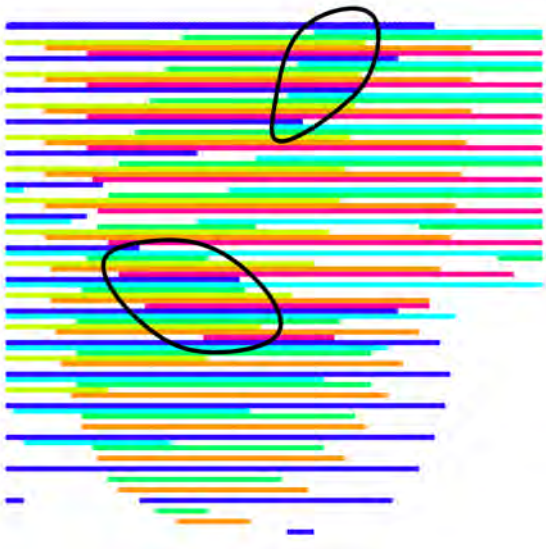


*Figure 6. Areas of density in the interspersed visualisation, indicating commonalities between objectives, and therefore optimal solutions.*

These results acquired through the user's visual judgement and inference can be confirmed algorithmically, by identifying the isoline curves for each gradient and calculating the intersection areas of those curves (Figure 7).

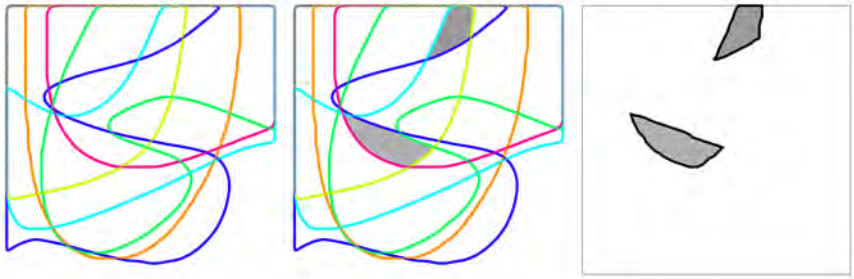


*Figure 7. Left to right, isolines, isolines with intersections, intersections.*

## 3. Setup of case Study and methodology

The case study scenario we construct to detail the implications of this strategy involves a six-dimensional parameter set. The parameters inform the coordinates of a grid of control points defining a NURBS surface, representing a gridshell. The points are distributed into six groups (Figure 8), and the z-coordinate of each point group becomes a parameter. Because these are NURBS control points, each parameter's individual impact on surface topology can only be determined relative to the rest of the parameters. The z-value of the defined surface, at a given xy position, depends not only on the z-value of that respective control point, but on the other control points in the set.

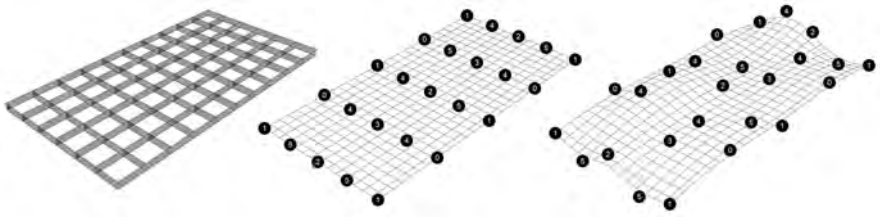


*Figure 8. The six groups of NURBS control points (numbered 0-5) in two positions, with the NURBS surfaces defined (and the gridshell represented).*

Each parameter's variables are continuous and periodic, as is typical in an optimisation setup. Specifically, each of the six groups of control points can have a z-value of 0, 2, 4, 6, 8, or 10. However, the possible parameter-based NURBS surfaces are time-dynamic morphologies, not static objects, undergoing constant geometric change by continuously updating to surrounding environmental conditions. In this case study, the geometric scaling of the z-

dimension of the defined surface is tied to the real-time solar conditions of the site. For instance, if parameters A, B, and C were equal to 2, and parameters D, E, and F were equal to 8, and these parameters did not change, the resultant NURBS surface would still have a different morphology in morning solar conditions than in it would in afternoon.

The following four objectives are applied to the case study: acoustic scattering (black), rain water drainage (blue), wind sheltering (purple), and solar exposure (red). These objectives are evaluated according to respective geometric abstractions. They are chosen because they do not inherently have geometric commonality. From now, they will be referred by their assigned hues.

We first run the scenario through the Evolutionary Solver in Grasshopper's Galapagos in Rhino3D. The native output of any single run of Galapagos is a single design solution that has been evolved according to a single fitness function. When optimising for multiple objectives in Galapagos, the multiple fitness functions must be numerically combined. Weighted combination into a single objective is arguably the most common strategy of optimising for multiple objectives (Deb, 2001). (The Grasshopper add-on Octopus, by contrast, handles multiple fitness functions and outputs multiple solutions (Figure 9). Our approach could be used in combination with this tool, by exploring and designing fitness functions that can then be used in Octopus.) For purposes of comparison, the objectives are given equal weights to be run in Galapagos, and the resulting solution is a topology similar to a barrel vault (Figure 9).

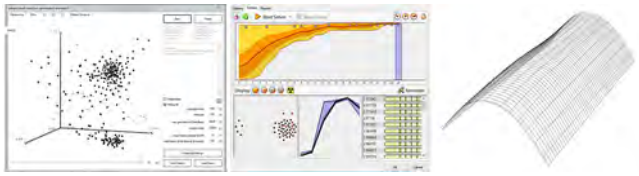


*Figure 9. Left to right, Octopus plot of multiple solutions and objectives, Galapagos interface in this case study, Galapagos case study output topology.*

We then investigate the same scenario with our approach, with the purpose of developing effective visual semantics to facilitate a user's deductive evaluation of dynamic design solutions. The possibility for such an interface is achieved by pre-calculating a comprehensive database of performance evaluations and then continually referencing that database as the user interacts with the interface. The pre-calculation of the reference database in this case study, in this early non-optimised prototype, took less than two hours of runtime. This suggests that an optimised version could be similar to the

runtime of a Galapagos optimisation (for this case study specifically, which contains 46,656 solutions; see Section 7 for scaling of the approach).

This aspires to embodied interaction to "help support the process of improvised, situated action by making the immediate circumstances of the work more visible" (Dourish, 2001), applied to visualisation of multidimensionality. In addition, this approach allows representation and engagement with both the full scope of possible solutions, and the full scope of environmentally-dependant timesteps that can occur in each solution, in stark contrast to the typical optimisation strategy of summarising.

## 4. Squarified treemapping and interspersion

The six-dimensional parameter space is visualised as a nested set model, through the visualisation strategy of squarified treemapping (Bruls et al, 2000). The evaluation criteria, visualised as an alpha-channel gradient on the objective's assigned hue, is overlaid onto the structure of the squarified treemap (Figure 10). Through the interface, the user can browse hierarchical orders for parameters, allowing the user to choose the hierarchy that makes trends in the evaluation criteria as visually legible as possible in that bespoke scenario (Figure 10).

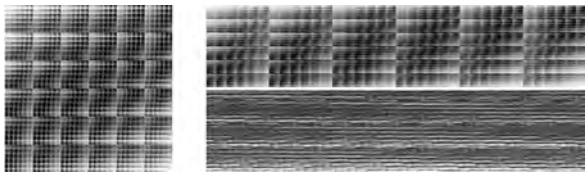


*Figure 10. Left to right, squarified treemap, possible hierarchical orders.*

The four-dimensional objective space can be visualised in the interface both as an extension of the squarified treemap enabling side-by-side comparison (Figure 11), and as an interspersed gradient map (Figure 11), loosely inspired by genotype microarray visualisation strategies (Kincaid et al, 2005). This enables the user to make evaluations not just about the performance of design solutions, but also about the appropriateness of the user-specified objectives to the design problem at hand, a fundamental issue of multi-objective optimisation (Deb, 2001). For instance, a user can easily ascertain from the side-by-side comparison that the black objective and the blue are in direct competition with each other, and can never both be fully optimised in a single design solution. The user might, in that instance, manage one of these competing objectives with a different strategy in order to achieve them both. Also, a user could ascertain that the distributions of the purple objective and the red are similar, and could accordingly make more

informed decisions about the design. Both of these insights, though almost trivial when viewing a visualisation of the entire evaluation set, could not be derived from the native output of the Galapagos evolutionary solver in any design problem that has many diverse local optima.

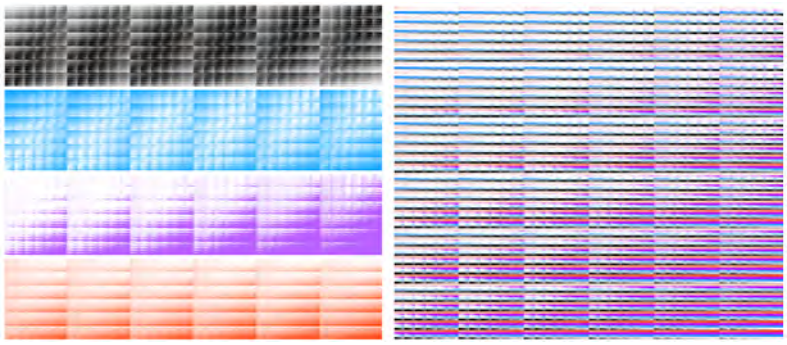


*Figure 11. Left to right, extended squarified treemap for side-by-side comparison, and interspersion of that extended treemap.*

## 5. Dynamic fitness thresholds

In this interface, the user has the option to change the weights of the objectives with real-time updates to the squarified treemaps and interspersed treemaps, through the manipulation of evaluation thresholds (Figure 12). This allows the user to interrogate his or her design of objective fitness, thresholds, and weights, a task that can be very problematic in typical evolutionary solver setups. For instance, the treemap in Figure 11 (equal weights for all objectives), shows that under the current thresholds, no solution can be fit for all objectives, and the most advantageous solutions are those in the bottom right (where there is low black, but high blue, purple, and red). After viewing this, a user could decide to make a trade-off (Deb, 2001) to be more lenient on the black objective and change the threshold to be more inclusive (Figure 12), making solutions in the bottom right corner fit for all objectives. Conversely, a user may look at the Figure 11 treemap and realise that the initial objective weights is a poor reflection of the design problem at hand, and needs to be modified substantially. If the user were to increase the importance of the black objective, and decrease the importance of all others (Figure 12), those in the centre of the map would surpass those in the bottom right and become the most fit.

If a user wished to modify the weights and thresholds using evolutionary optimisation, the solver would have to be re-run for each change in objective weighting, and it would be difficult and unintuitive to begin to understand the trends present in the dependencies of weights, fitness, and solutions.

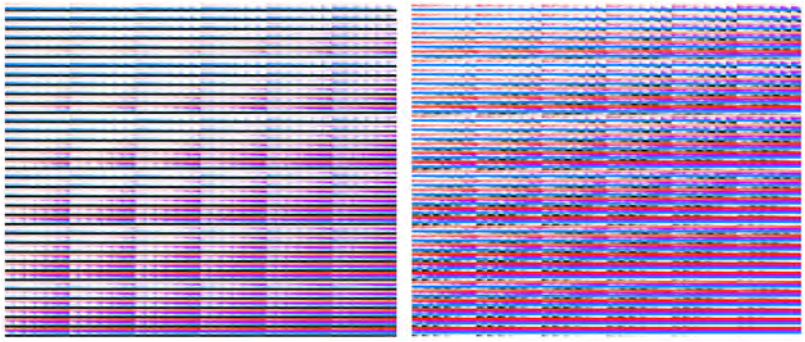


*Figure 12. Left to right, treemap with thresholds lenient for the black objective, treemap with thresholds that prioritise black objective.*

## 6. Mapping local evaluations onto solution topologies

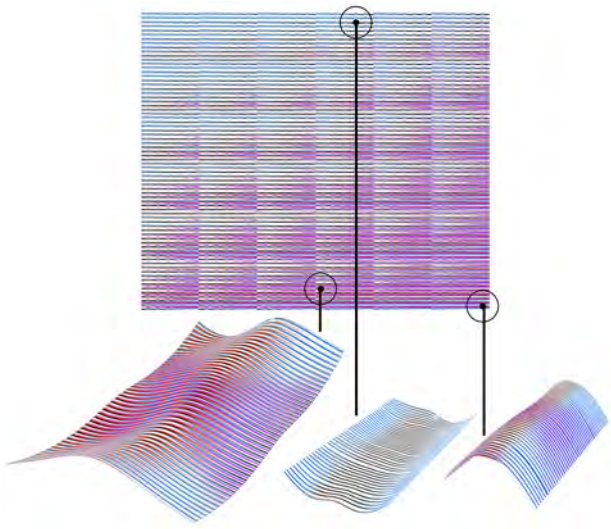


*Figure 13. Solutions' treemap locations and topologically mapped evaluations.*

The interface allows the user to select a single solution from the treemap (either by defining the parameter variables or by defining the position on the treemap), and to simultaneously view the local evaluations of that solution's geometric topology, according to each objective (Figure 13).

This visualisation, like the treemap, allows the user to toggle between side-by-side comparison and gradient interspersion. As solution browsing has real-time feedback both on the treemap and the topology, the user can internalise an intuitive understanding of which topological features spur which fitness results. This could empower the user to make a non-optimal

selection from the solution set, with the knowledge that a certain objective could be achieved by making other changes to discrete problematic spots. The user can also run time scenarios, with assessment interfaces similar to that of simulation. The user can simultaneously view the treemap and an individual solution topology as they undergo their time-based changes and continuous re-evaluation.

## 7. Conclusions and future work

This capability is the most significant distinguishing factor from typical multi-objective optimisation strategies, alone. In typical optimisation, behaviours would be summarised. Here, the user can engage with the full set of behavioural states, enabling inferences as from a simulation. It also enables understanding of a timeline of performance timesteps within the dynamics of a system. The user can understand, in a reliable, reproducible, and accountable way, the solution's changes over time, and evaluate how it is influenced by its context, influences its context, and performs according to objectives.

Future work should include placing the approach in pipeline with existing tools, like Octopus. It should also include the following within the Flora Robotica project: algorithmic identification of isoline intersections for system boundaries or phase changes, limits of universal legibility of interspersed gradients, scaling approach through sampling, and appropriateness of approach against various complexities of systems and scales of rates of change.

## Acknowledgements

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# MULTIVARIATE SCHEMATIC DESIGN TOOLING

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**Abstract.** This paper will examine the results from a research collaboration between (BIM Software Manufacturer) and (School), whose problem statement focused on supporting robust interoperability by defining goals focused on multivariate conceptual design tools. The collaboration included design faculty, students and software professionals, the latter providing access to a broad range of design simulation tools either commercially available or currently in development. The tools were developed first through case studies and background research, followed by the design and implementation of novel computational methods advancing the architectural design workflow by seeking to create comparative tools which allow a designer to connect multiple data typologies in a single model. With advanced computational tools employed both as standalone resources and embedded in parametric loops, we sought to provide immediate feedback on design goals.

**Keywords.** Building information modelling; simulation and prediction; education; optimization; scripting.

## 1. Introduction

The earliest and still most ubiquitous use of computing in the AEC sector remains 2D CAD, which reproduces and incrementally improves the production of document sets. A growing segment of the industry continues to adopt Building Information Modelling (BIM), substituting manually managed sets of 2D files with models from which instruments of service are partially derived. While an improvement over the more cognitively dependent CAD process, BIM largely persists as a repository of decisions made outside the computational environment. The application of multi-

disciplinary data integration through BIM modelling improves building performance when compared with typical design methodologies (Wang et al 2005). As an improved CAD, BIM excels at more adroitly capturing and delivering instructions for what is to be built, but literally leaves everything to the imagination when addressing why something should be built. BIM used in this way maintains the status quo in the project methodology as it has been established prior to the use of computers, maintaining a persistent paradigm of design formulation and project delivery. However, with a reconsideration of how BIM is used during each respective design phase, a significant shift in methodologies could occur.

Advanced computational methods provide the opportunity to enhance building design by delivering encoded expertise and context, applying technology to do far more than record and communicate building decisions while helping the designer focus precious cognitive resources on the subjective and/or tasks more suited to human completion. As cognitive psychologists have proven, true multitasking is not humanly possible (Meyer and Kieras, 1997). What is perceived as multitasking is actually, quickly switching between tasks. It has also been shown that humans, once derailed from their primary task take longer to get back to capacity on the original task. Computers, however, can process several task streams simultaneously. The project outlined in this paper will describe new methods for leveraging multivariable computation during the schematic design process to collapse the distance between analysis and design and create more immediate feedback loops between a designer and the understanding of design performance.

This paper will examine the results of a research collaboration between Autodesk, Inc. and the University of North Carolina Charlotte School of Architecture, whose problem statement focused on supporting robust interoperability by defining goals focused on multivariate conceptual design tools. The collaboration between the academy and software professionals provided access to a broad range of design simulation tools, either commercially available or currently in development, coupled with current research trajectories into leveraging computation to better inform a designer of the implications of their design strategies and decisions. The tools created were developed first through case studies and background research into existing computational tools and methods. This was followed by the creation of comparative tools, which allow a designer to connect multiple data typologies into a single model. The results linked advanced computational tools employed as standalone resources, embedded in parametric loops within discrete programs and as scripts designed to facilitate program interoperability. The common goal for each was to provide immediate

feedback to the user during the design process while implementing novel computational methods advancing the pace and accuracy of the architectural design workflow.

## 2. Context

In the current era of the Anthropocene, where the question of sustainability has become the primary focus a new theoretical redefining of our design practices can emerge.

Manuel de Landa (2002) has described a design technique that begins with the conceptual or 'cerebral' genesis of form, imposed on materials where the form or design is the primary focus of study – a teleological approach. A non-teleological technique in which materials are not inert receptacles of the cerebral idea is more aligned with a holistic energy-conscious design strategy whereby form (here material is understood in the broadest sense to include phenomena produced as matter and energy interact and then by extension in the field of architecture to include the social and programmatic), material and idea work in concert as multivariate partners towards a singular solution. De Landa builds an analogy for what this design methodology might be, based on physical material behaviors and the trajectories that emerge through gradient differentials to produce effects like phase transitions. De Landa offers up this analogy for a design method, whereby internal constraints and external conditions produce unique and specific results. If we can synthesize design constraints into similarly intricate logics or ecologies we can better understand their impact in the most holistic way; embodied energy, the properties of materials, and how those materials behave within a larger infrastructure to produce better design solutions from the lenses of the sustainable to the formal to the social.

At a theoretical level, De Landa's approach implies that only advanced computation can negotiate this complexity. The iterations (known as cycles in computation) required to complete even the simplest material simulations to understand their interrelations are beyond analogue capacity unless the simulations involve material computation such as Gaudi's hanging chain models. Material computation models such as Gaudi's are not entirely unique. Frei Otto's experimentations with minimal surfaces as thin-shell constructions are also examples of using material computation in design evaluation. However, even in these ground- breaking examples, the analogue technique does not go beyond the study of the relation between form and structure. The challenge De Landa is presenting is to construct a computational framework that behaves like the analogue models of Gaudi's – to immediately provide feedback that assist design decision- making.

At a practical level, this approach requires coordinating several discrete software packages, each of which possesses a singular focus. Recently, advances in the parametric capabilities of BIM packages such as *Revit* allow for geometric manipulations to be interconnected to substantial behavioral depths – beyond sharing data through .csv files. However, even the most robust packages only have capacity for very basic analytics when compared to discrete single function software packages – the question becomes is it possible to leverage the advanced analytics within a conceptual design framework in a useful way?

## 3. Multivariation

The intent for the organization of this project was to link seemingly disparate design elements together to create more intelligent schematic design systems. Inevitably each of the variables became more intricately linked as the tool was developed and relationships were formed through research into the values associated with each variable. By combining these data types and testing their relationships the project intended to discover new combinations of testable parametric fields, potentially including areas that had not been linked before. An abbreviated list of individual possible schematic design variables includes:

- Program organization
- Social capital
- Circulation
- Diagramming
- Site analysis
- Solar performance
- Daylighting performance
- Lateral loading and wind analysis
- Structural analysis
- Urban design performance
- Demographics
- Zoning
- Site connectivity
- Façade design optimization
- Rainwater control and collection

Each project was continually mapped using a logic diagram, to allow for further development by users and to allow for creative development by many involved in the research team, explaining how the tool works and allowing for others to test various iterations and create a collective workflow for each

tool. The example below illustrates the tool logic outlined for the use of a workflow from *Robot Structural Analysis* through to Revit and back again, through the use of various data types through each piece of software and *Dynamo*.

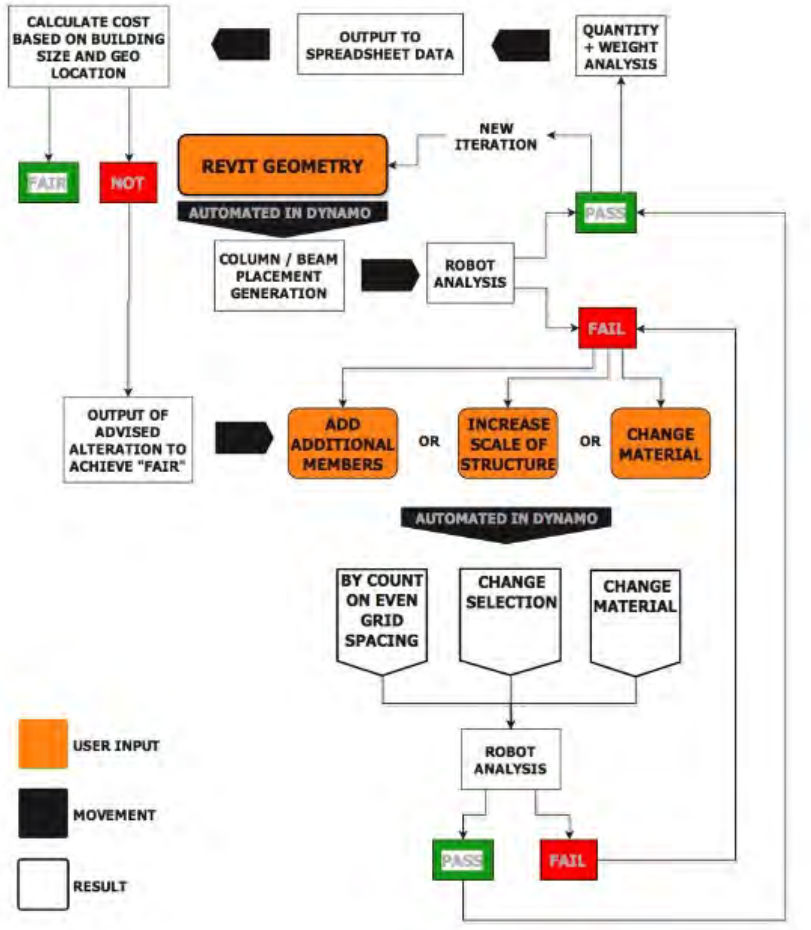



*Figure 1. Logic Diagram of Robot Structural Analysis tool to Revit*

## 4. Examples

Selected examples of projects that were successfully completed include:

- Creating a live link between *Robot Structural Analysis* software and Revit to evaluate structural member selection and spacing during schematic design phases.

- Using GIS information with a developed algorithm to evaluate each square foot of every floor in a proposed building assigning a relative value for each square foot based on available views.
- Writing a *Python/Dynamo* Script that interfaces through the API in *Autodesk Simulation CFD* and *Autodesk Revit* to evaluate façade design to optimize passive stack effects in tall buildings.
- Creating a value system for the creation of social capital (as a quality which improves workplace productivity) within a given programmatic assembly in large buildings.
- The creation of an adjacency tool for testing the performance of various organizational strategies for complex programmatic typologies.

Below we have unpacked some of these examples and provided a brief explanation of each of their data typologies and the link that was created between them.

## 4.1. STRUCTURE INFORMING PROGRAM

This tool attempts to empower the designer early in the design process by easily including basic structural design and analysis from the very beginning of a project's conceptual design. Any level of structural analysis this early on in a project is a common characteristic of a project delivery method known as integrated project delivery, however typically in practice, the structural system isn't quantitatively analyzed until the design has been more thoroughly developed. By empowering the designer with this tool, rather than relying completely on engineers to specify sizes for structural member sizes in a floor, wall, or roof assembly, the tool can automatically generate the structural model into schematic three-dimensional models that are sized according to design loads.

This tool gives the designer the ability to populate an entire building massing with structure as various massing models are attempted. This structure is then analyzed and sized automatically to conform to best practices in structural design. The resulting system shouldn't be perceived as the best solution or as a replacement for the work of an engineer, but rather a realistic representation of what the engineered system will eventually become as part of the project. This output equips the design team early on with structural quantities for the purpose of cost estimation and provides fail-safes that will prevent design changes due to poorly coordinated programs and their respective structural members.

Furthermore, this tool provides fully populated structural models that the design team can carry with them into design development. These models are easily updated and modified based on design alterations. Having structure

integrated so early in the schematic design of a building can increase productivity and dramatically reduce errors and conflicts between various consultants. (Asl et al, 2015)

Using *Python* scripting as an interface, the tool develops a simple organizational strategy for structural members in a *Revit* massing model, and then uses the proven structural modeler *Robot* to test for functionality. If successful, the script populates the *Revit* model with member sizes. If the system fails to define a realistic structural design, a range of modification options were presented to the user, including shifting the massing, changing constructions types or spacing, or the primary direction of the members. After any design interventions were completed, the calculation would begin again. When a successful model was tested, a cost estimation was provided, so that the designer might be better informed about how each scheme performed compared to schemes with alternative geometry, spacing or construction type.

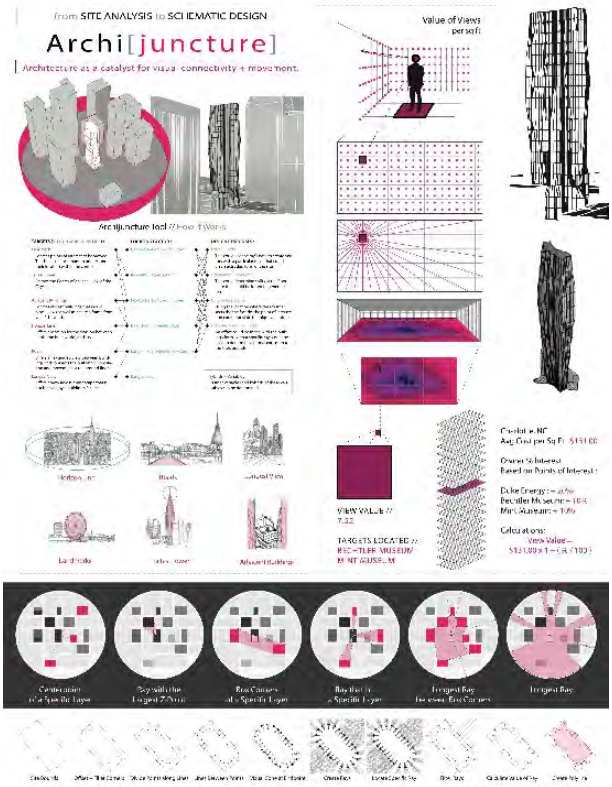



*Figure 2. Diagrams explaining a tool which assigned value per sq. ft. based on view analysis from a given sq. ft. or zone on a floor plate.*

This next tool attempts to assign value to a variable, which every building must consider but few understand parametrically, the quality of views. The design of this tool was produced with a combination of *Python* and *Dynamo* scripts and was based around rays projected in three-dimensions from eye level locations for every square foot on each floor plate to represent the regard of a building inhabitant from that point. The solution of the ray's intersection point with objects in a site model can be collected to create a data set that contains the potential for at least two clear methodologies. The first motive would be to assign value to all of the individual square feet on each floor plate so that a range of views throughout the building can be identified before it has even been built. The valuing system is flexible and dependent on each owner's criteria for potential points of interest and their marketing strategy. The second motive would be to use the tool for architectural design schematics so that more efficiently enhanced views of the site can be made.

## 4.2. THE BREATHING TOWER

The *Breathing Tower* generates performative geometries that encourage optimal, constant airflow conditions between intake and exhaust membranes of a building. The adaptability of feedback-driven forms makes this a flexible platform that can be applied on a range of scales. By simply selecting which profiles the tool can manipulate, the designer can limit the influence to a single facade, or allow it to shape the form of the building itself. This tool enables the designer to maximize the passive flow of air through a double-skin cavity, plenum space and core. This tool will allow the designer to place program elements (walls, cores, large furniture) as they desire, and let the algorithm optimize the geometry of the skin and core to achieve the desired flow at key measurement points.

This tool employed *Python* scripting to link the evaluation of each floor plate of a given *Revit* tower building massing. The floor plates were tested using *Simulation CFD*, which tested the rate of airflow through a double skin and across the floor plate to its exhaust. When objects impeded the flow of air across the floor plates, or as the height of the floor changes, or temperature shifts, all potentially would alter the rate of air interchange on a given floor plate. The system would identify changes to the geometry of the skin which would create more appropriate speeds and volumes for the given floor plate. The resulting geometry creates a map of air circulation through the double skin, while showing how differing designs for individual floor plates affect the overall tower massing when associated with its performance.

### 4.3. SOCIAL CAPITAL

The Social Capital (SoCap) tool attempted to create vertical and horizontal relationships in a tower design between programmatic components of any architectural typology into configurations, which would induce the creation of more social capital as a consequence of the design. Social Capital in this instance is defined by a variety of theories on understanding of human behavior and interaction in public spaces, including but not limited to Jacobs (1961), Briggs (2005), and Hsieh (2013).

All of these sources emphasize the need for programmatic organizations that encourage diverse groups of people to meet and collaborate for the sake of economy, potential for innovation, and societal impacts of performance. Most large cities encourage some level of interaction between diverse groups; but buildings largely fail to encourage these same kinds of genuinely diverse interactions.

SoCap analyzes the capacity for social capital in buildings at any stage of the design process. To use this tool, a designer first defines the types of occupants associated with each room (using a room tag) in a *Revit* model. SoCap then analyzes each floor for its capacity for social capital (much in the same way as occupancy loads are measured) by looking for matches between types of occupants. Example: if a floor has three types of occupants (Types A, B, and C), a full match between all three types counts as a full point towards the floor's match score while a match between types A and B only is weighted less than a full match. Then, the total match score is divided by the total possible number of matches to produce a diversity score.

Based on this analysis, SoCap makes recommendations to the designer that would increase the building's SoCap score. These recommendations may include connecting floors, by stairs and atriums, or inserting new programmatic elements onto certain floors. The designer can continue to make changes and analyze their designs at their discretion.

## 5. Conclusions and future work

While 21st century designers feel increasingly capable of managing multiple variables and compiling increasing amounts of information into a design process, we now know that humans are not capable of speedily shifting between tasks. Recent cognitive science research (Meyer and Kieras, 1997) has proven our brains are not capable of true multitasking or handling multiple streams of information simultaneously – rather we are good at switching quickly between tasks with a productivity penalty. However the amount of information a designer must compile is ever increasing. The only logical solution as mapped by other professions is to find ways to allow

for technology to better manage the information streams which can be automatically calculated so the human user can better focus on the tasks that they are more capable of completing. The cognitive limitations of designers and their capacity to synthesize ideas and information into a single solution will always define the ability to factor ever increasing amounts of meta-data into schematic design strategies.

Further constrained by computational limitations despite vast improvements in speed and scale and parallel computing methods, the linkages between design variables are typically complex and often abstract to the human mind. Even the best designers can't manage this complexity and constraint alone. Collaborative work scenarios create better solutions while computation and software continue to improve our abilities to use technology to move beyond design based on "expert solutions" and to begin calculating design solutions. Only then can we expect designers to create "non-teleological" design solutions, which results in holistically ecological *and* phenomenal spaces.

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# DIGITAL GEO-PLEXUS

*Instagram as a tool for re-evaluating notions of proximity*

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**Abstract.** The research presented in this paper describes the development of an Instagram-based multidimensional clustering algorithm. The algorithm analyses large datasets of Instagram images to establish new metrics that qualitatively assess proximity relations in a given geographical area —i.e. negotiates multiple acceptations of proximity. Influenced by Qualitative Spatial Reasoning, Lewis Mumford's geographic plexus and Kevin Lynch's perceptual mapping, a graphic GUI-based application has been developed to produce real-time visualizations —maps, network graphs, and charts— by means of browsing, downloading and post-processing Instagram feeds. First, the application's functioning will be described; second, several graphic visualizations will demonstrate the capabilities of the software; third, limitations and further development will be discussed.

**Keywords.** Instagram; big data; social network.

## 1. Introduction

### 1.1. NOTIONS OF PROXIMITY

Proximity is defined as "The state of being near" (Merriam Webster, 2016). The extent to which objects in space are either *near* or *far* from each other can be understood in Cartesian terms, or at a more abstract level, by similarities and differences at various levels of distinction. For one, Qualitative Spatial Reasoning seeks mathematical theories that qualitatively represent everyday interactions in physical space (Cohn and Hazarika, 2001). Cohn and Hazarika point out that since space is multi-dimensional it is "not adequately represented by a single scalar quantity" (2001).

Within everyday experience of the physical environment, *proximity* —i.e. the degree of nearness— provides a fundamental component to the ontology of space (Worboys et al, 2004). Therefore for architecture, the notion of proximity itself can lend itself to how spaces are *constructed and designed*. Yet the tools with which proximity is typically evaluated still pertain to a Cartesian definition, which is rather unidimensional and rigid—limited to the purely quantitative. Such an approach disregards additional attributes of proximity, which are more qualitative and intricate, multi-layered and ever changing, such as personal experience and perception. Proximity constitutes a multifaceted construct, derived from an amalgam of factors such as physical distance, together with more personal factors, such as routine, memory, individual taste and more. It is our observation that giving voice to the qualitative components of proximity in addition to the purely quantitative, can lead to new ways of understanding and designing the spaces we inhabit.

Ubiquitous social media and computational tools allow for a re-evaluation of how space is measured, represented, and therefore understood, by qualitatively and quantitatively analysing large information datasets.

## 1.2. MAPPING THE HUMAN ENVIRONMENT

For the most part, human environments are still mapped out in a very conventional and top down manner. This is partially due to the static constructs that lay underneath the notion of *space*, such as the incomplete, merely quantitative definitions of proximity. Consequently, the ways in which urban environments are mapped do not necessarily correlate to the richness and dynamism of their systems. (Batty, 2008).

During the advent of digital technology in the 1930's, Lewis Mumford called the city a *geographic plexus*—an interconnected structure of cultural, economic and material systems (1937). For Mumford, the city is an intricate physical and social network, constantly reshaped according to human activity. And as the perception of physical space is constantly distorted at a personal level (Worboys, 2004), the human environment could be understood as in motion, fluctuating in a continuum where the relationship between its parts is under constant change. In *The Image of The City*, Kevin Lynch demonstrates how this constant reshaping of the city is not merely a function of external forces, but the product of a deeply personal and subjective way of perceiving the urban environment. The city is as much a physical entity as it is a cognitive image of relations and connections that one weaves together. In that cognitive image, distances either shrink or expand according to personal experience and associations. Cartesian distance between objects in

space is almost secondary to the non-hierarchical connections drawn between them by individuals themselves.

### 1.3. OVERLAPPING SOCIAL MEDIA AND GEOGRAPHIC DATA

In broad terms, data generated in social media provide insights about certain aspects of human behaviour. Instagram, in particular, captures to some extent how people perceive and document their surroundings. It therefore conveys a latent, bottom-up construction of the urban environment that is dynamic and fluid, changing according to qualitative aspects of spatial, visual, and personal relationships.

Instagram offers a unique opportunity to add up some of the variables embedded in its media to establish a dynamic set of relationships diverse locations within the city. Such relationships transcend the traditional notions of proximity and define a landscape of emergent organization patterns that speak about the complexity of the geo-digital plexus —to expand on Mumford's ideas. From Lynch's perspective, they bridge multiple personal, subjective *images* of the city by a visualization that broadens the scope of purely Cartesian displays of information.

Some applications have explored the potential of ubiquitous internet images to gain a better understanding of urban environments (Salesses et al, 2013, Naik et al, 2014). Many others created digital interfaces to produce interactive visualizations of datasets; some of them operate in abstract spaces using raw data—like Immersion (http://macro.media.mit.edu/), while others overlay datasets with geographic information—like Harvard's Tweet Map (http://worldmap.harvard.edu/tweetmap/)—utilizing traditional Cartesian space to express relations of proximity. This application attempts to bridge the purely abstract with physical space by conflating raw data visualization with geographic data visualization, each aspect affecting the other.

## 2. The Application

### 2.1. BASIC DESCRIPTION

A GUI-based Windows application was developed in an attempt to create a visual geographic plexus, which re-evaluates proximities in space, by means of visualizing large datasets of Instagram images. All the programing was done using C# and Visual Studio. Using Instagram API 2.0, the application performs a geographic search for media which is subsequently downloaded, analysed and post-processed. The gathered and generated information is utilized to produce an interactive network graph that clusters and isolates Instagram media based on different criteria—*dimensions.* The real-time visualiza-

tion explores how this dimensions dynamically redefine what *proximity* means, producing each time a different reading of the Instagram media embedded on the city—the *digital geo-plexus*.

## 2.2. APPLICATION STRUCTURE

The application's structure is broken down into specific stages as follows: a) Accessing the Instagram API; b) Data Retrieval from Instagram; c) Media Processing; and d) Graph Construction and Visualization. Stages *a* and *b* revolve around Instagram API and require internet connection, while *c* and *d* deal with information processing and data visualization, which take place in the local machine only.

### *2.2.1. Stage a: accessing Instagram API*

In order to access data from Instagram, the application first initializes an authorization process to access the Instagram API. Instagram API uses *OAuth 2.0* authentication protocol. For the authentication process, we used *Instasharp*, a free C# library that works with the Instagram API. (http://instasharp.org/).

### *2.2.2. Stage b: data retrieval from Instagram*

After accessing the API, the application does a geographical search for *locations*, one of the endpoints of Instagram API. The query takes as arguments geographical coordinates for the search (latitude and longitude), and a search radius. The Instagram API returns a list of *foursquare-ids*, one of the location services that Instagram uses to geo-reference their media.

The application then does a search for recent media on each foursquare location retrieved. The Instagram media response consists of a JSON file which contains relevant data about each media object found.

### *2.2.3. Stage c: media processing*

The JSON file from the Instagram API's *location media* response is parsed into temporary objects in our software, which stores post-processed information about the Instagram media object. The information includes geographical coordinates, image filter, link of full resolution image and thumbnail, location (foursquare id), number of likes, predominant colour of image, username, tags, and timestamp.

After the location media response is processed, the application identifies every Instagram user from which a given media was retrieved, and requests a variable number of additional media from them. This query is called *user re-*

*cent media*. The response consists of a JSON file similar to the *location media* response, and is post-processed the same way as described before.

### *2.2.3. Stage d: graph construction*

The media objects are analysed and displayed in a graph structure The graph comprises nodes—post-processed media objects which contain all relevant data for assessing different proximity metrics—and edges—connection between nodes that pull them closer or farther apart.

The node objects inherit all attributes stored in the temporary media objects, and convert their geographical location attributes into normalized coordinates mapped into a visualization viewport. The edge object defines the relationships between *two* nodes in space, i.e. their connectivity. Connections between nodes are contingent on degrees of proximity defined by specific criteria, derived from their different attributes. Each edge object sets an attraction force between two nodes, and defines the basic structure of the map. The graph compiles the nodes and edges together. It controls the dynamism of the map, and contains a multi-dimensional spring system of varying degrees.

### *2.2.4. Visualization and interface*

The application's Graphic User Interface is built into a standard Windows Form Application. It is a composite interface containing text boxes for coordinate input, buttons for prompting access to the API and for controlling distinct data retrieval methods. It also contains additional rich-text boxes that visualize the raw data retrieved from the Instagram API, in real time, and an OpenGL viewport for data visualization.

The second component is an OpenGL viewport. The viewport reads back a real time graphic visualization of data manipulation performed in the GUI. For the OpenGL viewport, the free library OpenTK was utilized (http://www.opentk.com/).

## 3. Methodology for re-evaluating proximity

Our method is based on the observation that taking a picture in a specific location is a *meaningful* act—in almost an etymological sense, an act full of various *meanings*, one that can illuminate various characteristics of a given locality.

The information embedded on Instagram images allows us to assess relational proximities in space, based on data from the media available in a given area. Therefore, our methodology takes both quantitative data—such as geo-location and time of day—and qualitative data—such as the type of fil-

ter used, or number of likes—to assess spatial relationships based on non-Cartesian proximities.

A multi-dimensional clustering algorithm produces a *proximity coefficient* that dynamically changes depending on the weighting of the different variables. The coefficient is then incorporated into a graph structure, serving as the distance variable between multiple nodes in a dynamic spring system. Different *thresholds* were added onto the system, to further control how specific variables affect overall definitions of proximity; limits which define degrees of nodal connectivity—i.e. they establish a numeric measure to define whether or not two nodes are considered to be connected. The clustering equation follows:

$$SL = [(d_1w_1) + (d_2w_2) + \dots (d_nw_n)] / (d_1 + d_2 + \dots d_n) \quad (1)$$

Where *SL* is the spring equilibrium length—i.e. the *proximity coefficient*; $d_1$ up to $d_n$ are the different proximity dimensions (e.g. filter, user, time and date, predominant colour, geographic location, foursquare place, etc.) and $w_1$ up to $w_n$ the corresponding weights.

One limitation of this multi-dimensional clustering algorithm is that most of the different proximity dimensions are still too binary. Whilst proximities —i.e. similarities—could be determined in a relatively direct way, dissimilarity on the other hand is not varied or degreed—elements are either similar or they are not. Whereas measuring degrees of physical proximities could be simply evaluated by evaluating magnitudes of metric distance between objects in space, there is work to be done regarding degrees of dissimilarity between qualitative variables, such as filters, which are now equally dissimilar.

As a *qualitative* representation of space, this application re-evaluates proximities by visualizing spatial relationships between objects in space, *dynamically*, on an *interactive* platform. The visualization is key to our methodology since it weaves quantitative and qualitative data together as a composite and dynamic structure of ever-changing reference points in space; spatial relationships are derived from an array of multiple variables and in differing degrees of intensity.

The fundamental organizational logic of this data visualization program is based on clustering as a coherent method for communicating spatial relationships in a visual manner. Furthermore, real-time manipulation of the visualization enhances the *understanding* of the malleable and dynamic relationship between Instagram media in space so that users too could come to conclusions, and ask questions, regarding a given geographic location.

## 4. Visualization as analysis

From the dynamic proximity graph, a series of proximity visualizations can be made, by either focusing on the clustering of different nodes, the connections between different nodes, employing different representation techniques (e.g. using colours to denote different nodal attributes, or using images as a non-linear Instagram feed), or by collapsing information into different hierarchical levels (e.g. having a graph where each Instagram media is a node, vis-à-vis a graph where all the Instagram media share a common attribute, like user or place, are flattened into a single entity).

During this first development stage, some of these possibilities have been explored, while others remain to be implemented. In the following sections, different sets of images will demonstrate the application's capabilities.

### 4.1. GRAPH AS A DYNAMIC VISUALIZATION TOOL

Figure 1 shows, from left to right, a graph changing from clustering Instagram media by Filter (left) to clustering it by User (right), by changing their relative weights in the clustering algorithm. Both upper and lower rows display the same set of proximities, with the colour of each node modified to reflect its filter (upper row) and its user (lower row).

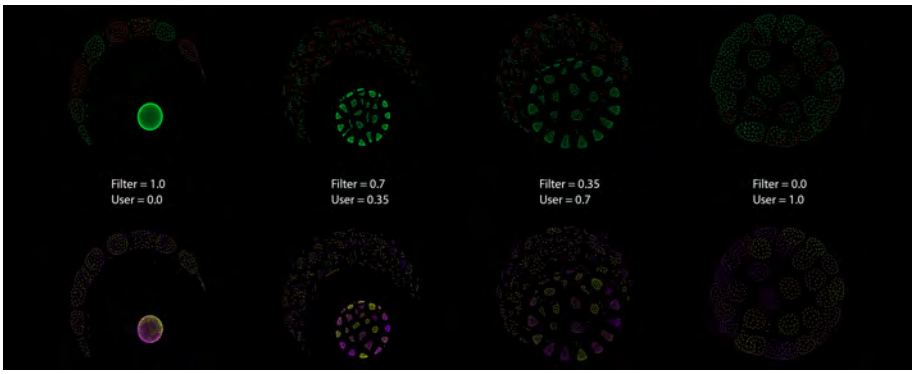



*Figure 1. Graph dynamic rearrangement to represent the same information organized according to different proximity coefficients.*

Figure 2 shows the graph adopting diverse configurations in response to variation on the proximity coefficient between every node. The edges are represented instead of the nodes, showing how nodal connections (controlled by an arbitrary cut-off value) vary as the proximity coefficient does.

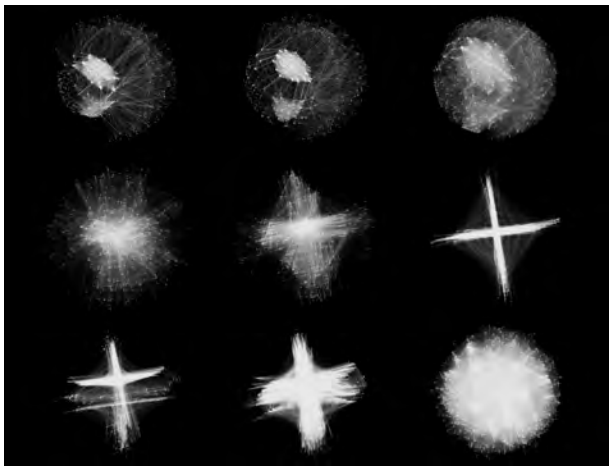


*Figure 2. Dynamic evolution of the graph as dimensions are weighted in different ways.*

## 4.2 INFORMATION DIFFERENTIATION TOOLS

As noted previously, the graph is a tool for dynamic visual rearrangement of information. Besides that inherent capability of graphs to display a dataset in multiple ways, the application deliberately includes different visualization techniques, demonstrated below.

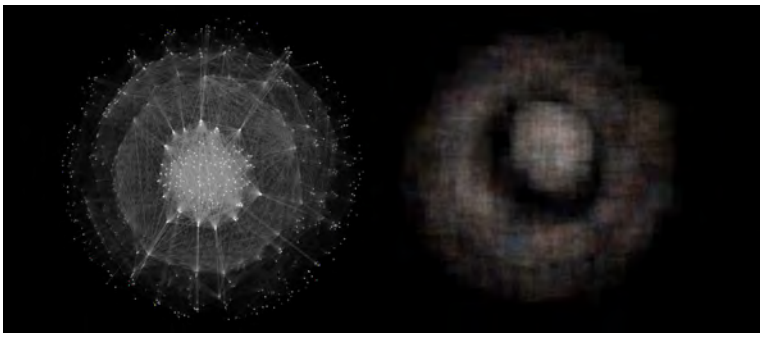


*Figure 3. Two visualizations (edges, and rasters) producing different readings of a graph.*

Figure 4 shows a graph clustering media by user, represented in different ways. Each cluster on the graph contains media taken by the same user. The upper row shows media nodes. From left to right, the colours of each node are controlled by the predominant tone of the image, the filter of the image, and the user. The second row shows only edges connecting two media. From left to right, the edges depict connections between nodes with a proximity coefficient smaller than 1.0; the linear trajectory from each node origin point

(i.e. geographic coordinates) and their current position: and all the connections between nodes that have a proximity coefficient smaller than 2.0. The bottom row shows the nodes only, but using the actual Instagram media instead of coloured points. From left to right, the size of the image increases, while the last image significantly reduces its translucency.

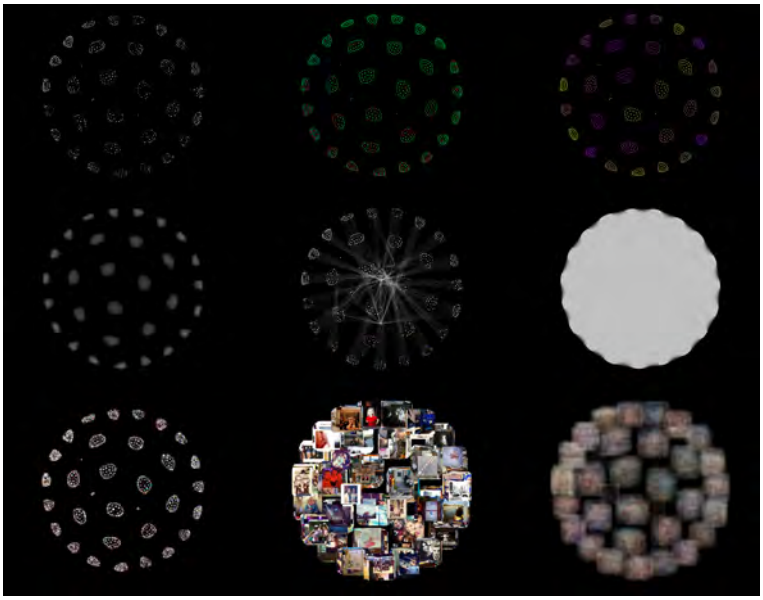


*Figure 4. The exact same graph represented in nine different ways.*

## 5. Conclusion: the digital geo-plexus as a living system and heuristic device

The Instagram based application presented here produces interactive visualizations which reveal spatial relationships of varying natures. The application obtains media from the Instagram API, which is consequently downloaded, analysed and post-processed in order to produce interactive graphs that cluster media in different manners, challenging the traditional notion of proximity as a purely Cartesian phenomenon.

As such, this application serves a dual objective. The first is to visualize a more multi-layered way of defining and representing spatial systems as dynamic, ever changing *living systems*. Doing so resists prevalent top-down, static definitions, and representations, of spatial proximity, as metric distances between *inanimate* objects (the *traditional* map).

Secondly, the developed multi-dimensional clustering algorithm, in conjunction with the different visualization techniques implemented, hold great

promise as a heuristic device for architects, planners and designers operating within the city. By means of a relatively simple process of Instagram data recollection, this application is able to broaden contextual understanding of urban spaces, and provides a dynamic *technique* for mapping out our urban environments, not merely as a chart, but as a *plexus*.

The application is now in alpha state, and some of its current limitations include conceptual reductionism in calculations of proximity for certain dimensions, performance issues with large datasets (over 2 million connections), and control of asynchronous real-time data acquisition. Further graphic enhancement and different visualizations, such as additional text information and exporting video frames, are currently under development.

## Acknowledgements

We would like to thank first and foremost Panagiotis Michalatos, for his dedicated support whilst first developing this tool in his class *Introduction to Computational Design*, at the Harvard Graduate School of Design. He continues to inspire us, as architects, to broaden our horizons, and dive deep into unchartered intellectual territory.

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# IN(FLATABLE) MOD(ULI)

*Air-buoyant, form-resistant, temporary structures*

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**Abstract.** Conventional inflatable material systems offer a quick and reversible means of construction, however presenting limitations in terms of adaptability. Conventional, discrete, form-resistant structures feature stability through the complex organisation of discrete elements, however featuring inertias in terms of flexibility and diseconomies if applied to projects with a short lifespan. This paper discusses an alternative application of inflatable buoyant moduli to a discrete form-resistant structure in order to provide an adaptive installation for temporary events. Numerical and physical models are developed through a series of benchmarks, first, and a design project application eventually. The inherent predictability of this complex system is studied in terms of constructability, costs, flexibility and spatial quality.

**Keywords.** Inflatable; buoyant; form-finding; modular; structure.

## 1. Introduction

Conventional material systems for inflatables and discrete form-resistant structures are described in separate literatures and provide suitable design means for permanent structures, in the first case, and temporary structures in the second. A critical review of these two separate categories inspires the futuring (Fry, 2009) over a hybrid application that draws, on the one hand, from the structural principles of form-resistant structures and, on the other, from the temporary features of inflatables. Following Dunne and Raby (2013), this aims to envision an alternative design and construction approach which allows users to become makers in assembling temporary structures.

Digital computation links form-finding with inflatable modular technology through an adaptive system (Hensel, 2006); the inherent predictability of such a complex system is implemented, with numerical models, in the

Grasshopper parametric environment. Physical models are developed in order to, first, validate the numerical ones and, second, test the constructability, costs, flexibility and spatial quality of the built system. A series of benchmarks and a site-application show how different factors affect the relationship between structure, materiality and space generation.

### 1.1. INFLATABLES IN ARCHITECTURE

The first theoretical application of inflatable technology in architecture comes from the 1917 patent by Frederick W. Lanchester (1917) "An improved Construction of Tent for Field Hospitals, Depots and like purposes". Only after the 1930's however, with the introduction of PVC, PE and PTFE, applications became more consistent.

In 1946, Walter Bird prototyped and built, for the US Air Force, the "Radome": a sphere radar cover and also the world's first example of inflatable architecture. The economic appeal of this technology allowed Bird to successfully commercialise inflatable cover structures – mainly generated through analytical surfaces, such as spheres and cylinders, in order to carry out both representation and fabrication through well-known shapes.

With form-finding physical models Frei Otto (1962), Heinz Isler (1961) and Dante Bini (2014) pioneered more complex geometry-generation methods, inspiring the 1967 "First International Colloquium on Pneumatic Structures" in Stuttgart. Inflatable technology also inspired the 1968 exhibition "Structures Gonflables" held in Paris. Such an exhibition showcased, as part of the "Utopie" movement, the exploration of the ephemeral and changeable features of inflatable architecture which was in ideological contrast to the inertia and repression of traditional post-war architecture (Dessauce and York, 1999).

Inflatable architecture reached an apogee in the 1970's with Buckminster Fuller's utopian architectures and the Osaka Expo pneumatic pavilions – among which the Fuji Pavilion by Kawaguchi and Murata is worthy of mention. The design of this air-inflated ribbed structure came from bending a square surface onto a 50m-diameter circle. By creating an anticlastic geometry, gravity and wind loads were successfully counterbalanced by tension forces (Adrover, 2015). Inflated ribs and anticlastic surfaces also drove the design of the 2013 Peace Pavilion by Atelier Zündel Cristea. Compared to the Fuji pavilion, this project brought innovation to the design process through the blending of inflatable technology with parametric modelling and digital fabrication (www.zundelcristea.com: Nov 2015). Both projects featured a quick erection / dismantling process – hence offering the possibility of them being reused. However, no actual shape reconfiguration was possi-

ble due to the fact that membranes were pre-formed. This reveals an intrinsic limit of pre-formed inflatable membranes in adapting to different site conditions.

A more adaptive system was explored through generative modelling by the Aerial Assemblies test performed by the MIT's Self-Assembly Lab. Each modulus of a buoyant particle system is made of a helium-inflated weather balloon encased in a frame with a positive or a negative magnet located at each tip of the frame. With the magnets attracting and repelling one another, the moduli eventually aggregate into a flying spatial structure. As the helium dissipates and the balloons deflate, this self-assembled aggregate touches the ground (www.selfassemblylab.net/AerialAssemblies.php: Nov 2015).

Such a self-organising structure is generated through the balancing of emergent systemic forces (Ahlquist and Menges, 2012), showing an application of digital design that surpasses, in terms of flexibility, the framework of discrete rules such as the ones used in the Peace Pavilion. This system can provide a more flexible, automated response to multiple boundary conditions, overcoming imprecisions and diseconomies related to analogic man-made construction. Nevertheless, applications and literature on adaptive inflatable structures remains scarce, suggesting, on the one hand, more focused efforts on the development and role of digital tools and, on the other hand, the development and application of suitable construction technologies. These explorations can offer relevant outcomes especially to the rising category of users/makers and the field of temporary installations.

### 1.2. DISCRETE FORM-RESISTANT STRUCTURES

Physical form-finding bases geometry generation on systemic acting forces and material properties. After setting parameters such as model topology, supports and acting forces, the system reaches a "form-resistant" static equilibrium, where shape resists loads through membrane behaviour – a state in which mainly in-plane stress and reduced or no bending stress act (Burkhardt and Otto, 1978).

Tile/voussoir vaults are a sub-category of form-resistant structures. These vaults allow covering large areas without intermediate supports by aggregating discrete small elements. Despite a low resistance to traction, such structures achieve cohesion and bearing capacity by assuming a funicular-like shape;.this allows compression forces to be transmitted throughout the structure through the reverse catenary principle (Block and Ochsendorf, 2014). The Church of Colònia Güell and the Sagrada Familia by Antoni Gaudí are two examples of this tectonic system (Tomlow, 1989).

The design of discrete form-resistant structures is a fairly consolidated field. Shape is generally generated by means of either analytical surfaces or physical form finding; however, examples of freeform shapes are scarce. The lack of well-established, flexible, industrialised methods for processing voussoirs are among the reasons why the use of complex, freeform geometries can be justified primarily for high-budget, long-lifespan projects.

Technologies such as stereotomy or the "Tile Arch System" provide viable means of construction for vaults (Ochsendorf and Freeman, 2010). However, these require a high degree of precision for both design and preparation. Because such technologies require high inertias and low flexibility, adopting a different, more adaptive, technology would allow delivering a more flexible design-to-construction framework.

Inertias and inflexibility also contribute to the discontinuities that can often arise in form generation, materialisation and construction. Philippe Block's MLK Jr Park Stone Vault project (Block et al, 2013) addresses the issue by developing a seamless, digital design-to-construction process. Digital tools are used to inform the system's complexity, from form generation to custom elements preparation. Such a digital framework can be applied to the field of temporary / reconfigurable structures and be simplified through the use of standard / modular elements rather than custom ones.

## 2. In(flatable) Mod(uli)

Inflatable Moduli (InMod) addresses the aforementioned gaps in the field of inflatables and discrete form-resistant structures. The driving criteria of the design processes are: to create reconfigurable complexity through low-tech / low-cost construction technology; to provide the makers/users with a simple design-to-construction/dismantling process; to provide a self-supporting structure; to deliver a temporary stage for small/medium, open-air, seasonal events such as White Night Melbourne and the Moomba Festival that are often hosted along the Yarra River. Tools and strategies from computational design are applied and tested for the purpose.

Similar to traditional discrete form-resistant structures, InMod is made of mutually-supporting small discrete elements that resist loads mainly through compression. However, where traditional elements are often hard and gain cohesion primarily because of gravity, InMod's moduli are buoyant, soft and gain cohesion through two combined actions: the action of (compressed) helium lifting the balloons and the action of a (tensioned) mesh wire sack pressing against them. Referring to Motro (2003), this resembles the features of a self-equilibrating tensegrity system. The sack's upper and lower faces are pinned together, where necessary, to prevent the balloons from piling.

Whereas traditional voussoir structures require a precise, a-priori, form-generation/elements preparation, InMod works more interactively: the overall shape is governed, first, by the mesh sack's footprint and, secondly, from the arrangement of the inflatable moduli.

The mesh sack initially acts as a dynamic formwork during erection, and then as a structural element during the operational life of the structure. This technological solution reduces the time/cost/waste that the conventional use of timber formworks and scaffolds often involve. The systemic adaptive behaviour also avoids the risk of imprecisions often related to discrepancies between form-generation and materialization/construction. This way, every systemic configuration is form-resistant, and can be flexibly controlled by changing the mesh extension or moving/changing the ground-restrained control points. The overall system is simulated and tested through benchmarking and prototyping first, and then applied to a design phase.

## 2.1. BENCHMARKS

Benchmark models aim to tune the systemic settings of the initial concept – such as moduli arrangement, sizes and quantity.

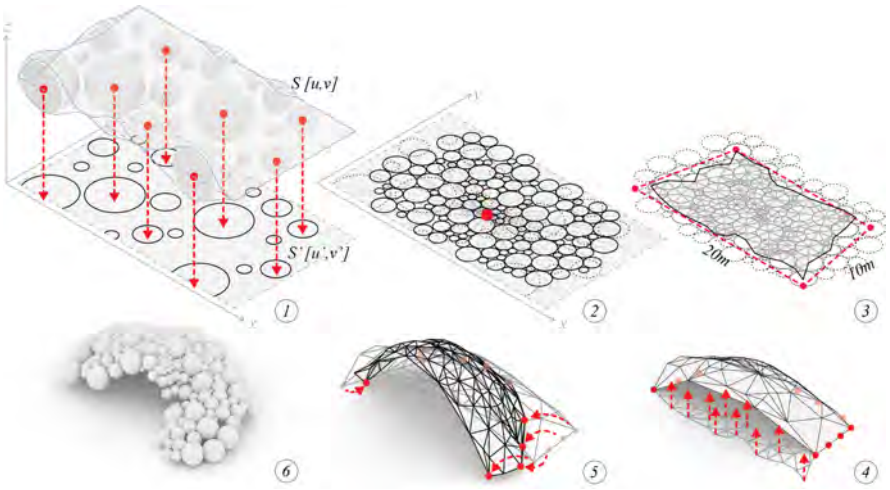



*Figure 1. Benchmark steps; step1: planar approximation S → S'; step2: CP (attractor point in red); step3: trapezoid control space and mesh; step4: DR (anchor points and applied loads in red); step5: post-forming process (control points in red), step6: final outcome*

A primary assumptions is that, since balloons are restrained between two mesh layers, the whole canopy can be approximated as the ideal surface that cuts each balloon in half – hence allowing representing the $\mathbb{R}^3$ system as a $\mathbb{R}^2$ surface *S* with a 3D-to-2.5D approximation. A further assumption is that

collision among moduli happens as a result of the combined action a centripetal force, by the mesh, and a vertical push, by helium. The overall system can thus be simulated as the sum of two separate sub-systems: a Circle Packing (CP) planar collision and a Dynamic Relaxation (DR).

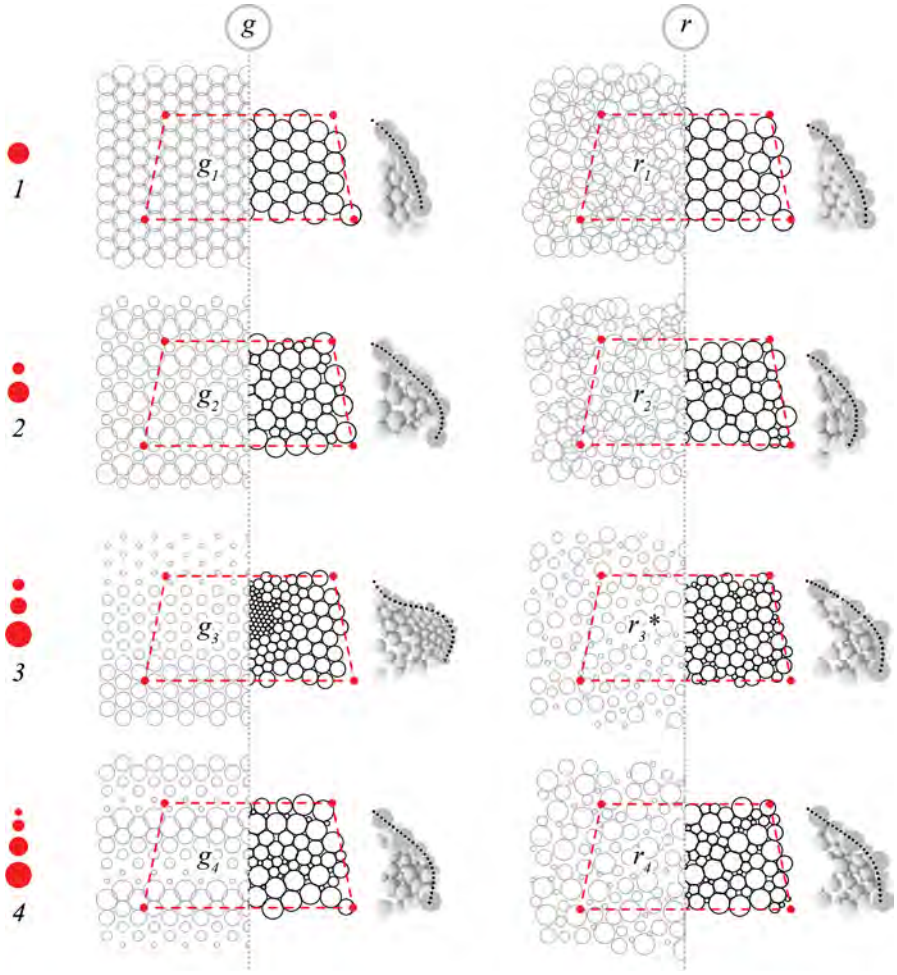



*Figure 2. Representative benchmarks showing: the 20m x 10m trapezoid reference-space in red; the starting layout on the left; the aggregated configuration on the right; the short middle section on the side. Left, column g: striped/patterned moduli arrangements over a hexagonal grid. Right, column r: random moduli arrangements over random grids. The initial layout doesn't visibly affect benchmarks $g_1$ and $r_1$. Interesting outcomes are provided by benchmarks $g_3$, $g_4$, $r_3$, $r_4$. *Benchmark $r_3$ is picked for further investigations.*

CP is implemented in the 2-D ground projections of the moduli (Figure 1, step 1). CP creates a combinatronic pattern of tangencies among the circles

and satisfies the geometric condition of contact with no overlapping (Collins and Stephenson, 2003). Figure 1, step 2 shows the CP implementation, in Grasshopper's plugin Kangaroo Physics, with a many-to-many collision; the collision attractor point is located at the centre of the system (Piker, 2013).

Once the circles are clustered, a 20m x 10m trapezoid control space is introduced. The circles within the control space only are picked and a virtual mesh is created by connecting their centres (Figure 1, step 3). Such a mesh is therefore transformed into an inextensible particle spring system in Kangaroo Physics. Figure 1, step 4 illustrates the preliminary settings for the Dynamic Relaxation algorithm (DR): setting the spring system's anchor points along the shorter base and the two sides; applying unary vertical loads at the springs' ends. DR is performed in Kangaroo (Kilian and Ochsendorf, 2005). Since springs are modelled as inextensible elements, the funicular outcome can be post-formed again to a desired height by moving the control points inwards or outwards (Figure 1, step 5).

Figure 2 shows some of the benchmarks developed from different boundary conditions such as: hexagonal / random starting grid; striped / patterned / random distribution; use of 1 / 2 / 3 / 4 moduli. Although a wide range of compelling solutions arise, benchmark $r_3$ only is picked for further developments since: first, fabrication is quicker when no specific pattern needs to be precisely followed – suggesting adopting a random initial distribution. Second, according to Majkut (2014), using similar-sized helium balloons can generate problems related to vibration/resonance – suggesting adopting two or more sizes of moduli in order to provide a good acoustic performance. The choice is further narrowed down by the range of latex balloons available on the market and by aesthetic considerations.

## 2.2. PROTOTYPING

After a preliminary series of draft models (Figure 3, top), a 1:5 prototype is developed on benchmark $r_3$ to prefigure its constructability and adaptability.

First, a 4m x 2m mesh sack is laid on the ground and restrained along the shorter base and the two sides. 40 latex balloons per each size are taken – respectively 10cm, 25cm and 40cm (Figure 3, top); a helium tank is used to inflate each balloon before placing it inside the mesh sack. According to the initial concept, a random scattering allows speedier construction while still providing visual complexity to the final outcome.

After filling the mesh, the upper and lower faces of it are pinched every 40-50cm; this keeps the centre of each modulus on the ideal surface used in the Grasshopper algorithm, preventing the balloons from piling up during DR and fostering an overall membrane behaviour (Figure 3, top).




*Figure 3. Top: Preliminary studies on the material system. Centre: time-lapse of preliminary, intermediate and final construction phases; the 3 balloons sizes: 10cm, 25cm and 40cm; the stretched canopy. Bottom: possible configurations; control points in red and white.*

Once the flat canopy is prepared, 9 anchor control points are set to control the post-forming process (Figure 3). By changing their position, multiple configurations are generated after the numerical simulations. Thanks to the

irregular distribution of different-sized balloons, both daytime and night-time light modulation is rather evocative (Figure 3, bottom).

Prototyping required two hours of unskilled labour and a budget under 200AU$, showing good replicability-adaptability to different site conditions while providing adequate structural and aesthetic performances.

The canopy's foldability and buoyancy allowed, on the one hand, easily and quickly relocating the structure around the site and, on the other hand, flattening / securing it to the ground to contrast severe weather conditions. Balloons preserved buoyancy for 3 days, proving InMod to be a viable solution for a temporary installation / a weekend event.

### 2.3. DESIGN

Design aims to further explore the extension and range of shapes InMod benchmark $r_3$ can achieve according to different site topographies (Figure 4). Form-finding is determined in each case according to the control points' position and the mesh shape; on the side of CP and DR, form generation is informed via the acoustic performance, analysed through a ray tracing simulation implemented in Grasshopper following Reinhardt (2012). Sound propagation is taken as a qualitative feedback from the structure, along with aesthetic and programmatic features.

Multiple design outcomes are achieved starting from a standard set of elements, showing how InMod can provide a flexible and elegant material system for temporary installation – especially if compared to other inflatable commercial products such as inflatable tents or bouncing castles, which need to be univocally, a-priori shaped and often appear massive.

## 3. Future developments

Future developments shall focus on implementing an aggregative system integrated directly in the moduli; this is likely to increase cost while, however, allowing transcending the fixed canopy configuration and enhancing the adaptive features of the system. A 1:1 model shall help to test further installation mechanism and construction details.

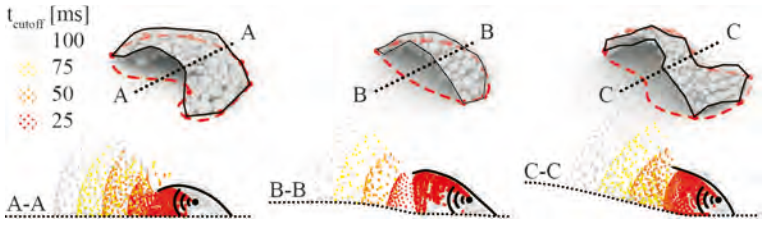



*Figure 4.Design-applications on a flat site (left), a gentle hill (centre), a steep slope (left). The sections show how the acoustic performance responds to the site topography.*

## 4. Conclusions

The work explores an integration of inflatable modular technology and form-resistant structures through the design and construction of a temporary stage. By focusing on the framework development rather than on the outcome, systemic variations are showcased and tested through numerical and physical models. InMod integrates adaptive principles in a modular system by combining digital computation and material; this offers an easy-to-construct, flexible, low-cost alternative to existing commercial inflatable products.

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# PROTOCOL OF ERROR

*The design and construction of a bending-active gridshell from natural bamboo*

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**Abstract.** This paper advocates alternative methods to overcome the impossibility of realising 'perfect' digital designs. It discusses Hong Kong's 2015 'ZCB Bamboo Pavilion' as a methodological case study for the design and construction of architecture from unprocessed natural bamboo. The paper critically evaluates protocols set up to deal with errors resulting from precise digital design systems merging with inconsistent natural resources and onsite craftsmanship. The paper starts with the geometric and tectonic description of the project, illustrating a complex and restrictive construction context. Bamboo's unique growth pattern, structural build-up and suitability as a bending-active material are discussed and Cantonese bamboo scaffolding craftsmanship is addressed as a starting point for the project. The paper covers protocols, construction drawings and assembly methods developed to allow for the incorporation and of large building tolerances and dimensional variation of bamboo. The final as-built 3d scanned structure is compared with the original digital model. The paper concludes by discussing the necessity of computational architectural design to proactively operate within a field of real-world indeterminacy, to focus on the development of protocols that deal with imperfections, and to redirect design from the virtual world towards the latent opportunities of the physical.

**Keywords.** Bamboo; bending-active gridshells; physics simulation; form-finding; indeterminacy.

## 1. Introduction

Bamboo is one of the most environmentally sustainable construction materials due to its fast rate of growth and material strength. Yet, bamboo is rarely

used in its natural form as a structural material for permanent architecture, and when used it is primarily applied in replacement of steel or wood rather than in ways tailored to its specific qualities. Its potential to be used for the construction of resource efficient form-active gridshell structures has yet to be exploited (Rockwood, 2015).



*Figure 1. 'ZCB Bamboo Pavilion' during an evening event: a light-weight bending-active bamboo gridshell covered with a glass-fibre-reinforced plastic polymer membrane.*

Natural bamboo has unique potential in its unprocessed form as a light-weight structural material with high elastic bendability. This is due to its typical cylindrical cellular build-up and strong longitudinal fibre structure. The 'ZCB Bamboo Pavilion' research project explores this latent property through the design and building of a large bending-active bamboo structure. The 'ZCB Bamboo Pavilion' is a four-story-high, thirty-seven metres spanning gridshell completed in Kowloon Bay, Hong Kong in October 2015 (Figure 1). It serves as a public event space for three hundred people and aims to promote innovative and ecological architecture. The structure combines traditional Cantonese bamboo scaffolding with digital design techniques for form-finding and construction documentation. It is built from unprocessed bamboo poles, hand tied together with metal wire following traditional scaffolding techniques, and is covered with a translucent glass fibre-reinforced polymer membrane.

The 'ZCB Bamboo Pavilion' research project overturns the conventional sequential design workflow of architectural projects by introducing a laboratory-based design & build approach. In this the roles of architects, engineers, consultants and contractors allow for an overall setup where feedback from all parties remained possible throughout the construction process. In order for the final construction to be feasible within the constraints of the site, protocols were put in place allowing material deviations, onsite inaccuracies, unpredictable material behaviour, and errors to be managed and included as

enablers rather than restrictors. This paper covers the final steps of the project and illustrates the simplifications of the construction process that were put in place to build this large architectural structure in a short time with minimal available onsite means or skills.

## 2. The indeterminacy of bamboo

### 2.1. EXPANDING CANTONESE BAMBOO SCAFFOLDING CRAFTSMANSHIP

Traditionally, Cantonese construction uses hand-tied natural bamboo as structural material for its scaffolding, temporary theatres, and temporary places for religious festivities). These structures are very adaptable in shape, dimension, and plan and rely on predetermined typologies, forms, and construction methods for their materialisation. Without need for architectural drawings they are designed and built onsite by licensed craftsmen who continue to sustain their century-old traditional methods.

The pavilion discussed here is part of a larger research ambition seeking methods for architectural innovation through the introduction of digital design tools into pre-existing construction methods. This specific project explores the potential of combining computational form-finding and construction documentation methods with Cantonese bamboo scaffolding craftsmanship.

### 2.2. BAMBOO

Bamboo is rarely used in construction as a structural material, partly due to its widely varying material properties when used in its natural form and to the lack of information on the structural strength of its connection methods.

Bamboo first grows up to 80% of its total height in the first month, after which its cell walls thicken by growing inwards (lignification phase) over a span of seven years or more without substantially changing its appearance. Bamboo gains its strength from a unique build-up of cylindrical interconnected cells separated by reinforcing diaphragms (Figure 2, left) and its longitudinal fibre structure. Each species has different material properties and the strength of each individual pole is further defined by the soil composition at its place of growth, climatic exposure, water availability, etc. Typically fresh cut bamboo has more flexibility due to a high water content.

The bamboo species Phyllostachys Edulis, also known as Moso Bamboo, or Mao Zhu (毛竹) was selected. This is a temperate species of giant timber bamboo native to China’s Guangdong province (Figure 2, right). Freshly cut, flexible bamboo aged between three and five years was used for this project.

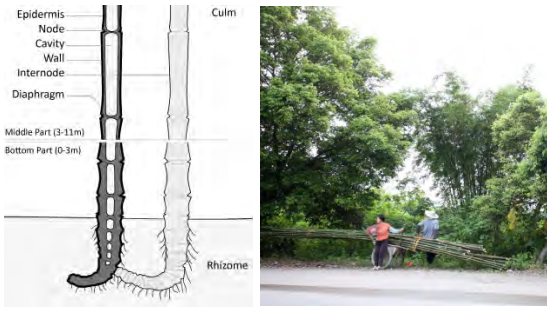



*Figure 2. Bamboo build-up (left); harvesting bamboo in Guangdong, China (right).*

Regulations on how to use this species of bamboo in a bending-activated structure was unavailable at the start of the project. The architectural and structural design therefore resorted to the rigorous use of physical and digital simulation models and prototypes to assess structural behaviour in the design phase and to define practical construction methods, detailing, and installation sequence (Figure 3).

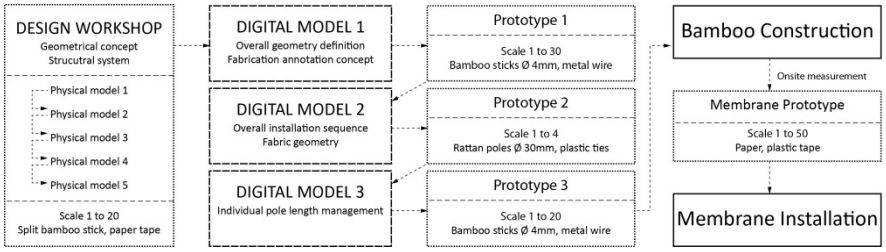



*Figure 3. Project design sequence through digital and physical prototyping.*

## 3. Geometry definition

Pioneering engineers like Frei Otto employed physical models, such as hanging chain models or soap films, as ‘physical computers’ to generate a structure’s optimal form for resisting specific design loads. The ‘ZCB Bamboo Pavilion’ follows this tradition, but incorporates digital real-time physics simulation engines in the workflow to define a suitable form for a bending-active gridshell.

The pavilion’s structure uses a hyperstatic hybrid system. This was the outcome of a series of 1 to 20 scale physical study models made from split bamboo that were seeking structural solutions appropriate to program and site. The structure consists of an extended triangulated diagrid that folds down onto itself to form three large hollow columns.

The digital design sequence was set up using Kangaroo as a computational form-finding tool. Kangaroo is a plug-in for Rhinoceros® and

Grasshopper® that uses particle systems in which interconnected networks of geometry control points respond to applied forces following laws of physics. The sequence started off from an intersecting planar curve network that was folded onto itself into the final geometry. This was primarily done by using two force types: Spring-From-Line forces, and Bending forces. The first applies an elastic spring force is between the end points of each curve segment aiming to maintain a specific rest-length. The second applies a bending force in between each curve's adjacent line segments aiming to straighten the curve. The resulting intersecting curve model was developed further to a non-intersecting axis model incorporating bamboo diameters and individual lengths of overlapping poles.

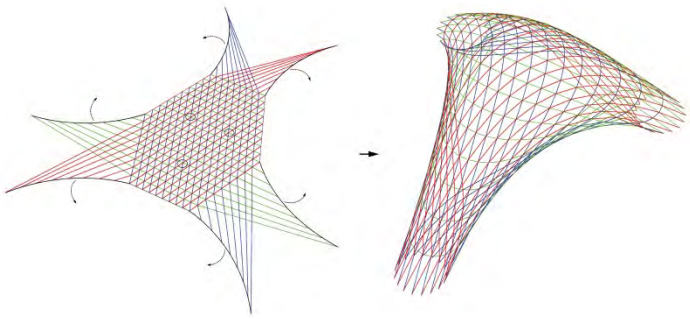


*Figure 4. Digital spring-particle physics simulation engine as form-finding tool.*

## 4. Protocols for indeterminacy

The construction was done by a local general contractor and a subcontracted bamboo scaffolding master. Neither had previous experience working with complex geometric configurations or bent bamboo. A construction system needed to be developed that was simple enough to bypass language and cultural barriers, and clever enough to incorporate the material variations of the bamboo poles and the construction tolerances of hand-tied connection knots. The system had to enable construction from temporary bamboo scaffolding without the use of architectural drawings.

### 4.1. HAND-TIES AND ONSITE COLD BENDING

Traditional hand-tied knots easily allow connecting poles of various dimensions. Cantonese scaffolding knots are made such that they allow tightening by winding the wires. These are locked in by sliding through the knot itself. As the poles do not have a constant diameter, but slightly narrow down in the middle of the internodes (Figure 2), the connecting of poles away from the nodes prevents them from sliding. As traditional knots are not fireproof

they were replaced with bundles of 0.7mm diameter metal wire (Figure 7, left).

The individual poles, with lengths of up to 7.2m and diameters of 80mm to 120mm, are very difficult to bend. Interconnected, however, the curves can be more easily shaped. To prepare for this shaping, base anchor points needed to be prepared and curve intersection points needed to be marked up.

## 4.2. BAMBOO PREPARATION

A practical labelling system was set up to mark the curve intersection points onto each pole. By matching corresponding labels onsite an installation system became possible where the structure could independently and gradually ‘find’ its form as all poles gently pushed back to the imposed curvature, aiming to straighten out.

To prepare the bamboo, all poles were cleaned, sorted according to material properties, and cut to length following a spreadsheet with information extracted from the digital model. Individual poles were tied together and labelled (Figure 7, middle). A sticker with all node intersection and pole information was placed at the correct distance (Figure 6).

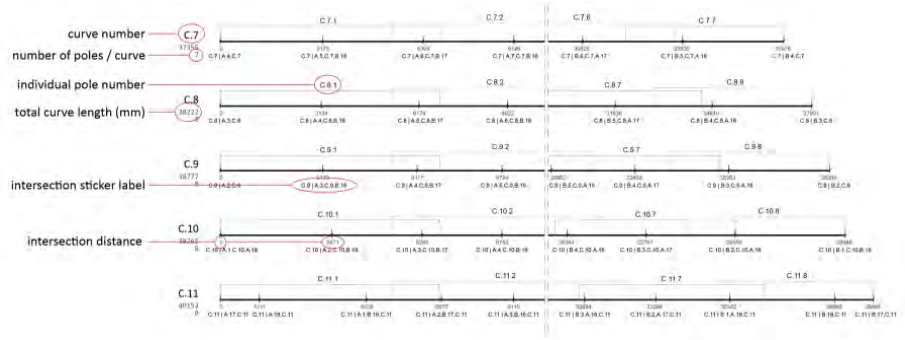



*Figure 5. Bamboo pole annotation drawings.*

## 4.3. FOUNDATION DRAWINGS

In parallel to the bamboo preparation, concrete foundations were cast. Bamboo poles are locked in place by anchoring them into a stone foundation plinth and casting protruding starter bars into the bamboo pole cavity.

Three 5.4m diameter, 500mm high concrete foundations were cast. The fifty-four starter bars were then bent into the correct angle using a hollow steel pipe and reference triangles cut from paper (Figure 6, left). PVC drainage pipes were hand-cut to angles, and used to cast the smaller foundation plinths for each pole (Figure 6, middle). Upon installation each pole was first

placed over its rebar. Once tied into place, non-shrink grout was poured into the poles through a small hole drilled above the rebar until the entire lower section was filled. The irregular interior section of bamboo (Figure 2) inhibits its sliding off. For safety additional metal clamps were added to prevent separation in case of bamboo cracking.



*Figure 6. Foundation connection: manual bending of rebar to correct angle using a steel pipe and a reference hand-cut paper triangle (left); individual pole foundation plinths cast into hand-cut PVC drainage pipes (middle); positioning of bamboo over rebar (right)*

## 4.4. BAMBOO INSTALLATION

The installation of interconnected bamboo poles started by lifting them onto scaffolding in two to three parts. End segments were placed over the starter bars (Figure 6, right) and corresponding intersection points were brought together (Figure 7, right). Key preliminary points were projected on the ground to give a 2D reference location. Subsequent nodes found their own position automatically as each pole tried to straighten itself out. A precise installation sequence had been set up that guaranteed the distribution of the poles into three layers. This prevented the localised tight bending radii weaving would require, and gave the pavilion its distinct striated look where certain directions can be seen pushing through the taut membrane.




*Figure 7. Bamboo pole connection: fireproof metal wire is used instead of polymer (left); sticker labels containing all connection information are applied using a measuring tape (middle); onsite installation by connecting corresponding labels (right).*

### 4.5. Membrane

The ‘ZCB Bamboo Pavilion’ was covered with a tailor-made, waterproof, non-elastic, translucent, glass-fibre reinforced composite tension membrane. Its fabrication required onsite measurement of the as-built pavilion. This could not be done through 3D scanning as the complexity of the scaffolding underneath would make it impossible to isolate the structure. A manual method was developed where workers used a cloud-based spreadsheet in which each triangle edge length was fed after measuring them by hand. From these edge lengths triangles were cut from fabric using a computer controlled cutting table. The triangles were welded into long strips (Figure 8) that were then welded together into one giant ‘sock’. This ‘sock’ was then manually fixed to the bamboo structure.

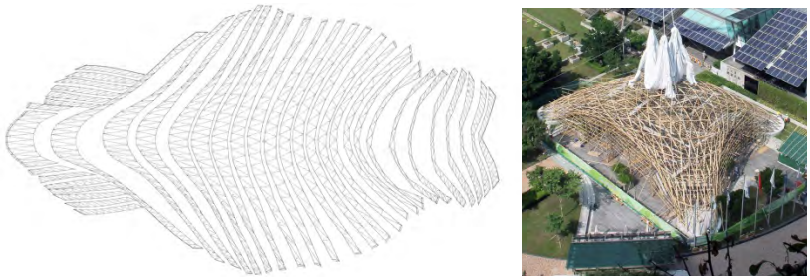


*Figure 8. Hand-measured fabric CNC-cutting pattern (left); installation of prefabricated fabric ‘sock’ onto bamboo sub-structure (right)*

## 5. As-built

The bamboo structure was erected in less than two months, and its membrane matched the structure closely. The capabilities of the bamboo poles to bend were slightly overestimated and the five poles with the tightest curvature had to be locally notched to allow for adequate bending. All other interconnected poles worked together to find the final form. Combined, the bamboo structure and membrane weigh roughly 7.25 tonnes, a fraction of the 101 tonnes of the concrete foundations and less than twice the weight of the 3,400m$^3$ of air the pavilion contains.

The cumulative impact of changing material properties, geometry deviations, surface deflections and construction inaccuracies, resulted in a structure that matched the digital ambition. A 3D scan shows how closely the as-built structure approximates the digital models (Figure 9). The largest deviations occur in areas where curvature is minimal for two of the three members. Here the third direction seems incapable of preventing the other two from straightening out more, resulting in a slight flattening of the area. This

unforeseen behaviour does not seem to affect the overall structural integrity as the overall synclastic nature of the geometry was maintained.

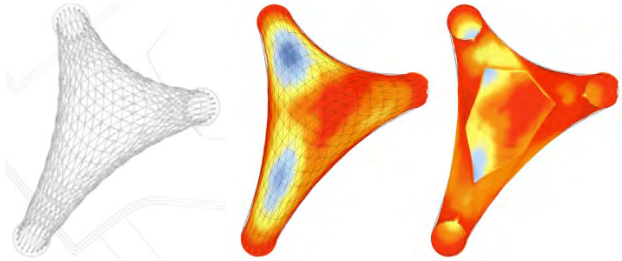


*Figure 9. As-built bamboo structure (left); 3D scanned vs. originally designed: red ≤ 50mm deviation, blue ≥ 1000mm deviation; Top view (middle); bottom view (right).*

## 6. Conclusion

In a country notorious for building speed and construction quality it is vital to question how to overcome the methodological mismatch of aiming to materialise idealised digital designs. Design priorities must be redirected from the ideal virtual realm to the latent opportunities of the physical world.

The 'ZCB Bamboo Pavilion' illustrates the complex dynamics of Hong Kong's bamboo construction industry as it surpassed traditional, technical, cultural, and architectural boundaries. The role of the architect was expanded to that of a facilitator. Computation was strategically used to program building information, simulate behaviour, and orchestrate resources. Indeterminacies were incorporated to allow for straightforward construction.

The 'ZCB Bamboo Pavilion' showcases how a constructive dialogue with traditional construction systems allows for experimental prototypes to be possible. By merging both worlds' methods and processes, alternative and ecologically sustainable futures become possible.

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CONSTRUCTION TEAM: MAIN CONTRACTOR: W.M. Construction Ltd.; BAMBOO CONSTRUCTION: Sun Hip Scaffolding Eng. Co., Ltd.; FABRIC CONTRACTOR: Ladden Engineering Ltd.; LIGHTING: CONA Technology Co. Ltd. & Brandston Partnership Inc.

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# ADAPTIVE DECORATIVE BUILDING SKIN

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**Abstract.** Traditional decorative ornaments were commonly used on the building skin of traditional architecture. Nowadays in urban areas, those ornaments become less popular for they are considered old-fashioned and due to the lack of technical function that matches with the modern building designs. Based on those issue, this paper proposed a type of building skin that aimed to revive a new expression of traditional decorative elements by applying digital design tools and technology as well as having an adaptive function. Traditional decorative ornaments merged in an adaptive skin that used traditional patterns as a controller of the effect of environmental changes in a building could provide a new expression of the use of traditional ornaments on a building in accordance with the times. Most of the adaptive building skin used kinetic techniques in order to make its formation and pattern transformable. This paper proposed a parametric-cam mechanism to transform the pattern of traditional ornament using pre-programmed analysis data of environmental changes to parametrically drive the number of rotation phase and length of nose that generated the shape of the cams. In conclusion, this paper has developed a prototypical tool that facilitates the new approach to kinetic decorative ornaments on building skin.

**Keywords.** Decorative ornaments; adaptive building skin; camshaft mechanism; kinetic building; building technology.

## 1. Introduction

Several national strategic areas that require intensive research to undertake various challenges of the nation have been declared (Tri, 2012). One of the areas is on arts and culture, creative industry, and culture technology. The strategic issue stated was the lack of development based on local wisdom and uniqueness, for example the lack of local specialty or expressiveness. Based on those issue this paper proposed a type of building skin that aims to

revive a new expression of traditional decorative elements by applying digital technology as well as having an adaptive function. Traditional decorative ornaments merged in an adaptive skin that uses traditional patterns as a controller of the effect of environmental changes in a building may provide a new expression of the use of traditional ornaments on a building in accordance with the times.

In most of the time within a year, the sky illuminance in the tropical climate is extremely high (>10.000 lux), therefore one of the function of building skin in traditional housing are used to control the lighting levels. Correspondingly, building skin is also used to express symbolical ornament or aesthetical preferences. Consequently, the ideal standard of visual comfort in most cases could not be achieved. Most of the daylight levels in traditional housing are below the standard of visual comfort.

With the use of adaptive building skin that could maintain the visual comfort. The nature of the adaptive building skin is that it can adapt to changing environmental conditions such as the changing sun path. Changes in the movement of sun per day and per year resulting in daylight levels received at any part of the grid surface of the building to be always changing. By applying an adaptive building skin solutions that specifically follows the changes in every part of the surface will be able to maintain the standard of visual comfort.

In order for every part of adaptive building to be able to move, large numbers of motors, sensors, and drivers are used. In order to operate that equipment requires electrical energy. Even with the use of photovoltaic, high costs will be required to produce such a device. Furthermore, mechatronics equipment, especially motors, has limited period of use, therefore the cost for maintenance and replacement of equipment will contribute to the high expenditure, and this will result in the overall energy inefficiency and the level of sustainability to be achieved can be very low.

Mostly, the applications of adaptive building skin are applied on high profile projects or expensive buildings and rarely on common housing. Therefore, this study also proposed a system that could reduce the kinetic mechanism problems of the above issues in order to lower production costs, save energy consumption of the appliance and maintenance by applying parametric camshaft methods. By using this method the amount of motor usage at each grid could be reduced and make it more centralized, this method could also reduce the number of motor drivers, and replace the use of sensors with environmental analysis data values.

## 2. Related research

There has been a growing interest to include intelligence in buildings to be energy efficient. Smart architectural design decision or intelligent technological devices can do this. Their defined active features are elements of buildings, which can self-adjust to the changes initiated by external environment (Ochoa and Capeluto, 2008). By actuating the facades and making them dynamic, they can now better adapt to the conditions and provide for improved comfort of the occupants. Facades can now sense the environment and make their own modifications in order to achieve prescribed goals. The building can be constantly working towards a better environment for the user as opposed to simply protecting them from it (Hansanuwat, 2010). By studying the many existing kinetic building skin systems and through the use of computer simulations and empirical testing, a sampling of the methods of kinetic movement can be analysed for their environmental benefits, compared to each other, and recommendations proposed (Skavara, 2009). Parametric design method can effectively make the building modelling and its configuration connected to the real world climatic parameters, and facilitates the study of building sustainability related to energy efficiency and it also offers an important way to explore the kinetic building components (Wang and Li, 2010).

The above researches have described that the mainstream drivers for adaptive and kinetic building components are sustainability and energy efficiency, however the adaptation of high-tech envelopes has been slow, sceptical architects foresee them being unplugged and later stripped off their building due to poor performance, broken actuators or deficient maintenance, plainly the road to the interactive envelope is a rough one (Sullivan, 2006).

These studies and literatures of kinetic and adaptive building issues present our research with the practical and sustainable insight into how to explore and manage the building envelope behaviours to the environment. The originality of this paper is to develop new system for adaptive skin to be more energy efficient and more widely used, in order to increase the number of green buildings.

## 3. Methods

Daylighting simulation at a specific location has been conducted to produce the values that will set the parameters of the adaptive skin. Location setting was in Jakarta, Indonesia (6.16 S, 106.48W), and the weather data was taken from 2010. Climatic condition at this location is tropical. Weather changes in a year is not too drastic, therefore this study will focused on the controlling of changes per hour in 1 day. The analysis data were taken on March 21, June 21, September 23, and December 22, on 09:00 AM 12:00, 15:00.

The study was conducted as follows, firstly this study focused on adaptive skin that was conducted by analysing daylight levels to find the appropriate opening angle and obtain effective visual comfort requirements. Furthermore, the analysis result of adaptive skin study was used to generate kinetic mechanism using parametric camshaft method (Sjarifudin, 2012).

Since the location was on the southern hemisphere, the building orientation for this study would focus on the South, Southwest, Southeast, and North side. The next study was to determine the model of room and shading device. The room model was set to the average housing dimension (width: 6m, length: 9m, height: 3m). The dimension of shading device was set to fit the unit facade (3x (2m x 3m)), and the fin was: 2m x 50cm. The daylight level was measured at the height of the working plane, in this study was set at the height of 60cm, and the depth of 450cm.

The study of adaptive skin was initially conducted by comparing facade without any shading, and with vertical / horizontal types of shading, the result of the simulation showed that the use of shading on a unit could lower the intensity of light coming into the room and the use of horizontal shading could reduce the intensity of light coming into the room higher than vertical shading. Figure 1 shows the comparison of daylight simulation using vertical and horizontal shading.

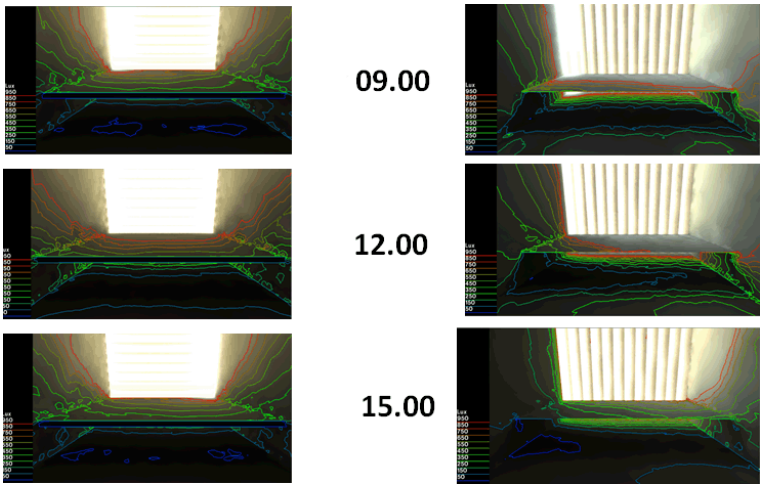



*Figure 1. Vertical and Horizontal shading comparison*

Following study was conducted to find the suitable shading angle for South, Southwest, Southeast, and North orientation of the units. Table 1 showed required daylighting levels on each time and building orientation, from the effect of different shading angles.

Table 1. Daylighting level on each orientation unit

| daylighting levels on 1st floor | | | | | | | |
|---|---|---|---|---|---|---|---|
| DL Standar | Building Orientation | Daylighting levels on desk height | | | | | |
| | | 09.00 | | 12.00 | | 15.00 | |
| | | Lux | *Shading Angle* | Lux | *Shading Angle* | Lux | *Shading Angle* |
| 750 Lux | South | 450 - 950 | 15° | 450 - 950 | 30° | 450 - 950 | 15° |
| | Southwest | 450 - 950 | 15°' | 450 - 950 | 30° | 550 - 950 | 45° |
| | Southeast | 550 - 950 | 45° | 450 - 950 | 30° | 450 - 950 | 15°' |
| | North | 450 - 950 | 15° | 450 - 950 | 30° | 450 - 950 | 15° |
| 600 Lux | South | 350 - 850 | 30° | 250 - 950 | 45° | 350 - 850 | 30° |
| | Southwest | 350 - 950 | 15° | 350 - 950 | 45° | 250 - 950 | 60° |
| | Southeast | 250 -950 | 60° | 350 - 950 | 45° | 350 - 950 | 15° |
| | North | 350 - 850 | 30° | 250 - 950 | 45° | 350 - 850 | 30° |
| 500 Lux | South | 250 - 750 | 45° | 350 - 750 | 60° | 250 - 650 | 45° |
| | Southwest | 250 - 750 | 30° | 250 - 750 | 60° | 250 - 750 | 60° & 75° |
| | Southeast | 350 - 650 | 60° & 75°' | 350 - 750 | 60° | 350 - 650 | 30° |
| | North | 250 - 750 | 45° | 350 - 750 | 60° | 250 - 650 | 45° |
| 350 Lux | South | 150 - 450 | 60° | 150 -550 | 60° & 75° | 150 - 550 | 60° |
| | Southwest | 150 - 650 | 45° | 150 - 650 | 60° & 75° | 150 - 650 | 60° & 75° |
| | Southeast | 150 - 650 | 60° & 75° | 150 - 650 | 60° & 75° | 150 - 650 | 45° |
| | North | 150 - 450 | 60° | 150 -550 | 60° & 75° | 150 - 550 | 60° |

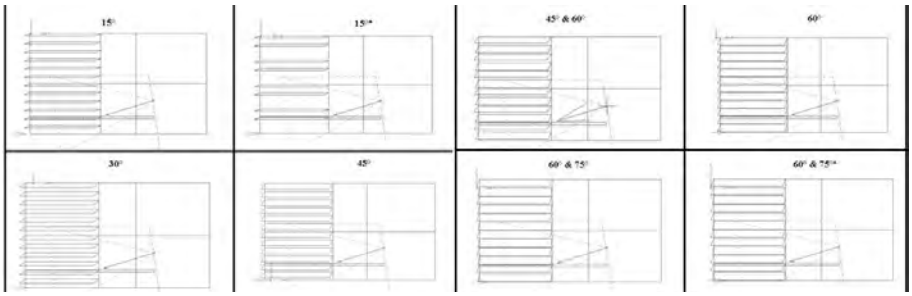
From the daylight level analysis at the time of building units facing South, Southwest, Southeast, and North before using shading was 950 lux but using shading could reduce the level of daylighting. Angles were used in this study to meet the standards requirements from 350 to 750 lux.

On 12:00 AM Building facing South and North should use an opening angle of 300. When using angles smaller than 300 the daylight level in the room could exceed the standard requirement.

On 3:00 PM Building facing southwest should use an opening angle of 450. When using angles smaller than 450 the daylight level in the room could exceed the standard requirement.

On 9:00 AM Building facing Southwest should use an opening angle of 450. When using angles smaller than 450 the daylight level in the room could exceed the standard requirement.

Table 2. Shading angle formation types



Furthermore, detailed analysis on the shading device formation changes of its fins was conducted and 8 different shading (fin) formation was found. Table 2 showed these formation would be used accordingly to adapt to the changing daylight condition throughout the day. Based on these formations, further study on the mechanism was conducted in order to develop simplified model of the adaptive shading using parametric camshaft method.

## 4 Parametric camshaft study

### 4.1. CAMSHAFT VS PARAMETRIC CAMSHAFT

This study used camshaft as a mechanism for controlling kinetic movements of adaptive skin system. Camshaft is a shaft to which a cam is fastened or of which forms an integral part, where a cam is a rotating piece in a mechanical linkage used specially in transforming rotary motion into linear motion. The integral parts of a cam are Base circle, Nose, Lobe lift, and Duration (Figure 2). These parts are used in this study as the modules in generating parametric camshaft.

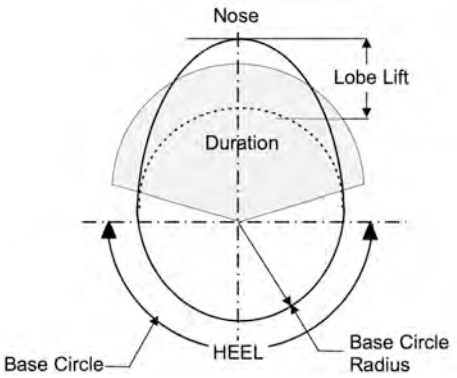



*Figure 2. Cam profile used on a car engine.*

## 4.2 PARAMETRIC CAMSHAFT

What distinguish the parametric camshaft in this study are the use of multiple Nose and Lobe lift on each cam. This will result in a non-linear movement and changes. The cam will control the size of the openings of each fin of the shading system.

The main parameters in the parametric camshaft are the length of Lobe lift (L) and the number of Duration (P). Each L and P has different values, and the values are determined from the result of shading angle study. Figure 3 shows the profile of parametric cam and non-linear movements it can generate.

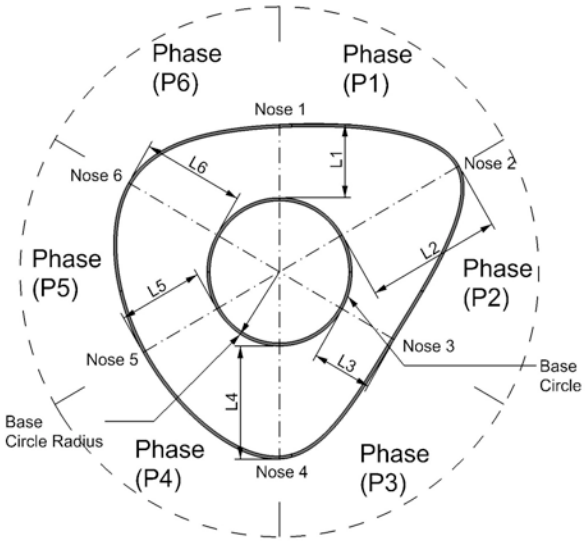



*Figure 3. Parametric Cam profile applied in each fin of adaptive shading system.*

The result of angle study was used to generate shape of parametric camshaft. The smallest angle was 150 and the biggest was 750, these values were then used as a parameter determining the minimum and maximum length of L and the number of P. To be able to produce the calculations and parameter settings, this research used algorithmic editor software Grasshopper which is a plug-in for CAD software Rhinoceros. Figure 4 shows the screenshot of the parametric relationship made in Grasshopper.

The algorithm made for controlling the fin was: The smaller shading angle would produce a small value of L that led to a mechanism to close the fin, while the higher shading angle would produce a large value of L that led to a mechanism to rotate the fin.

Then, the significant number of changes in daylight level would be used as a determinant of the number of P in a single cam. In this case significant changes in the value of radiation on one shading unit were 5 times, therefore the number of P=5 Figure 3 showed variation of L and number P in each cam.

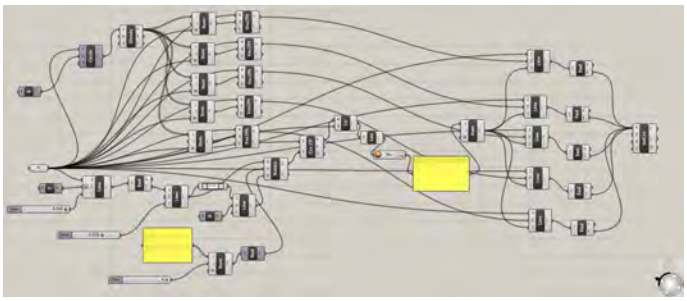


*Figure 4. Parametric control and component relationship in Grasshopper.*

Furthermore, the incorporation of cam rotation with specific shapes and driver mechanism would result in angular movements that varied according to the length of L and the number of P.

Furthermore, a motor would drive the operation of each camshaft. Each camshaft would be driven by a servo motor that rotated according to the number of P. Full turn (360°) would be divided by the number of P that operated for 12 hours, then off for 12 hours. These settings were done in the microcontroller that collected input data from Grasshopper (Figure 4) with Firefly plug-in that connected the data from Grasshopper to microcontroller to drive the servomotor. Figure 5 showed fundamental prototype development of parametric camshaft.

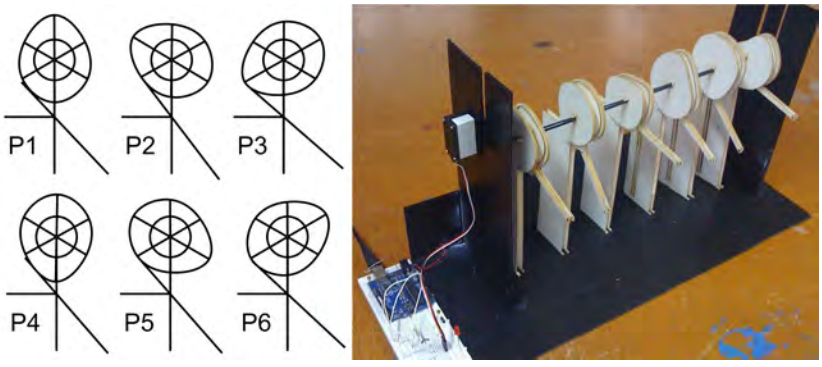



*Figure 5. Cam rotation movement with 6 changing phases (left), and simplified prototype of parametric camshaft (right).*

Finally, the whole shading each with own specific camshaft were applied to the fins of the adaptive skin. For one day the surface of this shading system would constantly change to follow the daylight changes.

These fins would be moved to reveal different patterns and inherently creates an interval of closed surface to opened surface that controls the effects of adaptivity. The amount of opening was determined from the length of L of the cam that has been adapted from the traditional pattern (Figure 6).

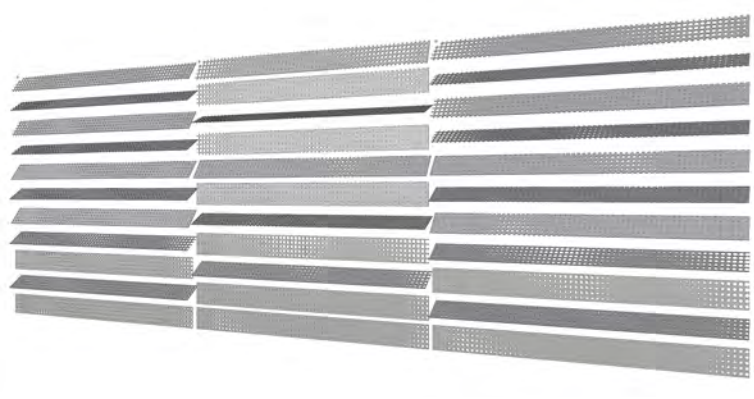


*Figure 6. The openings from adaptive skin*

## 5. Conclusion

This research has shown the use of parametric camshaft for controlling kinetic mechanism in adaptive building skin system. The affectivity of this system was observed more enduring in two-season climatic conditions whereas not many changes in environmental conditions occurred during the whole year. For example, if the buildings in the tropical countries used adaptive building skin system designed for four-season climatic conditions, there would be much dissipation, and the efficiency and benefits that could be obtained at the four-seasons countries would not be as much compared with the amount of energy required for operation of the system. In terms of cost-reduction, the application of this system on general buildings (non-high profile building) could be applied, so that more users could experience the benefits and advantages of adaptive building skin system.

Further research will be focused on the application of materials and assembly. The aim of research is finding the effective materials in terms of durability, cost, methods of easy assembly and maintenance. Other plans for further research is to build a physical prototype with 1:1 scale. This prototype will be tested on the actual environmental conditions to conduct some adjustments and other findings that could improve the efficiency and effec-

tiveness of this system. The main targets for these researches are to achieve higher level of sustainability and energy efficiency of an adaptive building component that can also express traditional decorative ornaments.

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# THE STG PATTERN

*Application of a "Semantic-Topological-Geometric" information conversion pattern to knowledge modelling in architectural conceptual design*

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**Abstract.** Generative modelling tools have become a popular means of composing algorithms to generate complex building forms at the conceptual design stage. However, composing algorithms in order to meet the requirements of general design criteria, and communicating those criteria with other disciplines by means of generative algorithms still faces technical challenges. This paper proposes the use of a "Semantic-Topological-Geometric (STG)" pattern to guide architects in composing algorithms for representing, modelling, and validating design knowledge and criteria. The STG pattern aims to help architects for converting semantic information concerning the situations of a project into design criteria, which are usually composed of topological relations among design elements, in order to explore the geometric properties of building components by means of generated 3D models.

**Keywords.** Generative modelling; design criteria; design pattern; semantic ontology; BIM.

## 1. Introduction

Generative modeling tools like Grasshopper have become a popular means of composing algorithms for generating complex building forms, optimizing multiple design objectives, and structural and sustainability control (Yu et al, 2015) at the conceptual design stage. The visual programming interfaces of Grasshopper are easier to learn and understand than textual programming tools. With the help of immediate feedback of visualized 3D models in Rhino, generative modeling tools allow architects to freely explore creative ideas expressing geometric intentions. Except the constructability issues involv-

ing complex geometry, however, one of the major issues affecting application of generative modeling is how to associate generative algorithms with known design criteria in order to evaluate whether the generated forms are acceptable or not. How to compose algorithms in order to meet the requirements of design criteria, and how to communicate those criteria and algorithms with other disciplines still faces many technical challenges.

The Alexander's "Pattern Language" concluded the good practices of endemic buildings that serve as a paradigm for acquiring the knowledge to solve common problems (Alexander et al, 1977). However, while few architects actually employ Alexander's language, more software engineers apply "design patterns" in identifying and reusing the best practices in known situations. In the software engineering domain, "design patterns" do not determine the final design of software, but instead specify methodologies for solving commonly occurring problems within a given context. Some design patterns have been accepted as best practices, such as the model-view-controller (MVC) pattern based on object-oriented programming. With generative modelling and parametric design becoming more popular and important in architectural design, how to translate design criteria into algorithms has become a widespread problem when applying generative modelling tools. However, there is still no pattern to guide architects in composing algorithms to implement their design criteria.

## 2. Computational patterns of digital architectural design

With the widespread penetration of digital tools into almost all areas of architectural design, including both education and practice, digital tool application skills and knowledge have become more important than in the past. To apply generative modelling tools such as Grasshopper, a designer needs more knowledge of mathematics and data processing than basic architecture knowledge and aesthetics skills (Woodbury, 2010). However, the need for additional skill and knowledge causes the results of parametric design to be disconnected from architectural contexts, such as material, user, and usage requirements, and causes designers to expend more effort on programming/scripting of algorithms than on architectural design (Yu et al, 2015).

Cognitive studies have revealed that parametric design mainly supports designers' geometric intentions (Yu et al, 2015). Beyond geometric intentions, designers tend to select existing solutions instead of developing new solutions for known problems, which meets the ideas of Alexander's pattern (Yu and Gero, 2015). Obviously, generative algorithms should potentially be able to go beyond geometric intentions (Terzidis, 2006). For example, the use of generative algorithms in optimization of spatial planning (Bazalo and

Moleta, 2015) and building performance (Chang and Shih, 2014) during early design stages has been explored. Although those attempts had implemented existing algorithms for specific design issues, such as spatial syntax for space planning, and genetic algorithms for optimizing multiple objectives concerning building performance, the results demonstrated potential application to more design criteria than just novel geometric intentions.

While the impact of generative modelling and parametric design on thinking and methodology during the early design stages, BIM have been used to improve workflow during the later design stages. Since users can manipulate more semantic and topological information of building components than 2D CAD and 3D models, BIM applications provide a convenient platform for visually communicating with different disciplines, especially concerning the mechanical, electrical, and plumbing (MEP) engineering of a project. Based on the design information schema of BIM, which consist of semantic, topological, and geometric information, and referring to the MVC pattern in software engineering, therefore this paper proposes an algorithmic design pattern based on a "semantic-topological-geometric (STG)" framework (Lin, 2015), and this pattern aims to enable designers compose algorithms for modelling general design criteria at the early design stages.

## 2.1. SEMANTIC ONTOLOGY AS INFORMATION MODELS OF DESIGN CRITERIA

The first component of the STG pattern is "Semantic Ontology," which consists of a semantic information model of design criteria. In a MVC-based system, a "model" module is used to capture behaviour and rules in the problem domain. To associate generative modelling with design criteria, it must first represent design criteria in a computable format. In early design stages, architectural design criteria are usually abstract and textual descriptions of various requirements. In order to represent semantic criteria into a computable format, semantic ontology was incorporated into the STG pattern.

Protégé is one of popular tools for encoding domain knowledge of AI. Protégé is based on the Ontology Web Language (OWL), which is an XML-based language, and was originally used to develop semantic networks. Based on the semantic web rule language (SWRL), which can used to express rules as well as logic, the logic reasoner in Protégé can validate and infer implicit knowledge within an ontology. If architectural design criteria can be expressed in OWL, then a SWRL reasoner can help architects and stakeholders of a building project to validate criteria, infer implicit criteria, and keep those criteria consistent throughout the design process.

For example, because an enclosed and quiet space may make children nervous, the Japanese architect Tezuka asserted that the classrooms in a good kindergarten should not have boundaries between inside/outside (Tezuka, 2014). Tezuka therefore designed the "Fuji Kindergarten," an award-winning kindergarten in Tokyo, which is without walls, and enclosed only by sliding patio doors (Figure 1). In this context, design criteria may be presented as a simplified set of semantic ontologies as follows: (1) "Classroom" with the "hasBoundary" property will prompt the inference of a "NotGoodClassroom" and "FeelNervous" property, (2) "Classroom" with "hasNoBoundary" property will prompt the inference of a "GoodClassroom" and "FeelRelaxed" property, (3) "Wall" is a kind of "Boundary," and (4) "Roof," "Floor," and "PatioDoor" with the "CanFullyBeOpened" property are not a kind of "Boundary." Although this ontology cannot directly generate a result of "GoodClassroom," the logic reasoner can infer that an instance of "Classroom" without "Wall" but enclosed by "PatioDoor" with "CanFullyBeOpened" property is an instance of "GoodClassroom."



*Figure 1. The classrooms of the Fuji Kindergarten designed by Takaharu Tezuka: (a) the classrooms are enclosed by patio doors but without walls (left), and (b) the patio doors can be fully opened to remove the boundaries of classrooms (right) (OpenBuildings, 2014).*

## 2.2. TOPOLOGICAL RELATIONS AS CONTROLLING ALGORITHMS OF DESIGN CRITERIA

The second component of the STG pattern is the "Topological Relation," which is a controlling algorithm for design criteria. Eastman declared that topologies are the fundamental definitions of parametric models in BIM (Eastman et al, 2011). In an early design stage, the topological relations of design criteria are usually abstract, and may consist of enclosure, extension, and concentration of indoor/outdoor spaces and building masses (Ho and Wang, 2009). Except for some geometric rules, such as the constraints in Autodesk Revit, abstract topologies for early design stages are absent from most BIM applications, however.

In an MVC-based system, a "Controller" module is used to accept operations from users to modify the data of models. "Controller" can therefore

control the interactive behaviour among different "models" in a system. Topological relations among design criteria can thus be regarded as the "Controller" of design criteria. In the case of the "Fuji Kindergarten," for example, the architect's design concept was that all "Classrooms" must be "Connective" and "Enclose" the "Playground," but "Avoid" existing "Trees" (Figure 2). The topological relations, such as "Connective," "Enclose," and "Avoid" relative to the "Classroom," "Playground," and "Tree," become the "Topological" components in a STG pattern waiting for implementation.

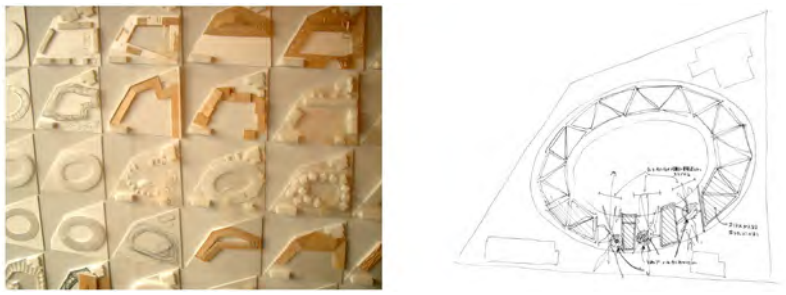


*Figure 2. The topological concepts of the Fuji Kindergarten: (a) conceptual models for exploring the similar concepts of topological relations (left), and (b) a diagram of the design criterion for avoiding existing trees in the site (right) (OpenBuildings, 2014).*

## 2.3. GEOMETRIC FEATURES AS VALIDATING VIEWS OF DESIGN CRITERIA

The final component of the STG pattern is the "Geometric Feature," which can validate geometric views of design criteria. In an MVC-based system, a "View" module is used to display a retrieved "Model" and the results of "Controller." In architectural design, architects always need visual feedback to validate the semantic ontologies or computing behaviours of algorithms. Immediate visual feedback of generative algorithms is one of the most attractive features of Grasshopper for designers. The visual validation of other design criteria, rather than geometric intentions, is usually ignored, especially in the case of those that are invisible or non-obvious.

In the case of the "Fuji Kindergarten," for example, the concept of building form consists of a simple circle around the playground. However, the architect must carefully arrange the geometric features of the roof into two ellipses in order to fit the irregular shape of the available land within the site, and avoid existing trees and buildings (Figure 3.a). Even though there may be some controlling algorithms concerning the shapes of the building and the site (Figure 3.b), those design criteria sometimes cannot be clearly observed in the design results. With the help of algorithmic generative modelling tools

like Grasshopper, which can take complex geometric features consisting of 2D shapes or 3D models as input parameters for algorithms, a designer can easily explore appropriate combinations of algorithms assign means of representing geometric intentions. The "Model" of semantic ontology and the "Controller" of topological relations of design criteria can help to associate algorithmic generative modelling tools like Grasshopper with the architectural design knowledge that was applied within those algorithms.

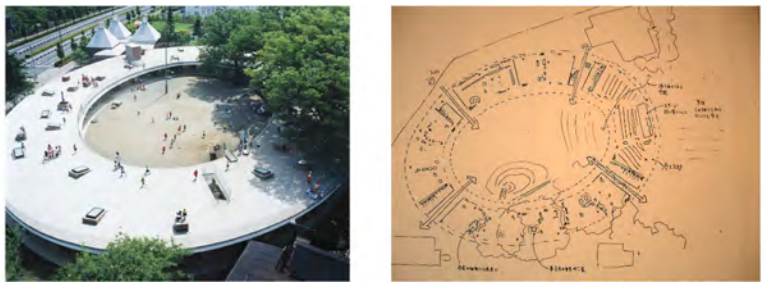


*Figure 3. Geometric features of roof of the Fuji Kindergarten: (a) the geometric features of the roof consist of two simple ellipses (left), and (b) a diagram of invisible design criteria concerning the building and the site (right) (OpenBuildings, 2014) .*

## 3. Implementation and initial testing of STG

In previous studies, a prototype Python scripts entitled "Design Criteria Modelling (DCM)" was implemented to help designers to model and validate semantic ontology within Grasshopper by hooking with OWL files and the SWRL reasoner of Protégé (Lin, 2015). The DCM prototype was provided to students for modelling their semantic criteria of a "Community-Friendly Primary School" design, which was a topic on Taiwan's architect qualification exam in 2015. The design context consisted of two sites located on north and south sides of a primary school (Figure 4.a), and the building's purpose was for the learning and leisure usage of seniors in the community. Except for such basic issues as the building code, the existing site contexts served as the predominant element for the development of design criteria.

In this test, some of the students found the strong patterns of existing buildings, including an axis formed by the central corridor, and the rhythm formed by parallel building masses. They therefore tended to follow the axis by extending the central corridor to connect both sites, and then arranged the new building to be parallel with existing buildings. Those students could consequently first code the "Parallel" and "Axis" topology, then sought to implement the algorithms of "Parallel" and "Axis," and finally select the input parameters, such as an existing building and its gaps as the generating rules (Figure 4.b).




*Figure 4. The rapidly design exam of a "Community-Friendly Primary School": (a) the context and content of the site (left), and (b) test modelling of design criteria (right).*

## 4. Discussion

Because of more requirements for prior knowledge apart from basic architectural knowledge, many misunderstandings of digital architectural design have also arrived with the increased availability of digital tools (Peters, 2013). Confusion about methods, thinking, and modelling among generative, parametric, and algorithmic approaches has emerged with more new digital tools. Kotaik therefore proposed a theoretical framework that addressed the differences among the generative, parametric, and algorithmic approaches in terms of computability (Kotnik, 2010). Kotaik remapped Oxman's five class of digital design, which are CAD, formation, performance, generative, and integrated compound model (Oxman, 2008), into three levels of design computability, which are representational, parametric, and algorithmic from low to high computability. A formal description of digital architectural design was proposed as a computable function for generating "variables" of architectural properties by inputting "parameters" of the architectural factors of design situations. The STG pattern is discussed as follows based on Kotaik's computability outlook of computable functions.

### 4.1. SEMANTIC ONTOLOGY AS THE INPUT PARAMETERS OF COMPUTABLE FUNCTIONS

Woodbury defined parametric design thinking as thinking with abstraction, mathematically, and algorithmically (Woodbury, 2010). Algorithmic thinking means to understand the interpretive correlations between algorithms and architectural design criteria (Bazalo and Moleta, 2015). However, most of abstract design criteria at early design stages are too abstract to input as parameters, and it is not easy to find an algorithm for generating or validating

them. For instance, designers cannot input a “FeelRelaxed” property into a function for generating the “hasNoBoundary” property of a classroom.

Kotnik indicated the output “Variable” should be a building property, such as a building’s form or components. However, the possible “Parameters” are left with open definitions. If the input parameters cannot be associated with any known architectural design criteria, in view of the principle of “garbage-in, garbage-out,” it is not surprising that parametric design is often criticized as being disconnected from basic architectural design knowledge. In order to convert semantic design criteria into computable parameters to facilitate machine processing, it is necessary to represent them in a formal and computable format. With help from semantic ontology based on OWL, it is easy to infer implicit design criteria and validate given design criteria by employing the SWRL reasoner of Protégé. Semantic criteria at an early design stages can therefore be regarded as input parameters into the algorithms of generative modelling tools like Grasshopper.

## 4.2. TOPOLOGICAL RELATIONS AS GENERATIVE ALGORITHMS OF COMPUTABLE FUNCTION

Generative algorithms are the cores of a computable function. However, a parametric model implies the algorithms are fixed, and the correlations between parameters and variables are predictable. Cognitive studies has found that designers spend more effort for finding appropriate algorithms fitting their intentions (Yu et al, 2015), rather than testing possible output variables by modifying the input parameters. The extra costs of applying parametric modelling usually do not mean those problems are so novel that the solving algorithms have not been invented, but usually only mean that the designer does not know the solution or has not mastered the algorithms.

Although Grasshopper requires no scripting skills, when designers’ intentions become complex, mathematics knowledge and programming skill become critical. Researchers claim that parametric design imposes new challenges by asking architects to play the roles of programmers (Yu et al, 2015). However, algorithms of some complex geometry have already been developed, and some even have been packaged as plugins, such as the “LunchBox” plugin of Grasshopper. The population of “LunchBox” plugin reveals that extra effort is usually spent on implementing algorithms by scripts, rather than converting design knowledge into algorithms. In the case of Fuji Kindergarten, for example, the architect can only identify the topological relations, such as connective and surrounding as the controller, and then identify classrooms and the playground as the input parameters. Thus, scripting tasks can be handed over to professional programmers/scripters.

### 4.3. GEOMETRIC FEATURES AS VISUAL VALIDATIONS OF COMPUTABLE FUNCTIONS

The original purpose of Grasshopper was to automate and accelerate modelling tasks. However, the computability of generative algorithms does not be restricted to generating complex geometries. According to Kotnik's opinions, a "threshold" between non-digital and digital design is located between representational and parametric models of design thinking and methods, and the representational applications of digital tools are only an alternative of paper drawings and hand-made models like traditional 2D/3D CAD software.

From the view of computability, the application of "LunchBox" to generate complex geometries actually is closer to representational than parametric. The critical design knowledge is not located in the selection of algorithms, but rather in the selection of input parameters and how to filter out generated forms. In the case of the Fuji Kindergarten, before the architect took an ellipse as the predominant geometry, he had to develop more criteria concerning geometric features of the playground and the building, such as minimal required spaces, and the necessary retreats along the trees and the site. Even though these criteria may not directly generate forms, the generated geometries still can be used to visually validate those criteria. For example, a designer can model existing trees into "subtraction" objects for generating the open spaces. Therefore the geometric features of generative forms can also visually validate those invisible design criteria of architectural design.

## 5. Conclusions

Parametric design is not only a novel tool of digital architectural design, but also a new methodology of architectural design thinking. Following the generative approach, Kotnik concluded that the exploration of computing functions is a critical feature of digital architectural design. However, there may be insufficient clues for discovering the computing functions of general architectural design criteria, especially for those abstract concepts proposed by architects and emerging in the early design stages. For expanding the use of parametric design, this paper proposes an "STG" pattern based on the "semantic-topological-geometric" information-converting framework to guide designers in modelling design criteria knowledge in parametric modelling.

In view of the fact that one purpose of the MVC pattern is to divide programming tasks in complex systems into small, discrete, and independent objects, the STG pattern divides parametric design into three parts characterized by computable functions, which can implement generative algorithms by different designers. As building projects become more complex, instead

of requiring architects wear many hats associated with other disciplines, it is better to hand over programming/scripting tasks of complex geometric generation and performance optimization to software and MEP engineers. It is therefore time to embed basic and traditional design knowledge back into the parameters and variables of generative architectural design.

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# EDITION-ORIENTED 3D MODEL REBUILT FROM PHOTOGRAPHY

*Giving affordance to 3D capture*

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**Abstract.** The topic of this paper is about a technique to turn pictures into an intuitively modifiable 3D model. The research employs an analytical method using algorithms to conceptualise and digitalise architectural spaces in order to highlight parametric shapes. Usually, from one group of digital photos, photogrammetry techniques produce a 3D-model mesh through a high-density 3D point cloud. This discordance between our intuitive partitioning of the mesh and its bare polygonal structure makes it interact poorly compared to the affordance of shape and component in our daily experience. Through a capture device, a visualisation of architecture in a digital data form is produced. They are processed by computer vision algorithms and machine learning systems in order to be refined into a parametric model. Parametric elements can be described as a compound of formulas and parameters. By keeping the formula and changing the parameters, these elements can be easily modified in a range of likenesses. After being detected during scans, these shapes can be adapted to fit the intention of the designer during the design phase.

**Keywords.** Photogrammetry; convolutional neural network; 3D model; design tool.

## 1. Introduction

Local surroundings in architectural design are often recorded by building surveyors prior to design sessions. Based on these records, and visits to the site, architects start to imagine possibilities for the future. Records are abstractions of the real site, so they need to be reconstructed in the mind of

the designer. With a complex site, it can be hard to work out how to develop it. A good way to help the visualisation process can be 3D reconstruction based on photography.

Usually, architecture practice is about creating new building. It implies that existing old architecture around is demolished. This policy of Tabula Rasa is exactly the opposite of a continuous design that: "generate in the flow of what is already there […]" (Wood, 2007). In the framework of the Algorithmic design, this architecture practice can be considered as minimal intervention in a system to solve a problem instead of fully create a costly solution from scratch. In order to move toward this idealistic practice, there needs to be a more comprehensive and integrated access to site data. This could be the key for an Algorithmic design sites intervention which carries and transfers weight to the existing constructive elements instead of wasting energy to move them away.

Photogrammetry is a technology that is becoming more accessible. However, despite the fact that generated 3D models can be very accurate, their internal structures are dissonant with our intuitive perception of spaces and objects. In the end, it makes 3D shapes that are hardly editable for architectural intervention. For instance, if you want to change the radius of what you see as a tubular section, it's often necessary to remodel the site with a built-in CAD software command upon the 3D scan. For a CAD user, it means the ability to modify parameters of shape directly. Without any remodelling or fuzzy vertice selection process, he can extrude a table or remove a window.

The 3D scan ease the precise and complete capture of geometric data but misses the semantic and constructive aspects. Previous research has brought innovative solutions to cope with this problem. Without being exhaustive: Tang et al (2010), Shen et al (2012) and Andelo Martinovic (2015) present similar goal to this research. This work can be related to "Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques". This review presents the overall context and the challenges of 3D reconstruction. This paper will explore a slightly different approach since it considers pictures as raw material and convolutional network as a technique to segment and identify the architectural component in the surroundings. Concerning the strategy, it may be similar to "Structure Recovery by Part assembly" except that it copes with the problem of detecting scattered parts of the component in various pictures instead of one.

Finally, these methods are slightly different. They use 3D point cloud analysis, computer vision oriented and shape grammar extraction but none of them use Deep Convolutional Neural Network (ConvNet) (Nielsen, 2015). The experiments conducted in this paper will focus on architecture models of

small volumes and enclosed spaces. Real scale can only be processed with large training data that is costly. So the training database is reduced to a number of easily testable cases. The results obtained using the limited database constraints can serve to speculate further scaling up to a larger system.

## 2. Overall process

This process, from data acquisition to 3D reconstruction, borrows Photogrammetry technique and links it to ConvNet. To create ConvNet, it is necessary to have a ConvNet architecture to train using a data set. As this uses ConvNet in two steps of the process, specific sections are focused on details of data set content and ConvNet architecture.
Like photogrammetry, the input data is a set of pictures that overlap each other. Homologue points between pictures are calculated. Then with internal and external calibration, the relation between the cameras is retrieved. Our process uses the same initial steps. It allows us to get pictures organised by their proximity to each other within the captured object space ( see Figure 1). After this step, the photogrammetry process continues with a dense correlation in order to generate dense point cloud. Points of the cloud are connected through a mesh triangulation algorithm. These steps create the effective 3D mesh. The method described in this paper replaces the dense 3D point cloud step and all the following steps.

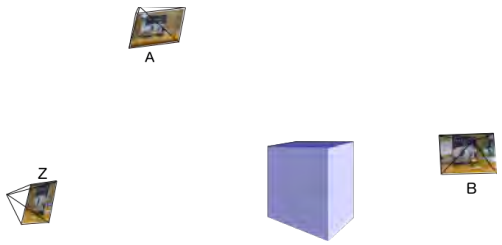



*Figure 1. Bundle Adjustment of the camera position.*

The images embedding their camera coordinate will be segmented into crossed categories based on the likeness, same objects amongst different images belong to the same segment, and type, same type of object in one picture belong to the same meta-category. Segmentation will be done by pixel labelling with ConvNet like in the work of Farabert (2013).

ConvNet requires data in a uniform format. The 3D coordinates of the camera position can't be provided next to a picture images. Even if they can be all converted to tensor matrix format, neural network components are not made to process 3D coordinates vector data along with a matrix of color data of each pixel. From a recent paper of John Flynn (2015), a way to implicitly

embedded camera coordinates and orientation within the pictures' image is discussed. This technique is used for the same need of ensuring data uniformity in their paper. Like in figure 2, it applies a perspective deformation on a picture (B) in order to match with the point of view of the previous picture (A). In other words, image (B) is reprojected into the target of the camera's picture (A). This system implicitly provides the relative coordinates of the picture (B) according to the picture's (A) coordinates into the picture (B). Since the coordinates of the cameras' pictures are provided with internal and external calibration, pictures can be chained based on their geographic proximity. Each picture will be re-projected in the subsequent picture space in the series as long as there is data available.

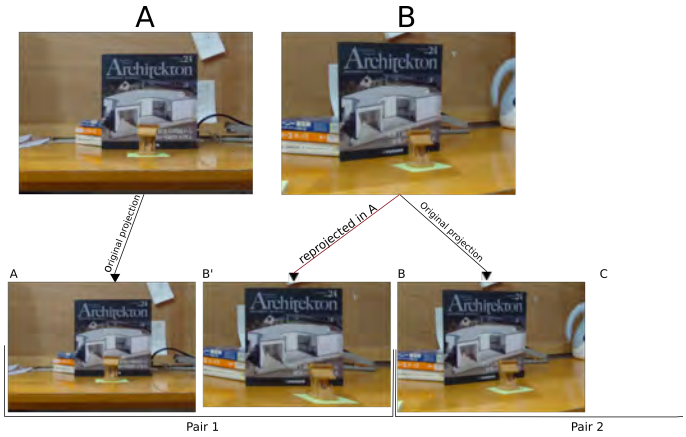



*Figure 2. Reprojection chain.*

The first ConvNet, (Twin consensus segmentation network[1]) will receive pairs of pictures: one in original space, another reprojected. It's segmentation ConvNet with an interaction of weight sharing at the full connection layer. The weight sharing will harmonise the segmentations between the two points of view in order to propagate the same segmentation class between different views of the same object while it differentiates objects that belong to the same class according to their relative position to each other. Indeed, their geometric deformation will extend their segmentation group but the camera movement will separate the object through their relative movement to each other. For instance, object next to each other and belonging to the same segmentation class are dissociated in the output as two segments of two different objects. The output classes of segmentation are divided in 8 common architectural components: walls, roofs, doors, windows, stairs, handrails, post, beams and 13 special temporary object classes. This excludes the ground, sky and "outside" classes that are potentially infinite seg-

ments. These three classes are not producing 3D model. Each of the segmentation classes are extending their area from picture to picture until the features appear in a discontinuous pictures area or no features of this class appear anymore. When features of this class reappear in another picture or in a discontinuous space, a new picture element's object repository is open. The special object classes will be temporary classes that stock simultaneously aggregated super pixels in object's facets per camera into different unknown objects with different label.

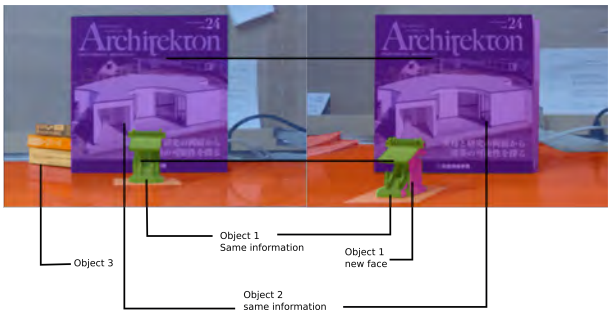



*Figure 3. Segmentation of 2 adjacent pictures.*

The output segments of the ConvNet are remapped in their original picture space and bind with corresponding camera coordinates. Then the picture elements of each object are stored in a database that keeps image segments of each continuous along adjacent picture segments. Each picture elements group are stored under their class label and a component identification number. Under each picture element of a group, the camera coordinates and the corresponding depth-map are retrieved from the initial input data.

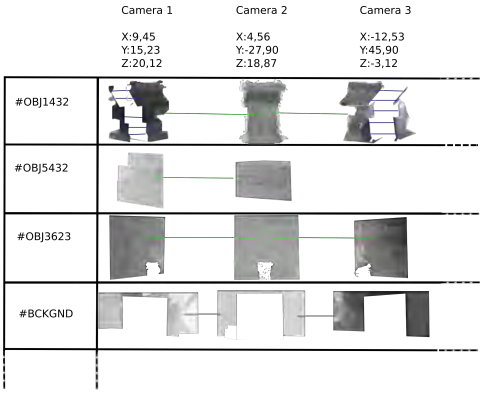



*Figure 4. Storage of the Object Pictures Elements: green line link different point of view of the same "face", purple lines indicate seam of part, black connect background.*

To retrieve the depth-map, we could use OpenCV command library on two close pictures, or photogrammetry software to reconstruct a temporary mesh from which a virtual camera extracts a depth-map on the same coordinates of the taken pictures. But in order to focus on the most ambitious step of the process and to avoid a technical convoluted process, we chose to use a plenoptic camera (Lytro Illum) that provides directly the depth-map matching to the color pixel of the pictures taken. Inherently, this camera produces already low level three dimensional information (depth-map) that ease and shortens the whole process described here. In future works, we aim to work with various capture systems like a 360 or stereorcopic camera.

Then, the second ConvNet (Depth feature detector[1]) is used to match depth features of primitive shape inside the unfolded puzzle of picture elements of each object. The features are tracked along the chain of picture elements in order to retrieve the closest primitive shape that can create a similar set of features. Since picture elements will not cover all the facets of the object, the ConvNet set a probability ranking of possible shapes according to the group of features detected. Then, amongst the possible shape that constitutes the object, the reconstruction algorithm selects shapes that are not overlapping each other. According to the most plausible ingredients, the algorithm will propose a recipe for reconstruction. This part is not yet implemented for complex shapes. For now the detection of shape is quite limited so the reconstruction is simple. It starts from the ground then block, tube, cone and sphere shapes are stacks one upon the other.

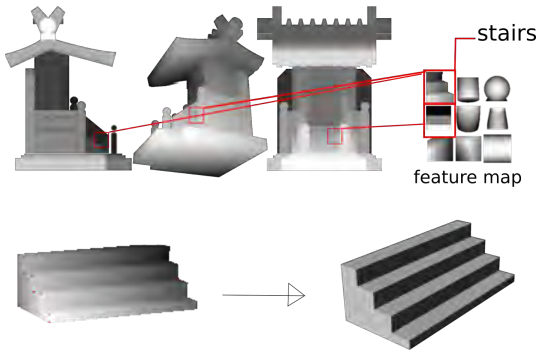



*Figure 5. Details from the different views trigger features in the ConvNet layer. Once the type of shape is detected, the appropriate computer vision algorithm extracts the key point for reconstruction.*

The reconstruction strategy depends on the CAD software used for reconstruction. It maps features of the depth-map with a corresponding command in the software and retrieves the coordinates of useful 3D points required by

the command. For instance, in Rhino 3D modeling software, a parallelepiped is defined with at least 3 points. The second ConvNet detects the shape and the area in the blue print that belongs to this shape. In this area, the signature of a corner is searched. The coordinate of the corner in the depth-map space is defined in 2.5D: x,y and the z position according to the depth-map. The identification of the pictures chunk from where the signature comes from corresponds to a camera position. With the 3 corner points and the 2 or 3 corresponding camera, the points are re-projected in the 3D space through the camera position. For now, the program is limited to detect and retrieve key construction points and lines of primitive shape: cones, spheres and parallepipedic shapes. Theses shapes are easy to edit and present in all CAD software. The step that connects the output of the system with API of CAD software is not implemented. Actual output is just shape names and a series of coordinates in a text file.

## 3. Data set construction

Data set construction is a difficult point in machine learning. To cover lots of cases, it needs to include a large number of pictures. In order to keep this project to feasible proportion, the detection expectation has been kept low. For the Twin consensual segmentation ConvNet, only a very limited number of examples of each class have been kept. Other papers that propose solutions for segmentation show good result with 400 pictures and corresponding ground truth segmentation.

For Depth features Detector, the training set depends of the number and the type of command from CAD software that are allowed to be used to reconstruct the captured architecture.

### 3.1. TWIN CONSENSUS SEGMENTATION DATASET

Images in the data set are a pair of close views with their corresponding segmentation. Segmentation is partially done with GrabCut[2] for the foreground objects and SLIC[3] for background partial elements. The 13 special temporary object class are attributed in depth order in the first picture of the chain − the closest object from the first camera in the chain will be the object #1. Pictures are mainly interior and exterior pictures of architecture building. No humans or animals are present in the pictures. Mobile elements are captured in only one state and not displaced between shots in a chain. Pictures chain are varying between 2 and 10 pictures. The overlap of pictures is similar to photogrammetry requirements: 60% of side overlap with 80% of forward overlap.

Meanwhile, the dataset is a decent size for training (600 images at least) and testing (200). A smaller temporary dataset of 40 pictures with just ground, background wall and foreground objects categories have been made just to test the consensus segmentation between pictures of a minimalist architectural model.

### 3.2. DEPTH FEATURES DETECTOR DATASET

Images in the dataset are depth-map pictures of primitive shapes: cones, cylinders, spheres and parallelepipeds of various sizes with various positions and angles of view. Labels are given by the name of the command used in the CAD software to produce the shape. Here, the goal is to produce a good feature description of a depth-map from a primitive shape. The picture format is 500*500 with levels of grey and an alpha channel. The depth-map is generated with a Rhino Python script that runs render of primitive shapes with random parameters and random points of view on the Depth channel. The ease to produce these images allows us to generate 10,000 of them.

## 4. Network architecture

ConvNet architecture is composed of various layers. Each layer has a specific function in the task. Usually, higher layers detect elementary patterns and lower ones associate these patterns into a bigger one. During the training phase, the ConvNet creates its own classification. By “own” we have to understand that it doesn’t necessarily follow a human classification logic. If a Deep neural network had to do the species classification, it will probably base is classification on other characteristics than taxonomy scientist did. It would result in organisation of the class slightly different from mammals, oviparous and vertebrate. It produces an efficient classification rather than an intellectually satisfying one.

Another important element is the convolution layers. These produce feature maps. These maps are abstract representations of patterns that are shared amongst images. We could think of features as an informative detail of the shape but they are hardly representable since they are an abstract relationship between pixels.

### 4.1. TWIN CONSENSUS SEGMENTATION NETWORK

Without detailing the function of each layer, the most important layer in the network is the Spatial pyramid. It changes the resolution of the input images and processes these different resolutions through a cloned network with shared weight. It allows us to create features of bigger scale: features that express the general image organisation. In the segmentation task, it avoids

incongruous errors like detecting people in the sky. Another critical point is the interaction between the twin networks. Objects in the foreground will tend to move more between two pictures. Disparities in the global area of the spatial pyramid between parallel layer will tend to detect the closest object to the camera.

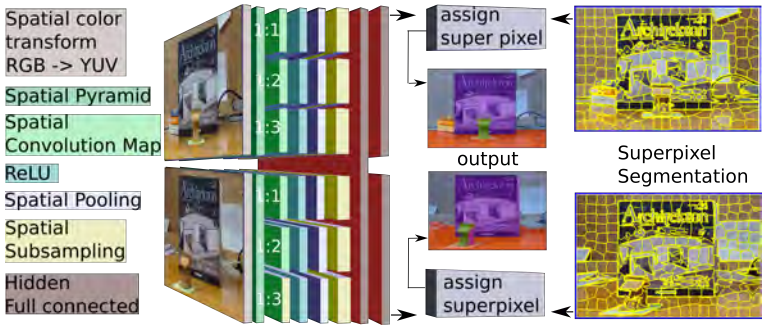



*Figure 6. Architecture of the Twin consensus segmentation network*

The architecture is here more conventional. Convolution layers followed by pooling ones is a very common way to extract the hierarchy of features. The input image is a depth-map and the output for classification is the name of the different primitive shape.

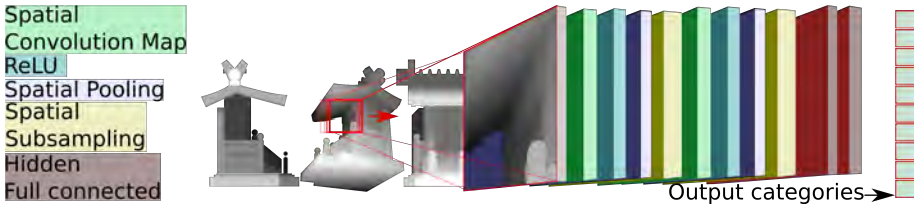



*Figure 7. Architecture of the Depth Feature Detector Deep Neural Network (ConvNet)*

## 5. Conclusion

To conclude, we can't, unfortunately, says that this system works. Any shape elements haven't yet been detected. It is likely due to the numerous glitches in the depth-map produced by the plenoptic camera (Lytro Illum). Some attempts has been made with a projected light system, but the same problems of depth-map quality have been encountered. Some parts of the depth-map are missing and the resolutions are even lower. One solution could be to use LiDar (light detection and ranging) but they are costly and it doesn't fit with the original idea of a low-cost capture system. As said previously, another cost-effective solution could be to generate the depth-map through a photo-

grammetry software. It's a complicated and inelegant solution but it is worth being tried since the attempt to ease the technical process was the source of failure.

Coherence between a 3D model reconstruction structure and an intuitive understanding of architecture could drastically extend the ability of Algorithmic architects. As a matter of fact, the design process alternates between the conceptualisation and the visualisation phases. The Computational Thinking[4] approach of design involves a "computational conceptualisation" which fits to envision architecture as structured data. Therefore, our perception and ability to act on the environment are deeply bonded, an algorithmic control of architectural data will stimulate more involvement of computational thinking into the phases of design. In the end, it leads to an Algorithmic design practice: an automated manipulation of data in order to solve a design problem. More practically, intervention on site specific problems like building modifications or extensions become easier. For instance, an office layout planer can reorganize the existing furniture and working space of a level. The real world becomes a repository of 3D models that are just waiting to be scanned.

## Endnotes

1. This name is not related to any papers. It's only made up name to ease the description.
2. Interactive foreground extraction algorithm using iterated graph cuts.
3. Superpixel Linear Spectral Clustering, segment image into superpixel according to perceptual meaningfulness
4. Method to generalise solution of problems in the intent to solve them with computer.

## Acknowledgements

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# SMART BIM OBJECT FOR DESIGN INTELLIGENCE

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**Abstract.** By enabling BIM technology, a building can be represented by a set of objects that carry detailed information about how they are constructed and also capture the relationship with other objects in the building model. Smart BIM objects can be classified as specific components encapsulating typical building rules and relations that can be predicted and defined by a few parameters and constraints. A framework is developed to show how a smart BIM object is developed. This paper presents the method of developing smart BIM object capable of better-informing design decision. To demonstrate the usefulness of smart BIM objects, a cloud BIM object library is developed and tested by academia and industry.

**Keywords.** Smart BIM object; cloud database; parametric modelling.

## 1. Introduction

Building information modeling (BIM) is one of the most promising recent developments in the architecture, engineering, and construction (AEC) industry. As the various professionals in the AEC industry become more experienced in the use of BIM, they will utilize an increasing number of intelligent design applications. Numerous BIM applications can be classified over several dimensions. One dimension addresses the integration of BIM tools used in the different stages of the building life cycle, such as code checking, building performance simulations, spatial configuration, and so on. Another addresses the development of smart BIM objects that can be shared, adapted, and reused across different projects within any stage in the life cycle. Designers can insert the smart BIM objects directly into a building model, ranging from low-level building products like doors, windows, to high-level design configuration, such as building core, and façade elements. Overall, this is the anticipated transition to design intelligence, where each of these BIM

tools and smart objects encapsulates the domain knowledge to put a building together for better quality and greater efficiency (Ibrahim et al, 2004; Sacks et al, 2004).

This paper explores the concept of smart BIM objects for design intelligence. By enabling BIM technology, a building can be represented by a set of objects that carry detailed information about how they are constructed and also capture the relationship with other objects in the building model. Each building model has typical building rules and relations that can be predicted and defined by a few parameters and constraints. While domain-specific BIM tools combined with parametric rules allow a building design to be better-informed design decisions, there is a lack of research to develop the procedure of utilizing the smart BIM objects capable of transforming their properties automatically and to identify requirements for object evolution throughout the building life cycle.

## 2. Smart BIM objects

### 2.1. WHAT MAKES BIM OBJECTS SMART?

The productivity of BIM depends on the applications of BIM objects. BIM objects are the combination of many aspects of buildings such as information that defines a building, physical characteristics, behavioural data, and visualization data. Some research work has been done to define BIM objects to be "smart". Smart BIM objects can be categorized into two aspects. One is the smart object that can interact with users and other objects. The smart object captures rich information to represent their functions in real situations (Díaz et al, 2014; Heidari et al, 2014). The information contains can be a composition of geometric definition and a database definition based on alphanumeric information transfer or specific formulas for describing the object properties. The other is the smart object that executes a procedure that contains rules, knowledge and data to perform a domain-specific task, and the programming code is necessary to handle various messages that it may receive (Halfawy and Froese, 2005; Sawhney and Maheswari, 2013). The smart object needs to combine the capabilities to represent various aspects of project information required to support multidisciplinary views of the object. It is encapsulating "intelligence" by representing behavioural aspects, design constraints, and life cycle data management features into the objects.

### 2.2. A TAXONOMY OF BIM OBJECTS

By having interviews and surveys of the uses of BIM objects in the AEC industry in Taiwan, we categorized the BIM objects with taxonomy into the

design, structural, and manufactured objects (Figure 1). Structural objects are building components that relate to the main structure of the building such as column, beam, and slab. Manufactured objects are components that are standardized and produced by manufacturers. Design objects are general components whose attributes contain values, variable, or formula to embed in the project for generative or adaptive modelling. It can be a customized object that is developed with API, database, the Internet to solve the specific problems interaction with the users.

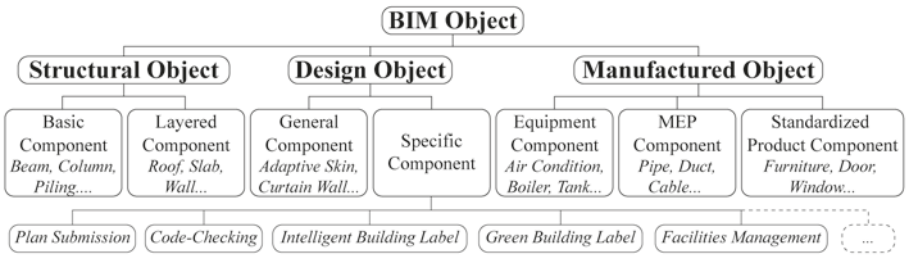



*Figure 1. A Taxonomy of BIM objects.*

## 2.3. DEFINITION OF SMART BIM OBJECTS

We define the smart BIM object that can be classified as a specific component that represents a procedure to utilize rules, constraints, relationships, and knowledge. Knowledge can be represented by programming code to interact with other objects for performing tasks, evaluation, and capability such as building code, building performance, constructability, workflow checkpoint, design criteria and so on to support multidisciplinary views throughout the building life cycle to enhance the BIM achievement. The objects must have the knowledge to behave smartly as the parametric design relies on the ability to change an object's properties without redrawing it again (Sawhney & Maheswari, 2013). The parameters can be represented by a predefined set of properties that the user has to select from, or follow their rules for the creation or alteration of a new object (Ibrahim & Krawczyk, 2003). The smart BIM object can be made "intelligent" by adding the functional, relational, structural and behavioural characteristic to the parameters.

There are three essential features of smart BIM objects:

1) Knowledge Base: The information contained in smart BIM object will be fine-tuned according to the specialization and delivery process by relating to others. For example, by embedding domain knowledge such as human factor engineering, building codes and regulations as constraints, the smart objects can identify its location to the spatial constraints and provide an alternative to

adjusting the parameters, allowing the designer to make a better design decision and update its shape correspondingly.

2) Evolution: Smart BIM object that represents knowledge as invariant and variant component automatically or manually updates their geometries or information according to the rules, codes or tasks during specific phases without redrawing the object. For example, the parameters belong to it can be updated and change automatically when the submission of fire inspection is needed.
3) Customization: Smart BIM objects can be regarded as a medium by linking the external cloud database and filtering the appropriate components to form a customized object. For example, by extracting the parameters from the object in the project, the suitable or suggested product object can be filtered dynamically and download directly from the object library when phase changing.

## 3. A framework

This research attempts to provide a design framework of smart BIM objects categorized in the specific component of design tasks. The smart BIM objects assist the user to achieve task requirements by using embedded constraints and knowledge, and then selects and replaces appropriate alternative product objects through the cloud database within the project life cycle.

### 3.1. DESIGN INTELLIGENCE

Design intelligence contains knowledge about building design, such as building code, building performance, constructability, workflow checkpoint, and design criteria embedded in smart BIM objects during building life cycle. The knowledge is represented by *constraints* that can be invariant or variant. We call it as invariant and variant smart BIM objects. There are two approaches of the invariant objects, one will prohibit actions that didn't fulfil the constraints and correct the parameters, the other one is a parametric interaction object that provides a linkage between each other to change the parameter automatically according to the task and situation such as the elevator and stair in building core. The variant object will show notification and suggestion to the designer for references on decision making like building performance evaluation.

### 3.2. SMART OBJECTS IN THE CLOUD

The cloud database acts as an object library that provides download, upload, and replacement of smart BIM objects. It can be communicating with the platform to filter object's information by software API or plugin. The smart BIM object will go through an information filter system to provide a rec-

ommendation list of the corresponding objects in the cloud database in response to change. Besides this, the comment section of the cloud database allows the user to give feedback and discussion of the object that can be used to maintain the quality of the object and knowledge base.

### 3.3. A BIM-ENABLED PLATFORM

A BIM-enabled platform is the place where the smart BIM objects embedded with knowledge to be used and applied. The BIM file uses API or plugin like Revit Dynamo to read or write the knowledge base and use the smart BIM object downloaded from the cloud database. The smart BIM object with different context will operate to a certain level and let the designer exchange or replace another object during the different phase of building life cycle with cloud database, as shown in Figure 2.

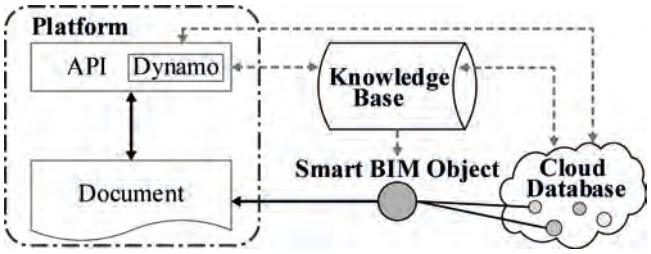



*Figure 2. Framework of the smart BIM object*

## 4. The implementation

An implementation framework called iBIM is developed by selecting two types of smart BIM object connecting the cloud database. The first implementation is the invariant smart BIM object that uses the building core element such as elevator and stair. Secondly, is windows and doors object to act as a variant smart BIM object for natural ventilation evaluation (Figure 3).

Firstly, the smart BIM object is uploaded and saved in iBIM for downloading when needed, and used in the Revit project. The knowledge, such as building codes, constructability, evaluation method will embed in the smart BIM object by two ways, one is represented by the attributes and parameters that contained formulas, constraints on the object itself, and the other is using API or plugin such as Revit Dynamo's nodes to represent.

After that, the smart BIM object in Revit project will interact with changes such as floor number, building core boundary, and spaces boundary and show on the number of the elevators, the number of the stairs, building performance visual notifications and so on. When the design is reaching a certain level in the building life cycle, the smart BIM object can use the Dyna-

mo as an information filter system to communicate with iBIM to filter and find another appropriate object that matches with smart BIM objects in the model, and makes object replacement for another task or product object.

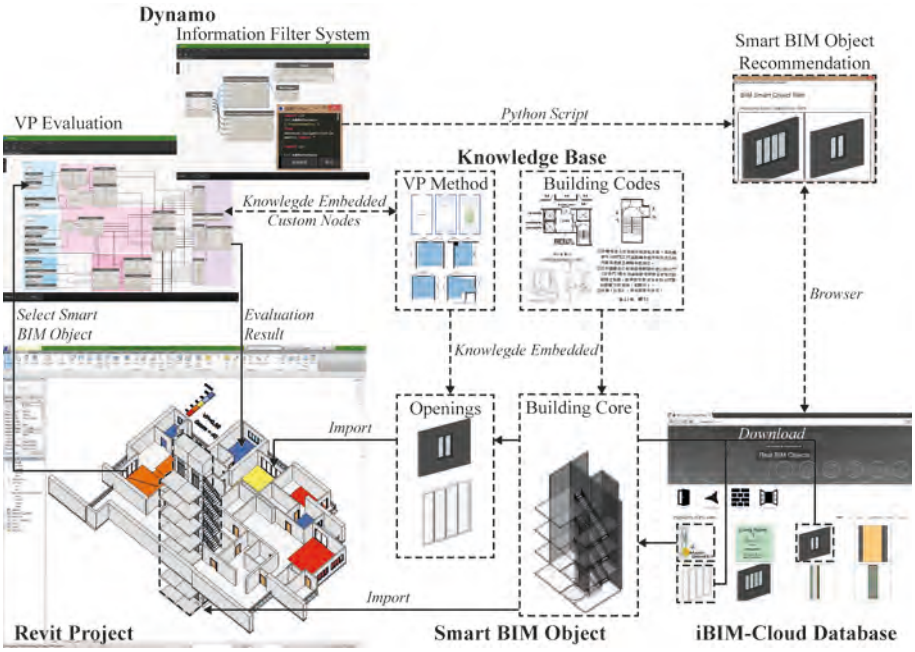



*Figure 3. Implementations of smart BIM objects*

## 4.1. INVARIANT SMART BIM OBJECTS

This demonstration focuses on automatic code checking and spatial configuration for building core using invariant smart BIM objects such as elevator and stair. By embedding knowledge excerpted from building technical regulations and accessibility guidelines for building and facilities of Taiwan, it enables the elevator and stair objects to configure automatically as the invariant smart BIM object and the two approaches of invariant smart BIM object will also be demoed (Figure 4).

The first approach is shown on the size and location of accessible guide route. The changes are prohibited according to the building codes and represented as constraint embedded in the elevator. The size of accessible guide route must be 30cm in length and 60cm in width. In addition, the location of accessible guide route must align the elevator control panels to the right and offset 30cm from the elevator wall as figure 4 (A).

Next, the second approach is shown as a parametric interaction smart BIM object that is flexible and extensible according to the constraints of

building codes. The elevator and stair will generate automatically by defining the boundary and floor numbers, and comply with the building codes at the same time figure 4 (B). For instance, the relationship between such as floor number and elevator's entrance, elevator shaft, the number of elevators, floor height and tread, run, rise of a stair is represented as formulas to embed into the attributes as shown in figure 4 (C). The constraints are the number of elevators that increase when the floor number is over 12, 24 and so on.

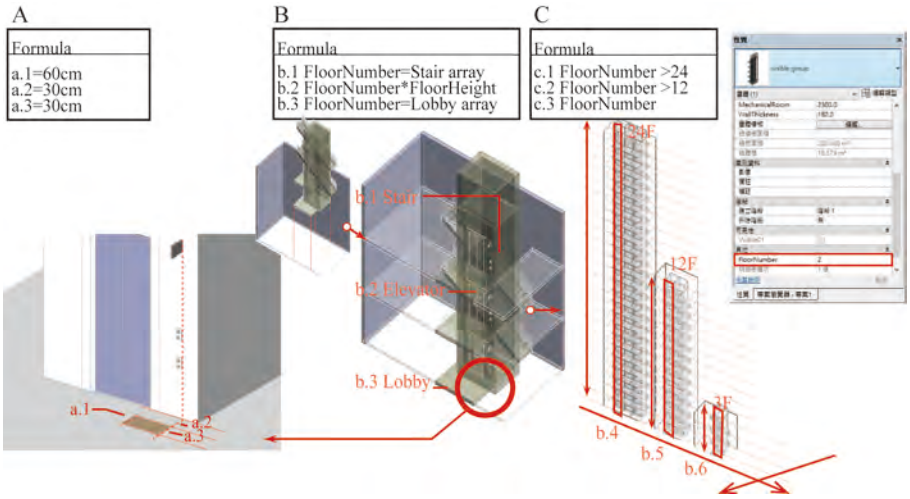



*Figure 4. Invariant smart BIM objects of building core.*

## 4.2. VARIANT SMART BIM OBJECTS

This implementation focus on the integration of windows and doors as variant smart BIM objects with Dynamo based on the Ventilation Potential (VP) evaluation method in the EEWH, the green building evaluation system of Taiwan to assist designers in design decision making by giving notifications and suggestions. VP is used to evaluate the building that openings can be opened and ventilated naturally. It is the ratio of the total area of single-sided ventilation (VAi) and cross ventilation (CAi) to the total area of living space (Ai) and resulting value is between 0 and 1 as the indicator scores from 10-100 in EEWH. The relationship between spaces and ventilation performance can be controlled visually by using this method to save effort, humane and integrated comprehensive evaluation without using complex CFD simulation (Lee, 2014; Lin, 2014).

By downloading smart BIM objects such as windows and doors from iBIM to Revit project, it enables Dynamo definition retrieves the parameters of the opening objects by selecting it from the project. The Dynamo defini-

tion was contained three main part custom nodes that were (a) openings selector, (b) VAi, CAi area and route drawer, and (c) object parameter editor (Figure 5).

The opening selector lets the designer select opening objects from Revit project and edit the main parameter for evaluation. The VAi, CAi area and route drawer act as the main node that contains all the calculation and logical computation of the VP evaluation method. It calculates the boundary of VP area and draws coloured polysurfaces generic model object according to the indicator score as a visual reference for the designer. The object parameter editor is a node to write the results of the evaluation to the opening objects and tags for text notification and schedule in the project. After that, the VP area polysurfaces, parameters, and tags will renew automatically when the designer makes changes. Furthermore, the designer can replace the opening object to a more detailed product object or other smart BIM object from the suggestions of iBIM by filtering the appropriate parameters by Dynamo that match as the design is reaching to a certain level.

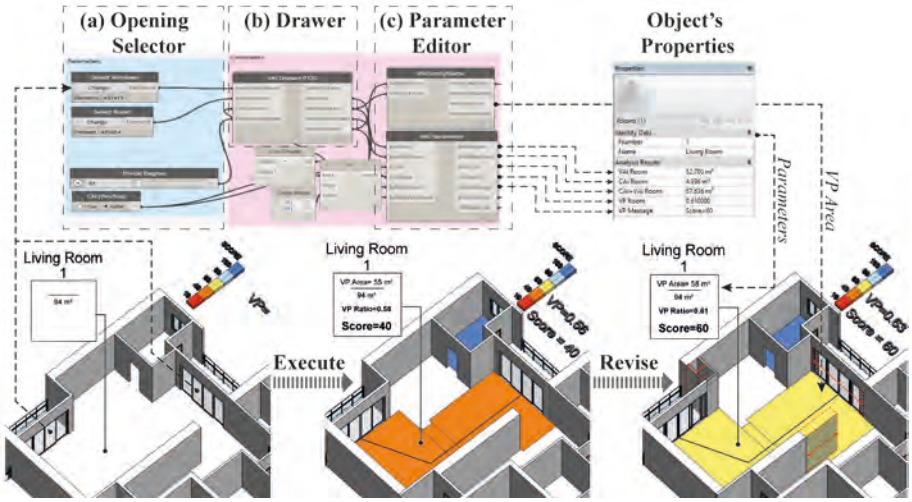



*Figure 5. Variant smart BIM objects with Dynamo*

## 4.3. iBIM: A CLOUD DATABASE

Most of the cloud database for BIM object exist in the market only provides the upload and download function of product object, it lacks the ability to communicate directly with the BIM model when needed and provide the recommendation of appropriate BIM objects based on the BIM model. iBIM, a new cloud database for smart BIM objects is proposed and built that enables users to share knowledge base smart BIM object in AEC industry, gain

the recommendation of product object by extract the information of customized smart BIM object and collect the data on BIM object use from iBIM. The iBIM can communicate with Revit project by Dynamo to select appropriate recommendation of product object when it is reaching a certain level in the building life cycle. The recommendation is passed through a comparison between the attributes of a smart BIM object in a Revit project and the description of objects in iBIM.

## 5. Discussions and future work

First of all, the smart BIM object exists for design contexts to a certain level in building life cycle. It can assist the designer for automatic checking or design decision making with different context by embedding knowledge base. It can be a product object like the elevator and also be an object that contained process like the checking of title block contents when plan submission.

By representing knowledge with constraints in the smart BIM object, it enables the invariant and variant smart BIM object has the flexibility and extensibility in design and workflow management. The smart BIM object can adapt to the changes without redrawing it by changing the parameters. Beside this, it is also easy to make object replacement with cloud database during phase change to extend the function of the smart BIM object.

Therefore, the design intelligence is supported by smart BIM objects in products, process and organizations of building design. It is a loop process that consists of knowledge representation, knowledge embedding of smart BIM object to set up a knowledge-based design that can be automatic checking, and responding to designer immediately.

However, there are some limitations in this research. The platform for smart BIM objects is a lack of friendly user interface like the common software API plugin. A single smart object is hard to solve multiple design problems in context at the same time. In addition, the filter system in the cloud database requires a huge amount of domain-specific information and design components to provide appropriate recommendations for users. The future research is to explore the software API to assemble different design contexts together with cloud databases, big data, and Internet of things throughout a building life cycle.

## Acknowledgements

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# BIM-BASED FILE SYNCHRONISATION AND PERMISSION MANAGEMENT SYSTEM FOR ARCHITECTURAL DESIGN COLLABORATION

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**Abstract.** In building information modelling (BIM), the amount of information increased and architectural design processes became more complex as projects expand. This is because while a collaboration environment is important for smooth communication among experts, this has not been realised because of unclassified file synchronisation and permission settings among team members. Therefore, this study aims to support cooperation in BIM modelling projects by synchronising BIM data from different computers and rendering BIM project management easier by providing a BIM model viewer and data through the Web. The proposed technology, which is a construction project-type, purpose-tailored browsing technology, provides BIM information related to construction environments and planning processes only to the relevant experts.

**Keywords**. Building information modelling (BIM); architectural design collaboration; process; file synchronisation; permission management system.

## 1. Introduction

### 1.1. BACKGROUND AND PURPOSE

Recent advancements in computing technology have expanded from construction to the application of building information modelling (BIM) technology. In BIM technology, due to the expansion of projects, architectural design processes became more complex and the amount of relevant information increases. Such changes create the need for several experts to be

simultaneously involved in the project, thus increasing the need for collaborative design. For a successful design in a distributed environment, effective communication among experts is important, and various digital media support this interaction. In particular, due to developments in the Web environment, a method to support collaborative design in a dispersed environment is currently being developed. File exchange and communication through the Web support the effective exchange of BIM information among team members. However, in the collaborative design process, information regarding file synchronisation and permission settings for team members are created at each stage, and such information is not presented in a form useful to experts from different fields, thus causing strained communication. In light of this, the purpose of this study is to help collaborative design in BIM by synchronising BIM data from different computers, and rendering BIM project management easier by providing a BIM model viewer and data through the Web.

### 1.2. METHOD AND SCOPE

This study focuses on the development of a technology related to file synchronisation and permission management in a cloud environment for BIM-based collaboration. The scope of this study encompasses multi-residential houses. We used Autodesk Revit® as a BIM file, the Web Graphics Library (WebGL) to generate a cloud environment, and developed a permission viewer as an application program in Microsoft Visual C# .NET. By way of a file converter to model a file viewer in the Web environment, we enabled conversion from a Revit file (.rvt) to a JSON file in Visual C# .NET, such that it could be provided as a plugin to Revit®.

The outline of this paper is as follows:

In this section, we have examined the background, purpose, scope, and method of this study.

In Section 2, we classify relativity among collaborative concepts in architectural design, participants in the design process, and cases involving collaboration systems in past studies, and examine the components of collaboration in these.

In Section 3, we develop a prototype collaboration system in a cloud environment based on the components required for collaboration determined in Section 2, and create an environment by classifying file synchronisation and permission types according to the subject of design.

Having identified problems by analysing the application of this system to multi-residential houses, we suggest in Section 4 a direction for the development of such systems in the future.

Section 5 contains our conclusions and research plans for the future.

## 2. Theoretical consideration

### 2.1. CONCEPT OF COLLABORATION

Unlike in the past, the scope of construction nowadays has expanded to the application and proliferation of BIM with the advancements in computing technology. To address complex and diverse projects, BIM-applied design processes subdivide relevant tasks that are addressed by experts from various fields. However, compared to diverse expertise in the relevant fields, the working hours allocated to architectural design are insufficient, due to which the subjects of design have to carry out group work in multiple design offices, or in a dispersed environment. Accordingly, for a successful project, it is necessary to create a working environment where the participants in the design process belonging to various fields can coherently contribute to the project. BIM-based construction is a result of the opinions and efforts of participants of design from various fields, and this process is called collaboration. Collaboration is the most important factor in BIM-based construction, and involves integrating the opinions and effort of the participants of the design process. For successful collaboration during a BIM-based construction process, effective communication and exchange of reliable design information are necessary. Collaboration can be defined as teamwork, or a method of cooperation to maintain consistency and productivity. In a collaborative environment, error in work during construction can be prevented and work efficiency can be improved through the effective management of correlations among various subjects.

### 2.2. DOMESTIC AND OVERSEAS COLLABORATION SYSTEMS

Archispace, developed by Virtual Builders, the ArchiBIM by Solideo Systems, and GTeam by Gehry Technologies are some local and international instances of collaboration systems. Archispace is a component-based integrated structure modelling tool that is easy to use and systematic, such that even non-experts can easily design a construction space and simulate changes in the design in three dimensions (3D). ArchiBIM is a BIM viewer that can be managed by combining it with the administrative system of local governments. GTeam is a web-based system that uses general sharing systems (N Drive, Dropbox), making it difficult use among experts.

These collaboration system technologies are listed in Table 1. Collaborative systems are developed and used in various areas, such as governance, research, construction, and manufacturing for systematic and efficient management, and to minimize technological limitations. However, these systems

cannot be shared because they are combinations of basic templates, and information is not classified in a manner useful for experts from various fields.

Table 1. Collaboration System Technologies.

| Division | Archispace LT | ArchiBIM | GTeam |
|---|---|---|---|
| Development Agency | Virtual Builders | Solideo Systems | Gehry Technologies |
| Development Year | 2010 | 2012 | 2002 |
| Coverage | Architectural Design, Interior | IFC Browser | Project Management |
| Web-based operation | X (Stand-alone) | O | O |
| Web standards | X (Stand-alone) | O | O |
| Cloud Environments | X | O | O |
| Collaborative management techniques applied | X | X | X |
| Guide | X | X | X |

### 2.3. COMPONENTS OF COLLABORATIVE SYSTEMS

Having examined collaborative systems, we can classify them as follows according to the scope of work and characteristics: a system to create design drawings using a BIM authoring tool, a conversion system that coverts BIM files so that they can be read on the Internet, and a management system the information stored by which is classified and shared in a form useful to experts. The components of such collaborative systems suggest the considerations listed in Table 2.

Table 2. Considerations of Components of collaborative Systems.

| Division | Considerations |
|---|---|
| Work System | whether it is easy to work on, amend, and supplement design drawings according to the experts' working environments |
| Conversion System | whether files created at each BIM working stage need to be converted for synchronisation among experts from various fields |
| Viewer System | whether multiple designers can freely conduct simulations regardless of their working environments |
| Management System | whether it is easy to synchronise the created design information or library, classify it by field, and share the relevant information |

## 3. Cloud computing-based file synchronisation and permission management system

### 3.1. OVERVIEW OF CLOUD-BASED COLLABORATIVE SYSTEM

The system proposed here enables multiple participants to check BIM data in real time, exchange opinions on design and, most importantly, manage files

by field because permission management settings are classified according to user type. The system also enables interested participants from various fields to freely collaborate in real time, or review or amend designs in regionally dispersed environments. For this, we used a cloud environment, which enables visible and real-time access to BIM data.

## 3.2. COMPOSITION OF CLOUD-BASED COLLABORATIVE SYSTEM

Our system is composed of three modules, as shown in Figure 1, and the functions of each module are as follows:

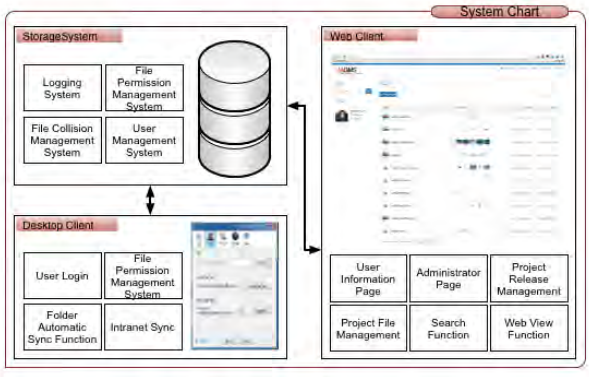



*Figure 1. Service Diagram.*

1) Storage system

The storage system manages the entire project. The system, located in the centre of the service, supports user permission management and opinion exchange among users, and manages the overall collaboration process. It contains and manages information regarding operation models and design file servers. Considering that it needs to manage users, we developed an application program using Microsoft Visual C# .NET. We also used Autodesk Revit as a commercial BIM authoring tool. To convert BIM model files into JSON files, we used Visual C# .NET, which is provided as a plugin for Revit.

The storage system is composed of a logging system, a file permission management system, a file collision management system, and a user management system. The logging system manages all work updates by converting them into logs, and can thus recover any point in time in a project. The file permission management system creates projects and sets permission by user account, file, and folder. The file collision management system sends alarm messages to clients, and changes file names to avoid collisions when users amend a file simultaneously. The user management system adds users and sets access permission them. These systems are embodied in a class and,

by setting users of the inner class and containing an operation module for the BIM authoring tool, are closely related to each other.

2) Desktop Client

The desktop client grants permissions to users to access the server. It is composed of a user login, a file permission management system, a folder automatic sync function, and an intranet sync. The user login logs into a user account and encrypts at 128 bits. The file permission management system enables the logged-in user to amend files in folders for which he/she has permissions, and to read or link to ones for which he/she does not have permissions. The folder automatic sync function automatically syncs work updates. As for the intranet sync, in case the system is connected to an intranet, it enables performance improvement as it is linked without going through a server.

3) Web Client

The Web client allows users to access a server, download BIM files for review, exchange opinions on design with other experts, and make amendments. The Web client is composed of a user information page, an administrator page, project release management, project file management, a search function, and a Web view function. The user information page identifies how users manage, amend, and change information related to a project, and manages user history. The administrator page manages the registration and permissions of project participants, monitors the current status of the project, manages errors, and updates logs. The project release management manages releases according to the progression of the project and the submission lists. The project file management enables file and folder permission management via the Internet. The search function is a function to search through work files, work information, and the library. The Web viewer function visualises release images through Web browsers.

## 3.3. CLOUD-BASED COLLABORATIVE SYSTEM SCENARIO

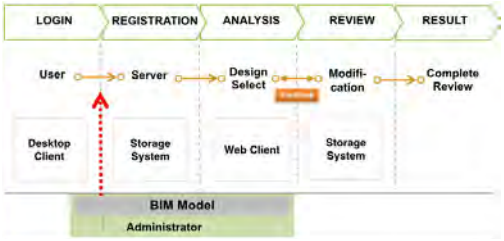



*Figure 2. Collaborative system scenario.*

The design collaboration order when using this collaborative system is as follows:

1) Users participate in collaboration as desktop clients.

2) When collaborating users decide on a BIM model to review, each user requests server registration and is granted permissions through the storage system.

3) When registration is completed, participants select what they need to review from the Web client, and determine the amendments to be made by examining the design.

4) If modifications need to be made, the user makes changes to the relevant item in the storage system.

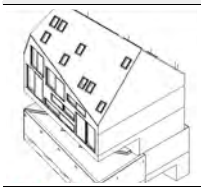
5) The modified BIM model is sent to each user for review.

## 4. Cloud computing-based file synchronisation and permission management system utilisation

### 4.1. THE SUBJECT OF COLLABORATION

We selected a multi-residential house as the subject of collaboration for our experimental scenario, as shown in Table 3. Designers as well as people/companies related to the design of the structure, facilities, and materials could participate in discussion on design in this system.

Table 3. Multi-residential house outline

| Modelling | Division | Contents |
|---|---|---|
|  | Address | Hwagok-dong, Gangseo-gu, Seoul, Korea |
| | Building area | 441.1 ㎡ |
| | Structure | Reinforced concrete construction, |
| | life | 60 years |

### 4.2. HOW TO CONDUCT DISCUSSIONS

To apply a cloud-based collaborative system, users needed to enter their names and Internet Protocol (IP) addresses on a collaborative server for access. For project management, the administrator grants users permissions to access the relevant folders. Therefore, users request the administrator for server registration in order to register their folders on the project server. If “My folder” is synchronised with the project server, the cloud environment provides a viewer for users to review BIM files. The administrator can designate files for review and grant access permissions to each user, and assist all participants simultaneously review a BIM file. Participants can select information in the BIM file that they want to review by using the viewer, and

access permission is classified according to user expertise. The users can search files they need to review from the file server and download them.

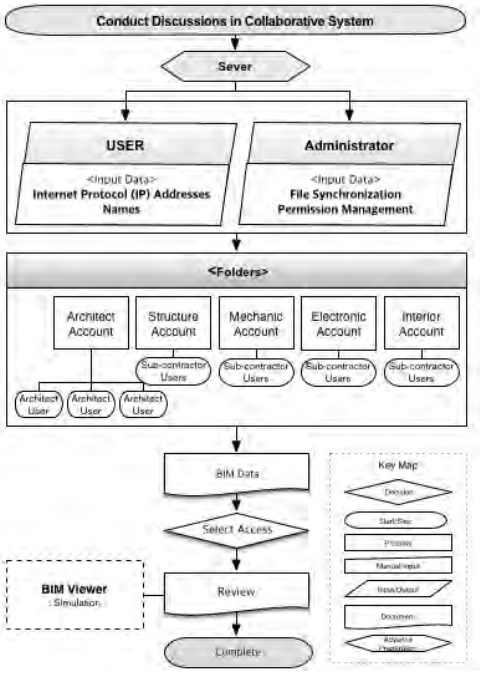



*Figure 3. Conduct discussions in a collaborative system.*

## 4.3. FILE SYNCHRONISATION AND PERMISSIONS

As shown in Figure 4 (left), users convert rvt files to json to review them in the cloud environment. To this end, files are provided in Revit plugin form. Each user reads files, for which access permissions have been granted, as JSON files. Users can review files in a mobile environment, as shown in Figure 4 (right).

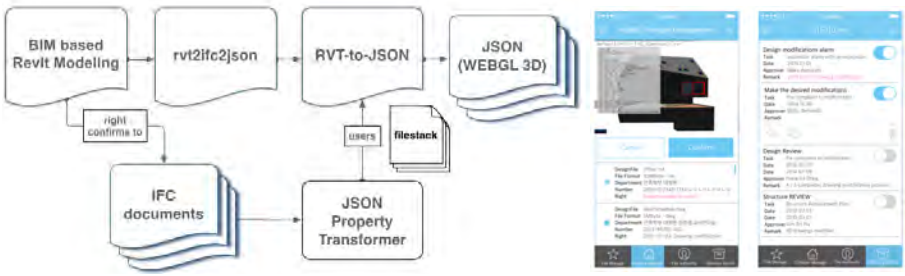



*Figure 4. Files convert process (left) and mobile environment (right).*

With the simultaneous review function, which allows administrators to make all users observe a model through the same view, users can exchange opinions more interactively. Furthermore, because folder access permission is granted to users according to expertise, they can immediately check the content they need to review for discussion on the design, and can request amendment. As shown in Figure 5, users check the model, provided following classification by the administrator, through the viewer.

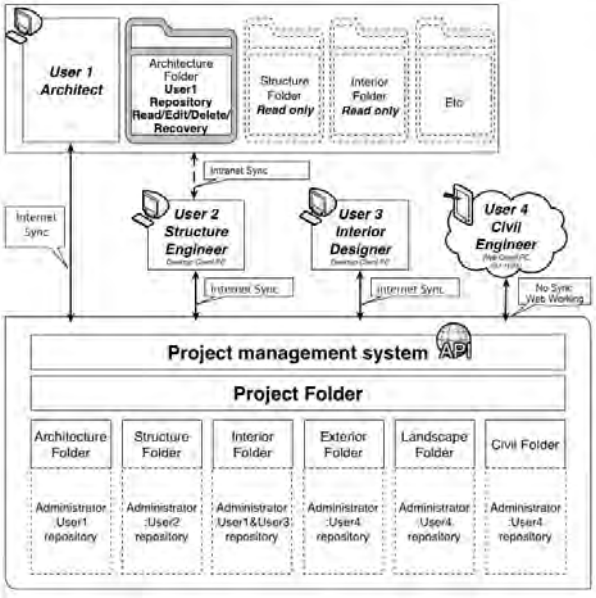



*Figure 5. Files classified by the user.*

This system is not identical to those proposed in past studies, which involve confirming and changing shape values using a BIM authoring tool. On the contrary, since the shape and attribute values of BIM files are provided as they are with the viewer through the Web, users can quickly make various amendments. Users can also review the model in real time. When there a request for amendment is made, the amended model file is re-sent to users. As shown in Figure 5, participants can again discuss the amended model, and this process is repeated if an additional amendment is necessary. If amendment is not needed, participants can move on to discuss the next model.

## 5. Conclusion

When a model classified by experts from various fields is provided to project participants, they can immediately check and amend files, thus enabling effi-

cient discussion on design and a reduction in the time spent on the design. Accordingly, in this study, we proposed a file synchronisation and permissions system in a cloud environment for efficient, real-time discussion on design. Unlike past methods in the area, which allowed users to change parameters in a limited design environment, the proposed real-time collaboration function is interactive, and enables users to examine models classified according to fields of expertise, in a visible cloud environment with a viewer. Based on our study, we can claim the following:

First, remote collaboration among various architectural design fields is possible through this system due to file synchronisation and Web-based file sharing using cloud computing.

Second, our system makes possible a dispersed version for data management, such as a 3D structure-modelling file, which is easy to manage.

Third, because work folders, which are classified according to permissions granted to each user, are built in storage form, which includes the entire history as well as information required to trace each item of the history, users do not need to depend on a central server; this increases efficiency.

In future, we plan to implement technology to reflect amendments made through discussion in real time, and implement architectural design in a Web-based environment.

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# ENHANCE ARCHITECTURAL HERITAGE CONSERVATION USING BIM TECHNOLOGY

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**Abstract:** Common problems tend to surface during the restoration and maintenance of wooden structures for architectural heritage: (1) recording and communicating geometric and non-geometric information, (2) integrating and managing the multiple phases of construction and (3) the structural damage that can be incurred during the dismantling process. This leads to less confidence in the quality of restoration and maintenance. This study considers the traditional wooden structures in Taiwan as a basis to discuss the issues faced during restoration and the gap in communication between designers and builders. Using new techniques, resources and the concept of BIM, a plugin is developed for guiding restoration. It serves as a BIM-based communication platform for designers and builders, enabling the real-time exchange of information to minimise any gaps that may exist between the designers' information and that of the builders. This allows information related to the restoration to be more accurate and offers the assurance that the traditional architecture retains its original structure and value.

**Keywords:** Architectural heritage; conservation; digital achievement; BIM; wooden frameworks.

## 1. Introduction

The study of the Building Information Model (BIM) has been steadily developing over the past ten years with BIM technology being widely used in different ways. Most research has focused on using BIM technology for planning and designing new buildings but recently research has been extend-

ed to using this technology for the restoration of existing buildings and the conservation of Taiwan's architectural heritage. Because of the importance of conserving our architectural heritage, using digital technology as a means of archiving and storing information about the buildings has become an alternative approach to addressing the best way to preserve them. However, the application of BIM for the conservation of historical buildings is still facing various challenges (Volk et al, 2014).

In this research, Taiwan's traditional wooden structure is taken as an object for restoration. There are common problems encountered during the restoration process and maintenance of wooden structures:

- The recording and communicating required geometric and non-geometric information.
- Managing the integration of the multiple phases required in the construction.
- The process of dismantling the building, which could lead to structural damage.

These factors can lead to uncertainty regarding the quality of any restoration and maintenance work. It is important that information related to any restoration is accurate and assurances provided that these traditional buildings retain their original structure and value.

In this article, guidance regarding how restoration should be done is given. The use of new techniques, resources and the concept of BIM is developed as a communication platform between designers and builders. It enables the real-time exchange of information to minimise any gaps that could have existed between the designers and those doing the construction.

## 2. Research problems and tasks

During the lifecycle of any traditional building, every aspect from designing, constructing, restoring and, ultimately, demolishing the building is normally carried out under the supervision of an expert. Therefore, the experts know a great deal about restoration. While some important restoration drawings are in 2D format, unfortunately 2D drawings cannot present all the spatial information, such as hidden parts of the building. During the restoration construction phase, inadequate or incomplete information can result in communication problems occurring during the design and construction phases, thus making it difficult to ensure the quality of the restoration.

Insufficient information and the integration of information present different problems in restoration work. In this case, three stages are established for the restoration procedure:

- **Stage1. Information modelling and decisions about the restoration:** (a) Integration of information about the geometric and the non-geometric model. (b) Traditional components can't be standardised. (c) Restoration analysis, efficiency and suitability of the decision.
- **Stage 2. Site construction records and management:** (a) Lack of understanding of the restoration drawings in the design phrase and the construction phrase. (b) Improper management of the restoration data available for the construction of wooden buildings. (c) The representation of the hidden components does not correspond to the drawings of the repair designs after the components have been dismantled.
- **Stage 3. Restoration schedule and reporting:** (a) Poor communication increases difficulties in management. (b) Reporting takes up the time of those employed to do the work. (c) Unexpected occurrences cause losses in revenue and time.

According to the three stages above, restoration projects would progress more efficiently if all data were integrated and collated on a daily basis. Therefore, to improve the factors noted in these three stages, BIM technology is applied as a guidance system during the restoration of historical buildings. However, most BIM technologies introduced into the process of preserving the cultural heritage emphasise the use of a 3D reconstruction of the geometry. They also design a surface model using 3D point cloud processing with 3D scanning technology, parametric modeling methods or virtual reality technology. This is so that there can be a direct simulation by means of the automatic processing of data to be able to visualise the more complex models (Shah and Mäntylä, 1995, Arayici, 2008; Chévrier and Perrin, 2009; Boeykens and Neuckermans, 2009; Fai et al, 2011, Baik et al, 2013; Murphy et al, 2013). However, there is a lack of research into the communication between the designers and builders and a discussion of how the design drawings are interpreted and presented by the professionals in different fields.

The goal of the BIM-aided restoration guidance system, as described in this article, is to integrate information from the various professionals into a model. It also aims to ensure coordination and collaboration, update and improve the model and give feedback to every participant. This will open up opportunities to gain knowledge and to share information so that we can communicate effectively. This will lead to proficiency in the project and will keep down the cost of the design, composition, construction and the management of the maintenance work.

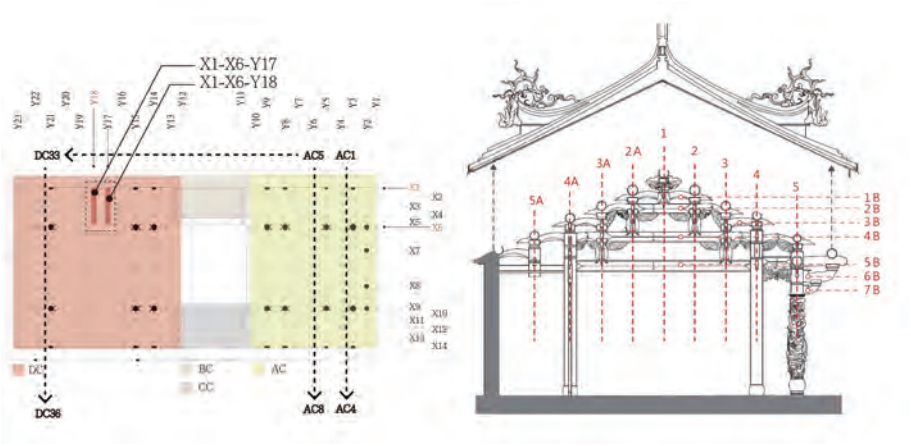



*Figure 1. Sectional view of the Diedou structure and coding sequence*

The task of this research is shown below:

- **Set up BIM components of a wooden framework and the classification of the information structure:** All the data relevant to the restoration, especially the history of each stage of the wooden framework, are included in the BIM model for analysis and categorisation.
- **Set up an information model of the deconstruction and construction of the wooden framework:** Introduce an evaluation method of the process of deconstruction and a structural analysis; optimise the analysis of the deconstruction and restoration procedure.
- **Restoration-aided design and guidance application:** Help in the communication between designer-craftsman and craftsman-craftsman. Verifying the feasibility of information about the actual construction.

## 3. BIM component development and classification

### 3.1. WOODEN FRAMEWORK STRUCTURES

The object of our research is the Hu Chi Temple located in Ma Tou, Taiwan. This temple belongs to the Diedou category of structure and every component is named according to its position; for example, the purlin and ridge that are situated in front of the main hall. However, coding by means of the spatial order in the paperwork shows that these lie along the x-axis and the y-axis, forming X1-X6-Y17 and X1-X6-Y18. In addition, for the application of the restoration-aided design and for construction management, another code will be added, based on the order in which the wooden component will be deconstructed.

The composition of the traditional wooden framework is complicated; every component has particular name. It is difficult to establish a label using a word for the coding of a component according to its spatial position. The label needs to contain essential information like the material classification, the size, the restoration record, time taken to restore, who the craftsman was, among other information. Therefore, the labeling identification code of components has to be clear and be able to be easily checked according to the visualisation model. In short, when using the BIM system for restoration, we first need a coding system, and only after this do we need to create a visualisation geometric model and non-geometric model for information.

## 3.2. WOODEN FRAMEWORKS

### *3.2.1. Information and visualisation*

Wooden structure mapping includes 3D point cloud, primitive data and pictures. Each component can apply BIM to create a plan, show elevation and section and at the same time, visualise the relationship between the measurements and spaces linked with picture. Besides presenting the component in 3D, BIM can show the damaged part of the component in a timed overlay.

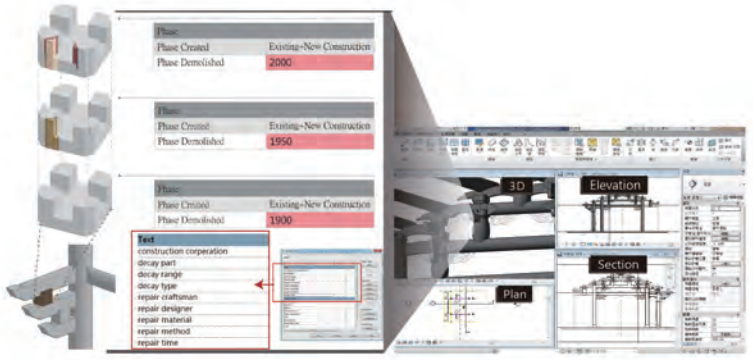



*Figure 2. 3D modeling showing the information part of the overlay in Revit*

### *3.2.2. Detail field*

A list of items for the restoration of historical buildings for non-geometric information is created mainly to describe the characteristics of a component and information about components that can't be visualised. These are normally noted by means of words and digits. The list is divided into six sections:

- Coding: Entire frame ID, unit ID, status ID, traditional ID, coordination
- Dimension of component: radius, width, and thickness.

- Materials and components: material, source, cost.
- Restoration craftsman: craftsman, contact.
- Restoration period: date of previous restoration, date of entire restoration.
- Restoration strategy: construction of restoration, level, restoration method.

Integration of the information to do with set up and time will allow staff to grasp all the information about the restoration of the wooden structure. In future, this research will be integrated with API and APP, leading to improved efficiency as any exchange of information or revisions will be instantly updated in the design stage and the construction stage.

*3.2.3. Dismantling information*

Every wooden component has an identification code: the damaged area, the mortise, the name along with the source of the material and the order of assembling/dissembling are all specified. To present these traditional wooden structures clearly, a few aspects are crucial. These include the arrangement of the space, the function of the structure, and the special characteristics of the different wooden components. More specific information about these areas helps to establish a 3D view, making it easier to address the exact issues. Furthermore, it is advised to work with technicians and architects to establish a 3D mock-up model. Simulation of the assembling and dissembling work process can be performed on this; it also serves as a preview structure and can be used to identify potential errors and prevent their occurrence.

## 4. The BIM-aided restoration guidance applications

### 4.1. CONSERVE COMPASS SYSTEM IMPLEMENTATION

In the introduction, we referred to some of the common problems that can be encountered during the process of restoring and maintaining wooden structures. This article attempts to find suitable solutions to these problems during the restoration work through the development of the BIM-aided restoration guidance system. We called it the Conserve Compass (C-Compass) system and it includes Revit plugin and mobile Apps. The main purpose of the C-Compass system we developed here is to assist with communication and coordination between the design of the repairs and the construction work on site. The data are shared immediately and on a regular basis. Further, the data shared is extensive in order to minimise any construction error. Therefore, the historical buildings are accurately preserved.

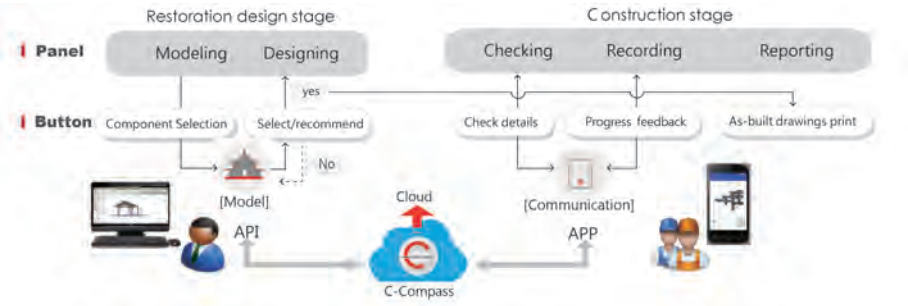



*Figure 3. Using the Conserve Compass system to assist communication and coordination between the repair design and site construction*

The main tasks of the C-Compass Plug-in are:

- The geometric and non-geometric data from designers or architects can be sent to the C-Compass cloud server through the Revit Plug-in.
- The construction managers capture the graphic and non-graphic data through the C-Compass cloud server. The parts to be repaired, the damaged cases, repair materials and other information should be reconfirmed before the construction begins.
- Instant feedback can be sent to designers from the construction site if the repair data is not understood or needs to be changed.
- Project and construction records, and reports digitally achieved are completed.

## 4.2. USING THE INTERFACE DESIGN

Based on the three stages of repair work mentioned in Chapter 2, five panels are established on the C-Compass plug-in ribbon toolbar: Model, Strategy, Communication, Record and Schedule. The Model and Strategy panels are derived from the model information and the restoration decision stage. The Communication and Record panels are derived from the site construction records and the management stage. The Schedule panel is derived from the restoration schedule and report stage. The function of each panel is described as follows:

There are two main panels and functionalities in the design stage for model information and restoration decisions:

- The Model panel helps designers to import the model into the Revit software seamlessly, convert the revised file and add public parameters.
- The Strategy Panel helps designers to get the data on the history of repair design strategies and provide suggestions.

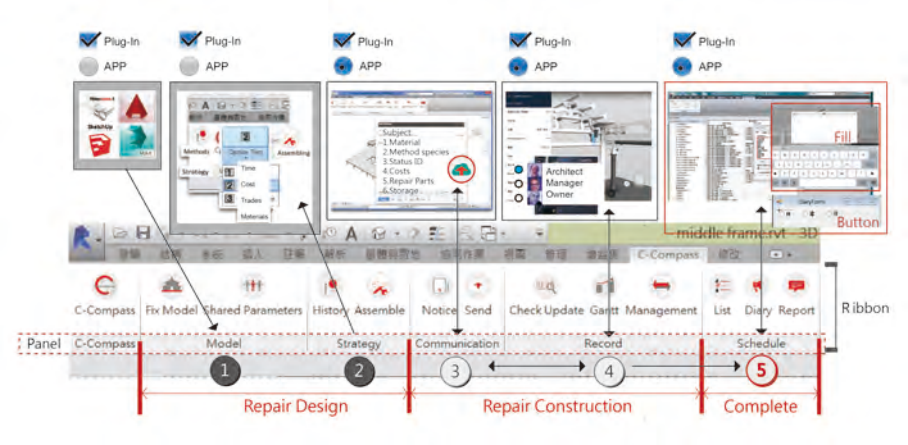



*Figure 4. The description of system workflow and panel function*

There are two main panels and functionalities both on the Revit toolbar and Mobile Apps in the construction stage for the site construction records and management.

- The communication panel on Revit transmits the designers' repair assignment to the field.
- The communication button on Mobile Apps assists the construction site managers to review and execute the assignments from the designers and get feedback to the designers immediately. Texts, pictures and videos that need to be included can be sent back by a mobile device to the cloud.
- The record panel on Revit helps designers to update replies about the assignment reply by the builders and complete the blank parametric field of the model.
- The record panel button on Mobile Apps help construction site managers to develop a Gantt chart for checking the progress and do the daily report.

After the project has been completed, a database can be built. This includes data such as an arithmetic information chart, a restoration design chart, identifying new damage that came to light during the dismantling process, unexpected damage, construction progress, material costs, etc. Designers and construction site managers can use the schedule panel to generate a construction diary, reports and charts.

## 5. Conclusions and future prospects

This research has discussed the restoration of Taiwan's ubiquitous communication problems between designers and builders in the building industry. To do this, it has introduced new technology and the concept of BIM to inte-

grate all the data related to restoration. During restoration, applications are introduced to improve the quality of construction. The development of a plug-in application showed the following results:

- During the design phase, using BIM with both 3D visualisation and captions, designers will not have to be on the construction site. Working through the cloud, they can instantly access the correction of restoration data.
- During the construction phase, the application of BIM can dismantle a complex component and recompose it through a visual information model. At the same time, BIM can present it as a 3D model immediately, receiving feedback and a new design instantly.
- In the final stage, the construction report is presented in dynamic form (geometric and non-geometric information), different restoration information is provided and collections used for users through BIM.

In the future development, we aim to try to convert design data into information, introduce the application of 4D/5D project management to pass on this knowledge to the next generation. In addition, the application of the Geographic Information System (GIS) and Augmented Reality (AR) will be added. Currently, BIM, PMSI and GIS seldom intersect with each other and are not in parallel use. Therefore these systems can be combined and integrated for management needs in whole life-cycles.

## Acknowledgements

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# DEVELOPMENT OF THE INTEGRATED MANAGEMENT ENVIRONMENT OF BIM PROPERTY FOR BIM-BASED SUSTAINABLE DESIGN

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**Abstract.** With the growing responsibility for the environmental load of building, the demand for sustainable building is increasing. Sustainable design requires an enormous amount of information, and most of this information can be captured by Building Information Modelling (BIM). In this context, the management of information in a BIM object as a container for exchanging information is necessary for analyzing a building's sustainability. However, there are problems in generating a reliable sustainability simulation model from BIM, such as the inefficiency of required information and low accessibility to a proper BIM object. In order to provide a new approach for generating a reliable sustainability simulation model in a BIM-based design process, this study suggests the integrated management environment of the property information of a BIM object.

**Keywords.** Building information modelling (BIM); BIM object; energy analysis; sustainable design; property information.

## 1. Introduction

The demand for sustainability has increased in the building sector, which has a responsibility for energy consumption and greenhouse gas emissions (Schueter et al, 2008). Sustainable building design means creating building with minimal environmental impact, by integrating the built structure and ecological systems of the biosphere (Yeang, 2006). Therefore, the realization of sustainable building design depends on the ability to gain insight into building performance through analysing and optimizing the design. In this context, Building Information Modelling (BIM) can help in implementing the sustainable design. BIM as a digital representation of building enables the application and maintenance of information in the form of a data reposi-

tory (Gu, 2010). The information involved in BIM can be reliably transferred to a simulation model for sustainability analysis (Eastman et al, 2011).

Sustainable building design requires a lot of information to conduct various analyses as the design proceeds to derive the best solution. In BIM, non-geometric information, which becomes specific and detailed depending on the progress of the design, is saved as a property of each BIM object. Therefore, a BIM object must contain property information at the required level to enable the composition of the simulation model for sustainability analysis. While some sustainability simulation tools, such as RIUKA, support data exchange between BIM and simulation to increase the accuracy of building information, BIM-based sustainability analysis is still regarded as error-prone, unintuitive and labour-intensive (Jong, 2015). A number of factors, such as insufficient information for the analysis of a BIM object used in the design, the absence of standards for the information requirement, and the manual input of required information (Crosbie et al, 2010; Kim, 2015), have been identified as major problems that decrease the reliability of the simulation model, which determines the accuracy of building performance.

Therefore, the purpose of this paper is to suggest the integrated management environment of BIM property information as a new approach for a generating reliable sustainability simulation model in the BIM-based design process. By providing the environment, where the required information in each design phase for the sustainability simulation is systemically managed and input automatically into BIM object as a property, this study aims to improve the work efficiency of the BIM-based sustainable design process.

## 2. Research methodology

In this paper, energy analysis which requires the largest amount of building information of various sustainability analyses is discussed. In particular, building envelope information is focused on because it can be clearly defined by a BIM object. However, the geometry, which is abstracted to a thermal building model according to the model view definition (Maile et al, 2007), is excluded from this study. This study has been conducted as follows:

- Conduct a literature review of energy analysis, a BIM object, and BIM object library to deduce issues and the direction of the research.
- Suggest an information management framework for BIM object, including classification, property structure and information requirement.
- Develop a BIM object property management system connected to an Excel-based database managing the information of BIM objects.

- Perform BIM-based energy analysis by utilizing the developed information management environment to evaluate its appropriateness.

## 3. Literature review

### 3.1. BIM-BASED ENERGY ANALYSIS IN DESIGN PHASE

Energy analysis predicts the energy performance of a given building with a simulation tool according to pre-established criteria and basic principles of energy simulation (Maile et al, 2007). Currently, the BIM Guides of the US and Finland define energy analysis as an essential task for utilizing the BIM model. The scope of BIM-based energy analysis in each design phase is as follows: 1) Concept Design: Simulation to provide information for design decisions; 2) Schematic Design: Evaluation design alternatives; 3) Design development: Analysis of selected design to modify building systems; 4) Construction Document: Analysis of remaining design decisions and evaluation of relevant energy codes (GSA, 2015; Senate Properties, 2012).

### 3.2. BIM OBJECT

Building is represented as a composed set of definitions of objects in BIM, which is object-based parametric modelling technology (Eastman et al, 2011). This means that a BIM object is the essential unit in which the information is stored. A BIM object takes the role of a container for the exchange of information (Hjelseth, 2010) between the BIM model and the analysis input model. The BIM-based design process can be interpreted as the process of modifying and recombining BIM objects to create the best design alternative. Therefore, BIM objects must be developed at a more advanced level in accordance with the design phase, and this level needs to be divided by a clear standard. A BIM object is categorized into three types according to its status in the project lifecycle. As a project progresses, the proposed Template object will be replaced by a Generic object to describe the designed building. Furthermore, this will be exchanged to Product object as an as-built part of the building (Afsari, 2014; British Standard, 2012).

### 3.3. THE STATUS OF DEVELOPMENT OF BIM OJECT LIBRARY

A BIM object library is a categorized collection of BIM objects and content, which are frequently used in the BIM design process, to ensure they are easy to be used. The availability of BIM objects is an important factor in achieving success in BIM (NBS, 2014). There is considerable interest globally in developing BIM object libraries to support various uses of BIM (Duddy, 2013). This interest has led to the development of various BIM object librar-

ies at national and private levels. Five development cases have been selected to investigate the generic framework and the comparison results are summarized in Table 1. Most libraries do not provide accurate information on the object type and provide the BIM object with un-unified levels of information under their defined content framework, according to manufacturers. This means that, eventually, the performance information must be manually input whenever a BIM object is used. This makes the user spend a lot of time acquiring the BIM object in a well-developed level corresponding to each design phase. In order to suitably use and manage information in BIM object, the followings have been identified as necessary:

- The classification of the BIM object and the property structure to establish contents framework on the purpose of BIM use.
- A clear definition of properties set by BIM use. Each property has to be suggested according to the information level of each design phase.
- Explicit information on the type and level of the BIM object.

Table 1. BIM object libraries and their generic frameworks

| | UK NBS National BIM Library | Product Spec | BIMobject | Autodesk Seek | BIM Components |
|---|---|---|---|---|---|
| Categorization of BIM object | Uniclass2 | Customized categorization | Uniclass, NBS code | OmniClass, Uniformat, MasterFormat | Customized categorization |
| Type of BIM object | Generic object, Product object | Generic object | Generic object, Product object | Generic object, Product object | Generic object |
| LOD information | Yes | No | No | No | No |
| Type of supported BIM performance | COBie | - | - | - | - |

## 4. Management framework for BIM object information

BIM objects are integrated into the BIM model to create a holistic building database. This integration requires the object classification, property structure, and naming convention to translate an object into the standard structure (Eastman et al, 2011). In this study, classification system, property structure, information level, and property requirements have been established to efficiently manage and use BIM objects in the sustainable design phase.

### 4.1. CLASSIFICATION OF BIM OBJECT

Classification is the basis of sharing information and the standard representation of information and enables the efficient data exchange and management

(Cho et al, 2014). Element classification of the Korean Construction Classification System (KCCS) has been adopted as the classification system of BIM objects for the Korean construction industry. This classification has been developed to be compatible with ISO and Uniclass and has various facets, which enable the identification of the construction work in multidirectional aspects.

## 4.2. PROPERTY STRUCTURE

In order to exchange and share information, a common property at a minimum level should be defined (Lee et al, 2014). Prior to this, property structure, as a definition and classification system of properties, is necessary for generating, identifying, and managing information in a common format. In the situation of an absence of a proper domestic classification for application, this study establishes the BIM property classification, as property structure under domestic conditions. The three classifications of Construction Materials Property Information and Standard of Korea, Omniclass table 49, Uniclass TableN have been analyzed, and seven common property types (identifier, product, space/program compliance, location, size, performance, and facility management) have been extracted. The BIM property classification shown in Table 2 is established by categorizing and layering the common properties. This classification consists of three levels, and each level has a two-digit code.

Table 2. BIM property classification (Level 1 and Level 2)

| Level 1 | | Level 2 | | Level 1 | | Level 2 | |
|---|---|---|---|---|---|---|---|
| Code | Item | Code | Item | Code | Item | Code | Item |
| 01.00.00 | Facility Info. | 01.01.00 | Project info. | 04.00.00 | Physical Info | 04.01.00 | Size Info. |
| | | 01.02.00 | Program/ Space Info. | | | 04.02.00 | Geometric Info. |
| | | 01.03.00 | Location Info. | 05.00.00 | Performance Info. | 05.01.00 | Material |
| 02.00.00 | Identification Info. | 02.01.00 | Object Info. | | | 05.02.00 | Performance |
| | | 02.02.00 | Classification System | 06.00.00 | Facility Service Info. | 06.01.00 | Repair |
| 03.00.00 | Product Info. | 03.01.00 | Manufacturer Info. | | | 06.02.00 | Inspection |
| | | 03.02.00 | Specification | | | 06.03.00 | Assurance |

## 4.3. INFORMATION LEVEL OF BIM OBJECT

The scope of energy analysis differs from that of the design phase, and the level of information requirements of BIM objects also differ from those of the design phase. The BIM object has to be fully integrated into the BIM

model to generate an energy simulation model that satisfies the energy analysis scope in accordance with the design phase. Therefore, mapping the BIM object type into LOD as a standard of the development level of the BIM model by design phase has been conducted in order to define the minimum information requirement level of the BIM object for establishing a simulation model. BIM Object type and LOD are clearly mapped, and the information levels of the BIM object is defined as type of information, as shown in Table 3. The information levels of three types of BIM objects are defined as follows: 1) Template object: LOD 100-200; 2) Generic object: LOD 300; 3) Product Object: LOD 400-500.

Table 3. Information level of BIM object type

| Object Type | Template Object | | Generic Object | Product Object | |
|---|---|---|---|---|---|
| LOD (Design Phase) | LOD 100 (Concept Design) | LOD 200 (Schematic Design) | LOD 300 (Design development) | LOD 400 Construction Document | LOD 500 (As-Built) |
| Definition | Intended to guide production of generic object | | Intended for use when the object is not resolved into a product | Intended to represent an obtainable product | |
| Information Level | Identifier Info, Physical Info | | Identifier Info, Physical Info, Performance Info | Identifier Info, Physical Info, Performance Info, Product Info | |

## 4.4. PROPERTY REQUIREMENTS FOR ENERGY ANALYSIS

Accurate information should be provided at proper level at the right time to successfully perform the energy analysis. In this study, the required level and type of information for the energy model of each design phase are supplied by BIM object type. Therefore, the property requirements for the energy analysis of BIM objects are extracted according to the object type. This study focuses on seven building element objects (column, external wall, internal wall, slab, door, window, curtain wall, and roof) and space objects. Riuska and EnergyPlus, which are recommended in GSA BIM guide, CO-BIM guide and Korean Public Procurement Service BIM Guide as simulation tools, were selected in order to analyse the input parameters of energy simulation. The BIM properties of eight BIM objects that must be defined to generate the energy simulation input model of Riuska and EnergyPlus have been derived. The derived properties are systematized according to BIM property classification and categorized by object type, as shown in Table 4.

Table 4. Property requirements (example case of BIM wall object)

| Level 1 | Level 2 | Level 3 | Template Object | Generic Object | Product Object |
|---|---|---|---|---|---|
| Facility Info. | Project Info. | Facility ID | o | o | o |
| | | Facility name | o | o | o |
| | Program/Space Info. | Space/Zone ID | o | o | o |
| | | Space/Zone name | o | o | o |
| | Room Info. | Room ID | o | o | o |
| | | Room name | o | o | o |
| | Location Info. | Story Number | o | o | o |
| | | Exterior/Interior | o | o | o |
| Identification Info. | Object Info. | Object Type | o | o | o |
| | | Description | o | o | o |
| | Classification Info. | Element code(KCCS) | o | o | o |
| Product Info. | Manufacturer Info. | General Type | o | o | o |
| | | Manufacturer Type | | o | o |
| | | Company Name | | | o |
| | Specification | Product Name | | | o |
| | | Product Serial Number | | | o |
| | Material Info. | Material | o | o | o |
| Physical Info. | Size Info. | Thickness | o | o | o |
| | Geometric Info. | Area | o | o | o |
| | | Volume | o | o | o |
| Performance Info. | Performance Info. | R value | o | | |
| | | U value | | o | o |
| | | Thermal conductivity | | | o |
| | | Specific heat | | | o |
| | | Density | | | o |
| | | Absorption-Value | | | o |
| | | Air Infiltration | | | o |

## 5. Integrated management environment of BIM object information

### 5.1. INTEGRATED MANAGEMENT SYSTEM OF BIM OBJECT

This study proposes the integrated management system of BIM object information, in order to solve the problem of the scalability in BIM modelling that many users encounter (Eastman et al, 2011), as well as the inefficiency in the management of property information discussed in the previous chapter.

The integrated management environment consists of the information management framework, the BIM object property database and the BIM object property management system. In this environment, property information for instances of eight BIM objects is managed in each Excel-based database to which the management framework is applied. In cases of necessity only, the property information is automatically input into the corresponding BIM object in BIM authoring tool, as illustrated in Figure 1. Using separately managed performance information for energy analysis, the BIM model could

include only the common and key information for generic usage. Therefore, the capacity of the BIM model could be kept to a minimum size during the design process. In addition, users can manage the specific property information of each object with accuracy and integrity, through the separately built Excel-based databases on eight objects.

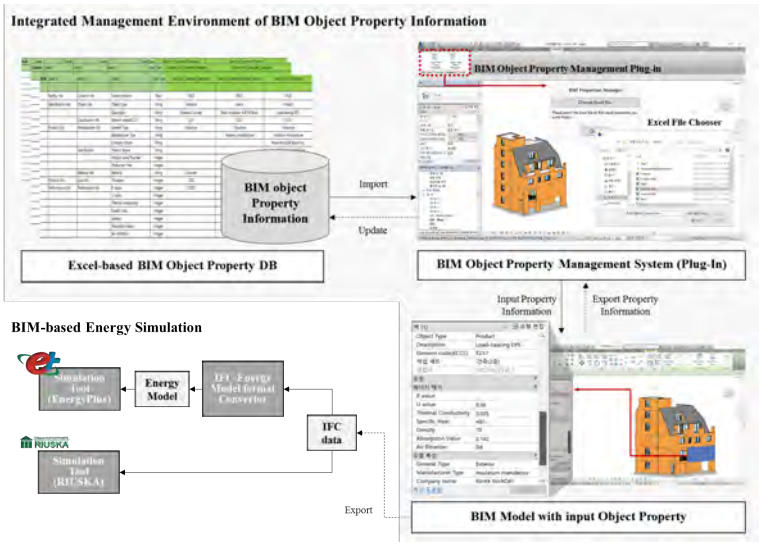



*Figure 1. Suggested integrated management environment of BIM object information*

This system is a plug-in program of Autodesk Revit, which has the highest market share in Korea. The system opens the property database and brings up the name and properties of a BIM object, and adds properties to the object of the same name in the BIM model. The property information of 1080 instances of three object types is defined in the property database.

## 5.2. VERIFICATION

To evaluate the appropriateness of the development, BIM-based energy analysis was performed in the developed integrated management environment of the property information. Energy analysis on a five-story residential building, which received Grade-4 (consuming 230~270kwh/$m^2$ in year) in Korean Energy Efficiency Rating, is conducted through the following three steps: 1) Create BIM models of the real building on three levels of LOD; 2) input the property information of the BIM object with corresponding LOD into the BIM model using the developed system; 3) generate the energy model (IFC format) from each BIM model and perform an energy simulation with RIUSKA. The results of the energy simulation are shown in Table 5.

Table 5. Results of energy simulation

| | LOD 200 | LOD 300 | LOD 400 |
|---|---|---|---|
| BIM Model |  |  |  |
| Used BIM Object type | Template Object | Generic Object | Product Object |
| Energy Consumption | 204.2 (kwh/ $m^2$·y) | 231.5 (kwh/ $m^2 \cdot y$) | 264.7 (kwh/ $m^2 \cdot y$) |

From the process of energy analysis and its results, the derived implications are as follows:

- The result of the energy analysis well depicts the building performance as BIM model becomes detailed.
- Key property information required for energy analysis is sufficiently provided through the developed system and property database.
- The information level of the BIM object closely matches the LOD.
- The energy analysis of the BIM model in each LOD is successfully performed without omitting object information.

It is indicated that the developed management environment enables to generate a reliable sustainability simulation model and support the BIM-based energy analysis process accurately and efficiently.

## 6. Conclusion

Sustainability analysis for building design is a process to evaluate a building performance by parameters. The reliability of the analysis result is determined by the accuracy of entered information. Similarly, in a BIM-based environment, the analysis result is influenced by the property information that is stored in the BIM object during the design process. Therefore, the accessibility of the right BIM object that contains the accurate information at the right time is essential in BIM-based sustainability analysis. This study is basic research for developing an integrated property management environment to effectively manage and utilize BIM object information. The information management framework, the property information database and the management system is developed as components of the environment. The results of this study could ensure the consistency and appropriateness of information, minimize the capacity of the BIM model, and improve work effi-

ciency of BIM-based sustainability design. The authors will extend the research scope to MEP BIM objects, and apply this property management environment to another use of BIM.

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# A STUDY ON DEVELOPMENT OF THE IFC-BASED INDOOR SPATIAL INFORMATION FOR DATA VISUALISATION

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**Abstract.** MOLIT authorised Indoor Spatial Information as Basic spatial information in 2013. It became a legal evidence for constructing and managing Indoor Spatial Information. Although it has a little advantage to utilise as service level that Indoor Spatial Information by laser scan or measurement, it has a lot of problems such as consuming many resources, requiring additional progresses for inputting Object Information. In conclusion, it is inefficient to utilise for the maintenance and domestic AEC/FM field. The purposes of this study is to output Indoor Spatial Information by operating IFC model which based on open BIM and to improve availability of Indoor Spatial Information with data visualisation. The open-sources of IFC Exporter, an inner program of Revit, is used to output Indoor Spatial Information. Directs 3D Library is also operated to visualise Indoor Spatial Information. It is possible to inter-operate between XML format and the objects of Indoor Spatial Information. It can be utilised in various field as well. For example COBie linkage in facility management, construction of geo-database using air-photogrammetry of UAV, the simulation of large-scale military operations and the simulation of large-scale evacuation. The method that is purposed in this study has outstanding advantages such as conformance with national spatial information policy, high level of interoperability as indoor spatial information objects based on IFC, convenience of editing information, light level of data and simplifying progress of producing information.

**Keywords.** Indoor spatial information, data visualisation, open BIM, IFC.

## 1. Introduction

In 2013, the Ministry of Land, Infrastructure and Transport officially added the highly valuable and applicable '3D spatial information model' and 'indoor spatial information' to the 'essential spatial information' to build and maintain the key national spatial information. To this end, the revised enforcement decree of the Act on National Spatial Information was enforced as from June 19, 2013. Indoor spatial information concerns the interior of artificial structures including ground and underground infrastructure. National spatial information infrastructure serves as the foundation of all spatial information, enabling the diverse application, integration and convergence of multiple spatial information. The indoor spatial information added to the national spatial information infrastructure has laid the statutory foundation for implementation and maintenance of national indoor spatial information. Also, in January 2014, the Ministry of Land, Infrastructure and Transport and the Korea Agency for Infrastructure Technology Advancement published the "2014 Infrastructure Technology R&D Project Implementation Scheme" intended to develop the technology for analysis/application of big data about spatial information and application of open sources and thus to help people create some happy space. Specifically, the plan is focused on developing the technology for building urban infra information and indoor/outdoor spatial information conducive to setting up the urban environment safe against disasters by 2020. However, currently, indoor spatial information is built with GIS-based measurement and laser scanning, which calls for much time and human/material resources. In addition, in the current method of building indoor spatial information, the opening/closing of doorway objects cannot define the space for themselves. Instead, captured images are mapped onto simple 3D objects without any property information. In this context, the present study perceives the importance of building the indoor spatial information, seeks a method of extracting and visualizing the open BIM-based indoor spatial information, and designs and implements a relevant tool. Moreover, to enhance the applicability of indoor spatial information, IFC which is the standard model of building information is used to secure interoperability. This is consistent with the Ministry of Land, Infrastructure and Transport's 3D spatial information model. In addition to that, the Ministry of Land, Infrastructure and Transport has established a legal basis for building and maintaining the indoor spatial information by designating the 'indoor spatial information' as part of the 'spatial information infrastructure.' Although the indoor spatial information based on measurement and laser scanning is viable for service, it is inefficient in terms of maintenance and applicability to domestic ARC/FM because it consumes significant hu-

man and material resources and requires extra information processing for properties to be entered. Thus, the present study sets up the following objectives and proposes a method of visualizing the indoor spatial information: first, to develop a viable method of data visualisation that is capable of meeting the needs for both special (analysis) and general (service) aspects of indoor spatial information; second, to map out a method of visualisation facilitating the data generation and the adaptation of information; and third, to secure the interoperability of 3D indoor spatial information objects and lighten the data about indoor spatial information.

## 2. Developing a tool for visualizing the indoor spatial information

### 2.1. DESIGN

The present study develops a module for extracting IFC-based indoor spatial information and an IFC-based visualisation module for visualizing the extracted indoor spatial information objects using Autodesk's BIM tool, Revit, which has the highest domestic market share and is used most frequently in relevant literature. Revit provides an API based on .NET framework. .NET-based languages, e.g. VB.NET, C#, and Managed C++, are used to develop Revit's API. Revit is revised annually. As for Revit plug-ins, the API for program development and the structures and properties of object classes significantly vary with revised versions. The present study uses Revit Architecture 2014 version to develop a module for extracting the indoor spatial information. C# is used here for development. C# and Open Cascade are used to develop the IFC viewer as a stand-alone application. The system development environment includes the following:

- Microsoft Visual Studio 2010
- Microsoft .NET Framework 4.0.
- Autodesk Revit Architecture 2014
- Open Cascade Library
- Microsoft Direct 3D API

IFC4x1 has now been released since the first development in 1994. IFC Release 1.0 is defined as a distributed project model used for AEC/FM projects for the entire life cycle. Earlier releases include models supporting the processes within Architectural Design, HVAC Engineering Design, Facilities Management, and Cost Estimating, but partially represent the range of project models, which warrants the reinforcement of earlier releases. Therefore, Release 2.0 and later versions expand the domain scope of IFC Object Model, and include such domain processes as building, estimation, FM, in-

frastructure and laws. Release 2.X and later versions provide stable cores and platforms for extended development, and retain the scope of IFC Release 2.0 model to improve the quality of model. These features provide developers with higher investment values in relation to core development, whilst ensuring users can make the most of information. At present, Release 2.X version has been significantly developed into IFC4, whilst IFC4x1 is being improved.

## 2.2. A MODULE FOR AUTOMATIC EXTRACTION OF THE INDOOR SPATIAL INFORMATION

The present study develops a module from the Revit model to generate an IFC file of space and doorway objects needed to define the indoor spatial information. The representation of openings, e.g. windows and doors, is added in defining the indoor spatial information to increase the applicability of the built indoor spatial information. The indoor spatial information including openings-related information is applicable to evacuation, military strategies and human behaviour simulations. As the extraction module of indoor spatial information, the open source of IFC Exporter, a program exporting IFC files from Revit, is used. The open source can be modified freely for intended purposes. IFC Exporter has the classes. Amongst all, Exporter.cs is a class in charge of controlling all the export process and calling associated classes to proceed with IFC output.

Excluding the output of information about the objects other than space and exits, this study develops a module to get IFC output of objects matching the purpose of this study by modifying the IFC Exporter module. IFC Exporter subdivides all objects of Revit largely into five groups before exporting them: SpatialElements involving spatial objects, NonSpatialElements involving doorways, Containers, Grids and Connectors. Here, only SpatialElements and NonSpatialElements are considered for spatial and doorway outputs. The IFC Exporter's interface shows an export option for extracting the indoor spatial information (KBIM) as in Figure 1.

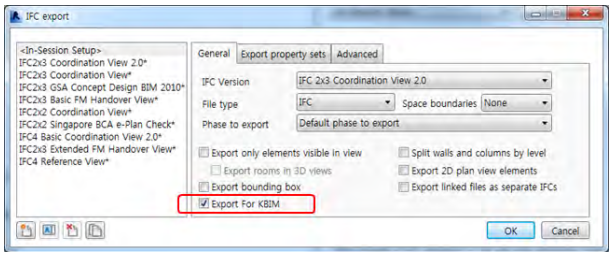



*Figure 1. Added IFC Exporter Option*

The present visualisation module of indoor spatial information reads space and door information from the output IFC (file) to identify the inter-space routes and represent them as 2D information. To visualise the IFC model, the IFC file is parsed and stored in memory in the format that can be read by the development program. For the 3D solid information operation, Open Cascade Library is used. For the 3D visualisation, Direct3D Library is used.

To extract IFC-based indoor spatial information, spatial location and forms, doorway location and directions of openings are defined using IfcSpace and IfcDoor, both of which are primary components for representing the indoor spatial information in IFC. Here, IfcSpace defines the location and volume (form) of indoor spatial information, whilst IfcDoor defines inter-space relations (connected routes). Minimizing the information usage increases data processing and the operation speed of the visualisation module. Also, the direction of openings available via IfcDoor is an indispensable component for dynamic simulation, e.g. evacuation and military training. The IfcSpace and IfcDoor information extraction modules developed here extract 2D and 3D information from IfcSpace and IfcDoor objects included in IFC and display information to users as requested. 2D information is applicable to the shortest path between locations, the emergency evacuation routes, and regulatory reviews. IfcSpace's form information is represented as FootPrint including 2D-based information and Body information including 3D information. The indoor spatial information visualisation tool is designed to embrace all approaches to form representation. The doorway information can be extracted from IfcDoor. Importantly, accurate information about the direction of openings need be extracted. Yet, IfcDoor includes information about location and direction of openings.

Therefore, it is necessary to refer to the Profile Representation under the IfcDoorStyle parameter to see the details about shapes and types of doors. At the same time, the FootPrint representation identifier helps extract correct 2D forms. The extracted IFC-based indoor spatial information is visualised in the system structure shown in Figure 2. In view of main functions, it consists of 'Create IFC Structure' module for systematisation of IFC information structure, 'IFC Parsing' module for reading the selected IFC model information into the system, 'Solid Calculation' for performing operation on the parts of the parsed IFC information that need solid operation, and 'Visualisation' module for visualizing and displaying information on computer screens.

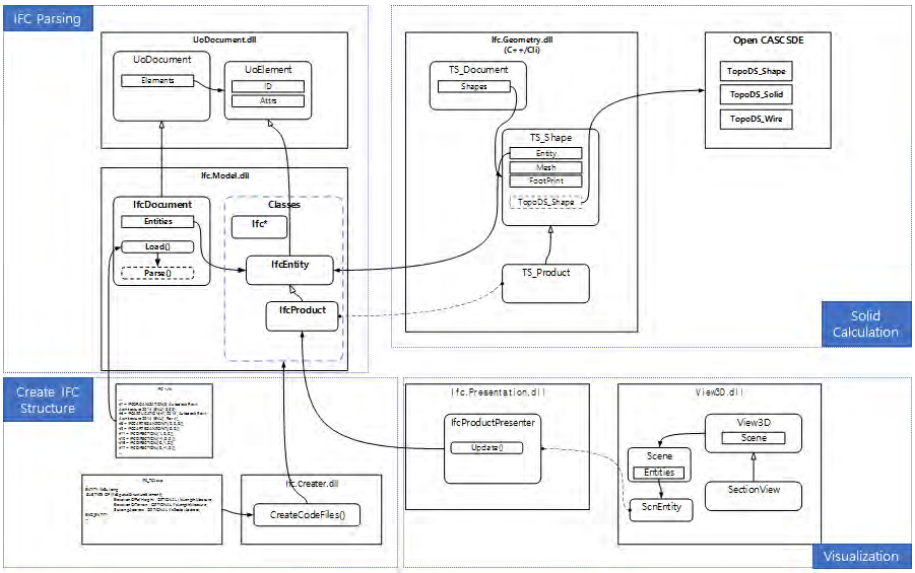
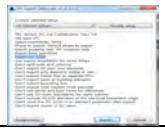
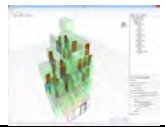
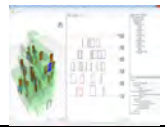



*Figure 2. Visualisation Structure of IFC*

## 2.3. VISUALISATION OF INDOOR SPATIAL INFORMATION

TABLE 1. Process of Indoor Spatial Information Visualisation

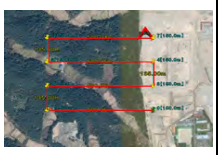
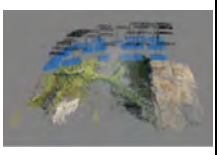
| ① | ② | ③ | ④ | ⑤ |
|---|---|---|---|---|
|  |  |  |  |  |

The visualisation of indoor spatial information goes through the following phases. ① Buildings are modelled with Revit 2014 version. As the test model, a random building designed for neighbourhood facilities which account for the highest percentage of all buildings is chosen. ② The automatic module for extracting the indoor spatial information based on Revit IFC Exporter developed here is used to generate the indoor spatial information objects with an IFC extension. ③ The indoor spatial information objects IFC file generated through the automatic extraction module is opened with the tool for visualizing the indoor spatial information developed here (the visualisation tool is designed to freely enlarge/reduce and rotate the indoor spatial information in 3D environment). Buildings' indoor spatial information is visualised as translucent boxes whose inner parts are visible. Given that

commercial IFC viewers distributed for free represent the indoor spatial information objects opaquely, the present study attempts the translucent visualisation for the sake of intuitive spatial perception. Also, windows and doors including directions of openings are represented as separate objects for intuitive viewing, with the information about the properties of IFC objects being fully implemented. The property information is placed at the lower right corner of the interface for the indoor spatial information visualisation tool. ④ At the upper right corner, each floor and object can be selectively viewed and converted from 3D to 2D display. ⑤ The conversion to 2D display enables component-specific selective visualisation of indoor spatial information objects from the perspective of floor plans and elevation formats.

## 3. Applicability to GIS-based UAV

TABLE 2. Status of BIM-based drawing guidelines

| ① | ② | ③ | ④ |
|---|---|---|---|
|  |  |  |  |
| Fright Route Set-up | Images Collect | Point Cloud24) | 3D Object |

Currently, to build spatial information about an expansive area, GIS-based UAV or low-altitude drones are used. Noted for superior functionality and portability, UAV is widely used for urban planning maps, bush fire surveillance, reconnaissance, combat missions, meteorological observation, coast defence, marine pollution detection and planetary exploration. Table 2 shows the process of creating the 3D spatial information via UAV. Spatial information generated with GIS-based UAV is effective for building 3D spatial information of an expansive area. As the spatial information is created based on real images captured, separate mapping is not needed. Yet, as the generated spatial (surface) objects are limited to coordinates and shapes, they are far from involving the information about buildings and infrastructure. Hence, the proposed integrated spatial information in connection with indoor spatial information is expected to exert significant effects. The conceptual schema of the integrated spatial information is shown in Figure 3. Likewise, it is viable to incorporate the spatial information produced via measurement and laser scanning of underground infrastructure.

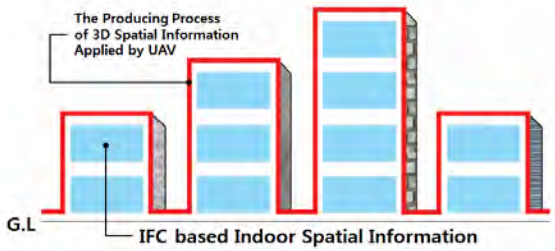



*Figure 3. The Concept of Integrated Spatial Information (Section)*

## 4. Conclusion

Given the importance of building and maintaining indoor spatial information and the need to retain the strengths of existing methods (e.g. accuracy of measurement/image capturing and laser scanning as well as relevant service provision) and to remedy the weaknesses (e.g. missed property information as well as time and cost taken to build such information), the present study uses the open BIM-based IFC standard format to design modules for extracting the indoor spatial information and develop a tool for visualizing the information. In addition, this study implements the indoor spatial information as 3D spatial objects, which are consistent with the infrastructure technology R&D project, or the open BIM-based technological environment development plan. The developed visualisation tool for indoor spatial information facilitates intuitive understanding of 3D indoor spatial information by applying data visualisation technology, and selectively displays information to users as necessary. The indoor spatial information objects are characterised by the following. First, lightness of data is secured by selectively extracting and defining the information on demand from IFC. Therefore, the information is applicable to urban and national simulation databases not just to small-scale buildings and infrastructure. The IFC original file size generated with LOD 200 equivalent to BIM modelling level is 14,765KB in comparison to 967KB of the indoor spatial information generated here, or approximately 1/15 times lighter than the existing file size. Second, information is easily produced and edited. There is no need to do extra work for indoor spatial information because the indoor spatial information is extracted from the open BIM-based IFC model, which facilitates the production and edition of information. This is attributable to IFC's structure where objects' properties can be edited. Editing properties is as simple as attaching memos to notebooks. Moreover, as the Ministry of Land, Infrastructure and Transport plans to replace the Seumteo System for building-related licence/permission with an open BIM-based 3D Seumteo and be supplied with IFC, there seems to be no need to build separate indoor spatial information using devices such as

3D scanners for building the indoor spatial information in case any building environment requires developing a BIM model. Third, the indoor spatial information objects using IFC are XML-based, having a high interoperability with other formats (CityGML, LandXML) in the field of AEC/FM. Also, they are applicable to spatial maintenance of infrastructure in connection with COBie and GIS-based UAV, as well as diverse simulations including evacuation routes and military strategies. To build and apply the indoor spatial information in near future, it is necessary to define and extract objects relevant to informal indoor space, to extract the information about inter-space routes (stairs, elevators) and about openings available for evacuation/escape for an accurate analysis of evacuation simulation and to visualise relevant data for intuitive representation. Furthermore, a specific process need be clarified regarding the interoperability with COBie for the space-based maintenance of infrastructure.

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# DEVELOPMENT OF SCHEMATIC ESTIMATION SYSTEM THROUGH LINKING QTO WITH COST DB

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**Abstract.** Cost estimate in architectural projects is an important factor for decision-making and financing the project in both early design phase and detailed design phase. In Korea, estimate work based on 2D drawing has generated problems of difference form QTO according to worker's mistake and know-how. In addition, 2D-based estimation are obtained uncertainty factors of estimation depending on lack of information due to becoming larger and more complex than any other project of the architectural project. In order to solve limitations, this study is to suggest an open BIM-based schematic estimation process and a prototype system within the building frame through linking QTO and cost information. This study consists of the following steps: 1) Analysing Level of Detail (LoD) to apply to the process and system, 2) BIM modelling for open BIM-based QTO, 3) Verifying the quality of the BIM model, 4) Developing a schematic estimation prototype system. This study is expected to improve work efficiency as well as reliability of construction cost.

**Keywords.** Cost DB; Industry Foundation Classes (IFC); Open Building Information Modelling (BIM); schematic estimation; Quantity Take-Off (QTO).

## 1. Introduction

Cost estimation in construction projects is an important factor for decision making in both the early phase and the detailed design phase. The construction phase based on Quantity Take-Off (QTO) can function for procurement and predicting construction costs (Tuan and Park, 2014). In Korea, estimate work based on 2D drawing has generated differences from QTO based on workers' mistakes and know-how. In addition, 2D-based estimation lacks uncertainty factors for estimation (Choi et al, 2006). Accordingly, construc-

tion project seek more accurate QTO and cost estimation. Reliable estimates require accurate building information. Inaccurate information from QTO produces estimation errors because schematic estimation in the early phase process is multiplied by unit cost. To solve 2D-based QTO task problems, research on 3D based QTO has been active. However, various problems exist in 3D based QTO (Kim et al, 2013).

The purpose of this study is to describe methodology connecting BIM data properties (e.g., volume, area) with cost and develop a schematic estimation prototype system. The scope of this study includes primarily a building frame. This accounts for more than 50% of the total cost of a project. Schematic estimation is helpful to select design alternatives and construction plans. The schematic estimation prototype system developed in this study has schematic estimation modules for reinforced concrete work and steel frame work. This paper is based on a research first reported in the *JCDE*. This study was extended to the scope on the previous research (Choi et al, 2015) conducted by the authors.

The methodology of this study to achieve this purpose is as follows.

- The authors have investigated research on QTO/cost estimation.
- The authors have suggested an open BIM-based QTO and schematic estimation process through BIM modelling, physical quality check and data quality check for schematic estimation of the framework.
- The authors have developed the building frame QTO and schematic estimation prototype system called *InSightBIM-Estimation* using information from the IFC model and the linkage between quantity information and cost DB.

## 2. Literature survey

### 2.1. DEFINITION OF SCHEMATIC ESTIMATION

The cost estimation for each design phase can be defined as follows: conceptual estimation in the planning phase, schematic estimation in the schematic design phases, and detailed estimation in the design development phase, respectively (Vaidya et al, 2009). The purpose of schematic estimation is feasibility study and rough cost estimation. The goal at the end of schematic design is to have a design scheme, program, and estimate that are within budget. The method of this study is to extract architectural elements' quantity through BIM model for schematic estimation. It is difficult to extract the volume per unit area for construction costs. This induced schematic estimation reliability increases.

## 2.2. ANALYSIS OF ADVANCED RESEARCH

QTO and estimation have used automated systems since the 1990s and have changed from 2D-based automatic systems into 3D-based automatic systems. The trends of research are shown in TABLE 1.

On-going researches trend has been studied methodology of 3D-based object-oriented and increased studies on linkages among various tasks about CM-Cost, Energy-Cost and so on. Previous research on 3D-based QTO and estimation used a data model for QTO/Estimation for the reason that it was not performed the task through 3D model. This study proposes an integration model using QTO task and estimation task through the concept of Open BIM. The concept of the IFC model can progress through the entire task of the building life cycle, as long as workers input the necessary data for the task; design, construction, facility management. Thus, this study suggests a methodology for schematic estimation due to IFC model in the early design phase.

Table 1. Analysis of the research trends.

| Trend | Keyword | Research contents |
|---|---|---|
| Automation QTO | Object-oriented | Automation estimation system applying element information in 3D model (www.wbdg.org/design/dd_costest.php) |
| | IFC model | Development of QTO application in IFC 3D model (Hwang, 2004) |
| | Schedule-Cost | Development of modules for QTO according to the schedule (Karshenas, 2005) |
| Automation estimation | Automation based on method of construction | Automation based on method of construction using 3D model (Lee, 2004) |
| | Energy-Cost | Cost estimation of factors impact on energy performance assessment factor affected using IFC model (Oh et al, 2001) |
| | Automation estimation for high-performance building | Estimation assumption for high-performance building through cost of building functional (Vaidya et al, 2009) |
| Efficiency of estimation | Automation Finishing work | Methodology of 3D automated modeling for BIM-based QTO (Kim et al, 2008) |
| | Build a DB for automation estimation | Algorithm and development of database in object-oriented software for estimation task (Bazjanac, 2005) |

## 3. Suggestion of QTO and schematic estimation process

### 3.1. OPEN BIM-BASED QTO AND SCHEMATIC ESTIMATION PROCESS

BIM-based estimation requires a BIM model and database for unit cost information. Reliable estimates require accuracy for the QTO result and a high quality BIM model has a decisive effect on the accuracy of the QTO.

The process is comprised of five steps: BIM modelling, physical quality verification, property verification, quantity take-off and schematic estimation (Figure 1). The physical quality of the BIM model is verified by commercial software, *SMC* (*Solibri Model Checker*). This step can ensure the accuracy of quantity information. Verification of property involves extracting structural elements and checking the construction code in order to extend the estimation work.

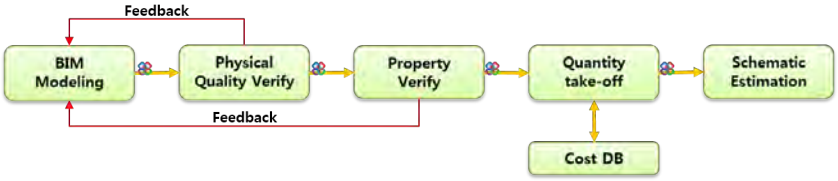



*Figure 1. Open BIM-based QTO and schematic estimation process.*

### 3.2. BIM MODELLING

The test model is done by Revit 2015 using KBIMS-Library established by *buildingSMART KOREA*. The model requires estimation data since this study is not only QTO but also for schematic estimation. Input properties are *LoadBearing* for extracting structural elements and code of construction classification for the estimation.

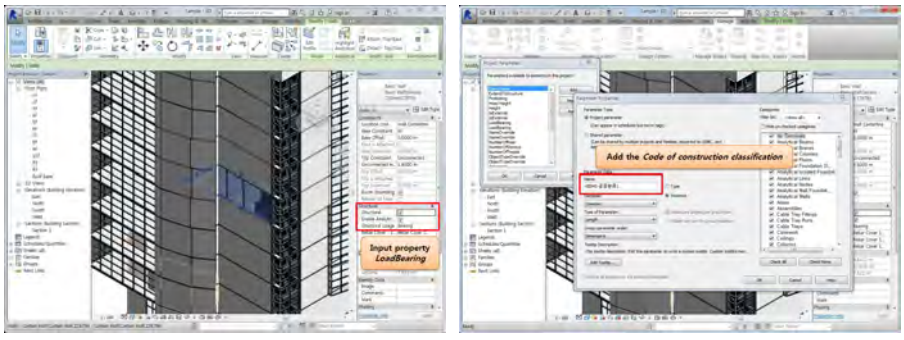



*Figure 2. Method of inputting properties for the schematic estimation: (left) input LoadBearing for extracting element of the building frame, (right) input the code of construction classification for the estimation.*

First, the structural property shown in Figure 2(a) allows selection of a Bearing or Non-Bearing wall. The structural property of the wall is entered as true or false in the IFC file *LoadBearing*. The only true value of the element to extract the *LoadBearing* values are calculated quantity of the building frame through columns, slabs, beams, stair is entered the property in the same way as walls. Second, the method of inputting construction code for the estimation is to add the *pset* and to enter codes in each element as shown in Figure 2(b).

### 3.3. VERIFICATION OF PHYSICAL AND DATA QUALITY FOR QTO

The model is created using an authoring tool to verify the physical quality. Physical quality checking is a minimum requirement for shape representation and intersections among elements can increase the accuracy of the calculated quantity. This study used *SMC* with a rule-set that depends on the checklist.

The checklist depends on domestic law and has a checklist for physical quality, logical quality and data quality. The criterion for physical quality is "*There should be no interference between the main element*", "*There should be no overlap between elements*", "*All structural elements should be supported by other structural elements*" and so on.

The BIM model undergoes a process to modify BIM authoring tools according to error facts. After checking the physical quality, it selects input properties that code for construction type in BIM data.

Verification of data quality is used to check whether or not required data is input, and to detect the errors in input data. First, the data quality detects the error, when structural elements don't have the structural property. Secondly, a check item verifies the error in the construction code which has non-existent code or a wrong code, since the construction codes are used by mapping between the element and unit cost.

### 3.4. CONSTRUCTION OF COST DB

This is referenced by "Construction Code Operating System - Construction Classification" by Korea Public Procurement Service and "Construction Type and Unit Cost apply Actual Cost of the Construction Project in 2012" (MLTM, 2012) by the Ministry of Land, Transport and Maritime Affairs. The code has 6-digits, three alphabetic and three numerical. Each code includes the construction type, its standard, its measure and its unit cost. Two types of codes can be used for code mapping to standardize the estimation.

Cost DB is referenced by "Construction Type and Unit Cost apply Actual Cost of the Construction Project in 2012" (MLTM, 2012) by the Ministry of

Land, Transport and Maritime Affairs. The database contains building construction life-cycle information, and contains unit cost information about a total of 600 construction type. Unit cost consists of a composite unit that contains the material costs, labour costs, expenditure.

## 4. Developing of QTO and schematic estimation prototype system

### 4.1. VERIFICATION OF DATA QUALITY

A QTO prototype system separated into two modules has been developed. Verification of data quality is conducted by the Pre-check module in the system. Results of Pre-check are to check on error elements and description of errors. It presents two types of error that detect the presence or absence of code and the format of code. A BIM model can be modified by an authoring tool using the error report exported in MS-Excel format. After completion of quality checking, the BIM model can conduct QTO.

### 4.2. QUANTITY TAKE-OFF OF THE BUILDING FRAME

QTO of the building frame is divided into two parts; one is the reinforced concrete work, and the other is the steel building frame. Bearing walls, columns, slabs, beams and stairs applicable to the QTO of the reinforced concrete work can be extracted from the IFC file as shown in Figure 3.

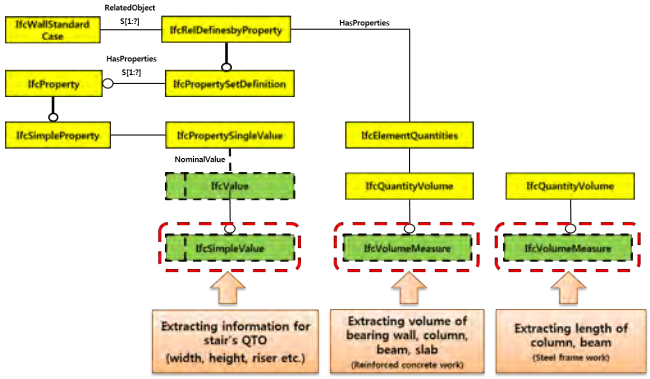



*Figure 3. Extraction method of QTO information in IFC (Choi et al, 2015).*

Columns and beams applicable to the QTO of the steel framework extract its length from the IFC file, since shape-steel's quantity multiplies its unit weight by length. The concrete quantity is extracted in the BIM model. The quantity of the rebar and the form are calculated by the ratio of concrete (Kang et al, 2003). In reinforced concrete, work is calculated based on the

volume of concrete and quantity of rebar and forms. The volume of concrete is extracted using the volume of each element that is a bearing wall, column, slab or beam. The quantity of the rebar and the form are calculated by the ratio of concrete according to the method used in practice.

In the steel building frame is calculated volume of shape-steel. The volume of steel extracted its length from IFC file, for the reason that method of shape-steel's quantity multiplies its unit weight by length. The ratio for calculating quantity can be modified using the quantity of the rebar and the form rating per concrete quantity. The model includes quality verification and set-up calculation options to calculate the quantity with *InSightBIM-Estimation* as shown in Figure 4.

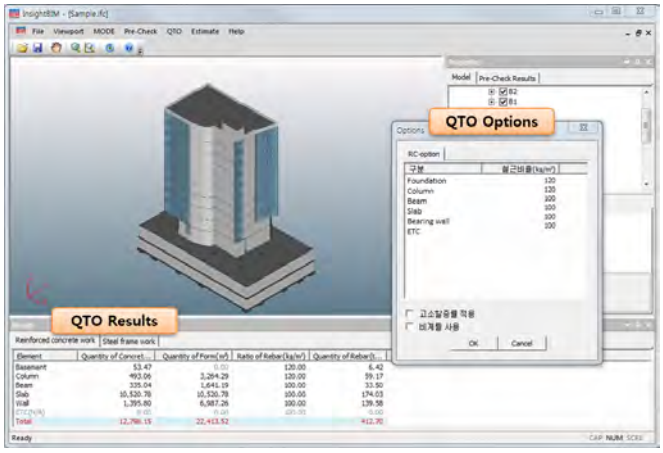



*Figure 4. Set-up calculation option and QTO result.*

## 4.3. SCHEMATIC ESTIMATION THROUGH THE LINKAGE OF QTO AND COST DB

The QTO information is extracted from the system is journalized quantity corresponding to the cost of the construction type. The schematic estimation of building frame is calculated through the calculation of the quantity and cost.

In reinforced concrete, concrete placement cost is applied to the volume information (*IfcQuantityVolume*) of the IFC model. The concrete curing cost is applied to the area information (*IfcQuantityArea - GrossArea*) of the IFC model. The form cost applies the required portion (*IfcQuantityArea – GrossSideArea*) of the form area. The rebar cost is calculated by the use of reinforced concrete against rebar ratio, the unit is converted to a ton is applied to the unit cost (Figure 5).

| | A | B | C | D | E | | F | | G | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Quantity | GrossArea | Volume | GrossSideArea | Quantity of Concrete(m3) | Cost of Concrete | Quantity of Form(m2) | Cost of Form | Quantity of Rebar(ton) | Cost of Rebar |
| Wall | | | | | | | | | | |
| W1 | 2 | 68.14 | 20.44 | 60.24 | 40.88 | 429,323 | 60.24 | 1,041,550 | 4.088 | 1,187,851 |
| W2 | 2 | 128.18 | 38.45 | 121.13 | 76.9 | 807,607 | 121.13 | 2,094,338 | 7.69 | 2,234,485 |
| W3 | 2 | 16.94 | 5.08 | 13.45 | 10.16 | 106,702 | 13.45 | 232,551 | 1.016 | 295,219 |
| W4 | 2 | 25.4 | 7.62 | 22.12 | 15.24 | 160,050 | 22.12 | 382,455 | 1.524 | 442,829 |
| Slab | | | | | | | | | | |
| S1 | 3 | 169.26 | 25.39 | | 76.17 | 788,664 | 169.26 | 2,926,505 | 7.617 | 2,213,273 |
| | | | | | Concrete | 2,292,346 | Form | 6,677,398 | Rebar | 6,373,657 |
| | | | | | Total | 15,343,402 | | | | |

*Figure 5. QTO and DB (Example of reinforced concrete).*

Concrete cost = Σ [{(A * C) x E} * unit cost of DF20 (10,132)] + {(A * B) * unit cost of DF00 (222)} (1)

Form cost = Σ {(A * D) * F} * unit cost of DA (17,290) (2)

Rebar cost = Σ G * unit cost of DB00 (290,570) (3)

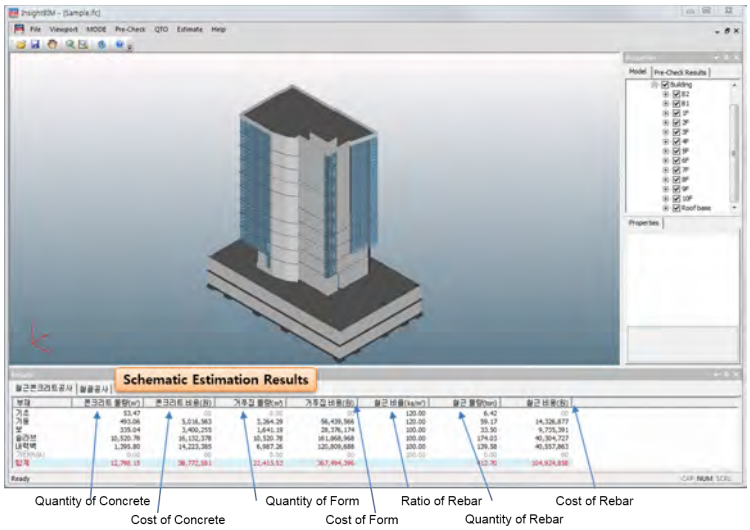



*Figure 6. Results of schematic estimation of building frame.*

The result of QTO and estimation is confirmed in *InSightBIM-Estimation* (Figure 6) and exported in MS-Excel format. The value of the result in the reinforced concrete work is the quantity of concrete, rebar and form of each element. In addition, the ratio of rebar and form per volume of concrete is used to provide the basis of the calculation. In the steel frame work, it is used to calculate the quantity of columns and beams.

## 5. Conclusions

This study suggests a solution of schematic estimation for low reliability of estimation manually, and difficulty about huge amounts of data management by building's complication and larger. Specifically, it is based on open BIM for a schematic estimation process in the early design stage. The detailed study results are as follows;

This study suggests an Open BIM-based method and schematic estimation process. The process contains 5 stages; BIM modelling for schematic estimation, verification to increase accuracy, verification of data quality for estimation, a method of QTO to extract quantities and calculate methods, and a method of schematic estimation through linkage of QTO and cost DB.

The authors developed a schematic estimation prototype system called *InSightBIM-Estimation*, which is an important factor for decision making in early phases. Thus, the methods are helpful not only to increase accuracy in QTO, but also to verify quality in the IFC model. QTO results can improve the schematic estimation task and improve the reliability of the estimate.

In this study, the scope of the applied QTO methods was limited by building frame. This caused difficulties with the practical application of the QTO methods applied in this study. To remedy this, the application scope of the QTO methods should be expanded.

## Acknowledgements

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# THE DEVELOPMENT OF KINETIC FAÇADE UNITS WITH BIM-BASED ACTIVE CONTROL SYSTEM FOR THE ADAPTIVE BUILDING ENERGY PERFORMANCE SERVICE

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**Abstract.** This paper proposes a novel concept and practice to engage the BIM model as a control system of building energy performance service. This issue can be divided into two sub-issues including the development of more eco-friendly façade which can interact with its local environment, and the related active control system which can process the environmental parameters for eco-friendly actions. This research designs the Parametric Adaptive Skin System (PASS) to engage the adaption of natural sunlight use for higher building performance. PASS consists of kinetic façade components dominated by the BIM-based parametric engine called Dynamo. The PASS prototype demonstrates that the workflows is successful in using a real light sensor plus simulated solar terms to drive the interaction of virtual Revit model and physical PASS model.

**Keywords.** Building information modelling (BIM); adaptive building; energy consumption; building performance; kinetic façade.

## 1. Introduction

The operation of buildings accounts for 40% of global $CO^2$ emissions. These emissions are directly linked to the energy a building consumes in order to maintain its usability (Schlueter, 2009). Due to the rising awareness of climate change and eco-friendly living, building designers increasingly have to consider the energy performance of their building designs. Recent developments in computational design tools are providing methods for improved design practices. Building Information Modelling (BIM) combining with third-

party analysis software is currently one of the major paradigm shifts for designing an eco-friendly building. Early design studies based on those computational tools can test the effectiveness of building systems before they are actually built. However, it still has a grant gap between “as built” and “built”. Once buildings are actually built, they immediately switch to the operation phase and need to face real climate conditions. Unfortunately, the climate conditions are diverse and dynamic, especially in the complex urban context. Buildings need to present more adaption than their as-built simulated phase.

The concept of adaptive building for more eco-friendly building approach is not new (Guillemin, 2001); rather what makes it currently possible are sensor technologies to detect environmental parameters, computer power to process big data, and the automated control system to drive buildings’ operations. Adaptive building could collect real-time data, compare them with scenarios we define in advance, and choose a strategy to optimise the building performance. This form of cognitive optimisation benefits from the “Adaptive” façade controlled by the intelligent building system to interact with environmental conditions.

This paper demonstrates the integration of environment sensors, building scenarios, and interactive façade components by using BIM-based control system. The BIM-based system is programmed with Dynamo software and works as the building brain to determine the interactive control scenarios.

## 2. Literature review

### 2.1. INTELLIGENT BUILDINGS WITH HIGH PERFORMANCE

Designers have both passive and active control methods to make buildings respond to changing environmental conditions. Most of passive control solutions are simulated before buildings are really built to assistant designers’ decision making. Many historic examples exist that show the use of passive control methods using natural features to manage daylight amounts of buildings, or mitigating seasonal heat and wind variation by the use of mass position. For example, the traditional houses in Taiwan are designed to face south in order to acquire better climate conditions. The passive control methods may provide the effective solutions for buildings to adapt the long-term climate conditions. However, the effect of micro-climates is dynamically changed after buildings are built and operated. It causes the users’ comfort level and building performance over time. The buildings that only adopt passive control methods are unable to reach benefits during the operation stage.

One of the valid ways to solve this problem is to integrate active control methods. Active systems are incorporated into building design and facilitate the interactive control during building operation stage. This has evolved into the concept of intelligent buildings and intelligent building facades. In the early development, the concept and technologies of HCI (Human-Computer Interaction) have been added and studied at a much smaller and experimental scale, such as dECOi's Hyposurface (2000), Michael Fox's Bubbles interactive pneumatic environment project (2009).

However, there is a lack of integration with multiple conditions that represent the complex of environment. Designed properly, an intelligent building should be able to dynamically adapt in changeable environments and to address the different environmental conditions over its lifetime due to seasonal and even climatic change. The intelligent building façade itself acts as the interface between the inside and the outside, re-adjusting itself based on building performance conditions, responding to the interaction of humans and the environment. For example, the Media ICT project, led by Enric Ruiz-Geli, is formed by large iron beams covered in a plastic coating of inflatable bubbles, which offer glimpses of the fluorescent structure of the building. The inflatable bubbles called ETFE skin acts as an external covering and a mobile sunscreen that helps light to penetrate and affords heat savings. The interaction of ETFE skin is controlled by computer which monitor the light and temperature balance between indoor and outdoor environment. Another intelligent building example, Al Bahr Towers, is covered by protective skin of 2,000 triangle elements that automatically open and close depending on the intensity of sunlight and related climatic data. According to the active control system, each triangle is programmed to respond to the movement of the sun as a way to reduce solar gain and glare. It is estimated that the dynamical adjusting of building facade based on climate changes will reduce solar gain by more than 50 percent, and also reduce the building's need for energy-draining air conditioning.

## 2.2. BUILDING PERFORMANCE ANALYSIS

Recent progress in CAAD for green buildings put forwards the research and applications of simulation-based optimisation methods in the building sector (Nguyen, 2014). Building performance simulation (BPS) or Building performance analysis (BPA) has the potential to provide relevant design information by indicating directions for decision making of design solutions (Hopfe and Hensen, 2011). A major challenge in simulation tools is how to deal with difficulties through large variety of parameters and complexity of factors such as non-linearity, discreteness, and uncertainty. BPS or BPA in

general is used to calculate, through predictive simulation, a variety of outcomes of the proposed design, such as energy consumption, building performance of heating and cooling systems, distribution of air borne contaminants, dynamic control scenarios for smart building technologies, and others (Augenbroe and Hensen, 2004).

The aim of BPS or BPA is to predict real physical conditions in a building by using a computational model. Building simulation, according to Morbitzer (2003), expands the concept of performance prediction. With the help of BPS or BPA, the user can specify parameters that have an influence on the overall building performance. The simulation results achieved in the prediction are as close to reality as possible. BAS or BPA is a multidisciplinary, problem oriented, dynamic tool using numerical methods that approximate a solution of a realistic model.

The decision making between competing design option and design optimisation can be enhanced by including the effect of uncertainties in simulation outcomes that are presented to the decision makers, or used in the optimisation strategy. Current simulation tools can be enhanced to deliver this new functionality in a way that it is practical and acceptable to design practice. Some BPS or BPA software such as Ecotect, Green Building Studio (GBS) and Virtual Environment are engaged in the design process for BIM-based sustainability analysis. Furthermore, it is useful to initially connect BIM-based BPS or BPA to physical sensors for more appropriate and accurate analysis. The integrated solution can acquire more immediate and spatial representation of building performance.

## 3. The framework of BIM-based system design

This paper proposes the “Parametric Adaptive Skin System” (PASS) based on BIM aided computation. In this project we focus on the building façade design and make it play an active interface to mediate between the building and its located environment. It aims to create the eco-friendly building which can transform itself according to diverse climate conditions. The PASS develops kinetic façade components which have self-adjust ability to response the dynamic changes of micro-climate. The main framework of PASS consists of kinetic components, environmental parameter, and interactive adaption.

(1) Kinetic components

The kinetic components are attached to the whole façade to become the interface between the building and its located environment. With the kinetic components layer, building can adjust the façade opening to adapt the diverse micro-climate changes. The design of kinetic components is modular-

ised in order to repeat and cover the whole façade face. Besides, the environmental sensors can be embedded in each modular kinetic component systemically to equip sensing functions. Thus the whole façade is turned into the ambient sensing network via distributed modular kinetic components. According to the distributed sensing network, the building can determine the regional distinctions of microclimate conditions.

(2) Environmental parameter

The environmental climate conditions are dynamically changed over time during the building operation stage. Taking the advantage of natural energy to decrease the consumption of electric power is necessary for the high performance building. The active control system may support a good solution both in the low maintain cost and high building performance. The physical climate conditions such as sunlight, wind force, or rainfall are translated into serial quantitative values regarded as environmental parameters. In addition, the virtual climatic conditions which are simulated via software, such as solar term, weather forecast, and so on, are also adopted as environmental parameters. Those environmental parameters are associated with the discriminants of scenarios in event triggering. The integration of physical and virtual parameters ensures that the interaction of active control can both satisfy instant changes of microclimate and the permanent constraints of season.

(3) Interactive adaption

The main purpose of active control system is to enhance the building performance via interactive adaption. The façade and related facilities controlled by the active control system change their status to adapt the microclimate variation instantly. The workflow of interactive adaption is divided into three phases including 1.input, 2.process, and 3.output. In the beginning, the micro-climate conditions are detected and translated into quantitative parameters. The parameters are delivered to the computing engine as references. Base on the reference of multi-parameters, the computing engine dominates the comparison of scenarios in the database. Then the matched scenario triggers the following events including the kinetic adjustment of building facades.

## 4. The practice of PASS

### 4.1. DYNAMO: A PARAMETRIC PLUGIN FOR THE REVIT API

The Autodesk Revit API (Application Programming Interface) allows users to add features and create customised plugins. Dynamo is under develop-

ment by users as a plugin to Revit using the Revit API. As a parametric modelling engine, Dynamo is designed to extend Revit's parametric functions by adding a level of associativity that does not exist. It can drive parameters based on external inputs, such as by sensors delivered from Arduino or by data taken from Revit's analysis. Through the Dynamo engine, we can map the appropriate parameters derived from the input source and dynamically generate the script results. In addition, Dynamo engine also allows us to output the control commands and trigger the change of simulated models or physical electric components.

In the PASS project Dynamo has been used as the primary engine of adaptive façade control system. The main functions include the connection between the Arduino board, a light sensor, a servo motor, and the compiler of BIM-based interactive scenario. The elements with which users interact in Dynamo engine are referred as "nodes". Each node can have a number of com ports, which enable communication between nodes along connecting line. Com ports can only be connected to other com ports whose output type matches the input type, or to any com port whose output type is further up the inheritance hierarchy of the com port's input type. The connected elements in Dynamo engine create the data workflow to define the interactive scenario. The interactive scenario called "dynElement" provides the framework on which all elements function together. It consists of three steps including destroy, build, and update. The destroy step is used to clean up elements' temporary data. The build step is used to re-generate Revit elements based on the input connections. And the update step is used to build downstream nodes to execute their own loops. Successive downstream nodes are evaluated until either an exception is raised on a node or there are no more nodes to process.

In order to distinguish the internal and external dataflow, Dynamo engine classifies nodes as "transactional" or "non-transactional". Transactional nodes open a database transaction during their build step, and all elements created during that step are committed updating to the database; Non-transactional nodes cease transactions as they do not need to change the Revit database. An example of a transactional node would be one that creates a group of family instances. A non-transactional node, by comparison, could be one that interacts with serial data such as an Arduino sensor, allows the input of a numeric value, or provides an output command to a query about the database without changing anything in the database. Based on the Dynamo engine nodes, designers can pre-define the scenarios which link with the Revit simulated data and the real-world sensing data. In addition, the trigged scenario also delivers its commands to the Revit model and the physical building.

## 4.2. INTERACTIVE CONTROL SCENARIO OF PASS

The simulated façade model with modular kinetic components is created in the Revit. Each component is linked to the instant light level parameter from distributed Arduino photoresistor. The photoresistor provides a value from 0 to 255 received from the ambient environment and delivered to Dynamo engine via Arduino. It supports the lower hierarchical control of components' opening degree. Except the actual value from photoresistor, the sun position in Revit also provides the higher hierarchical control to affect the components' opening degree. The reason we define two parameters, one higher and anther lower hierarchical controls, is to simulate the real world daylight condition. The sunlight in Revit simulates the correct solar terms and daytime. It limits the range of opening degrees preliminarily to prevent inappropriate opening scenarios. For example, the window should not reach the full opening in the winter due to the cold issue. Since so far we do not adopt the other environmental parameters such as wind, the short-term expedient provided by higher hierarchical controls is helpful. The lower hierarchical controls dominated by real sensor values allow us to simulate the instant changes of daylight. For example, sometime even in the similar daytime, the light level may different due to the weather issue. Hence lower hierarchical controls need to connect the real-time micro-climate conditions. The scenario with higher and lower hierarchical controls is programmed by Dynamo engine (Figure 1 Right).

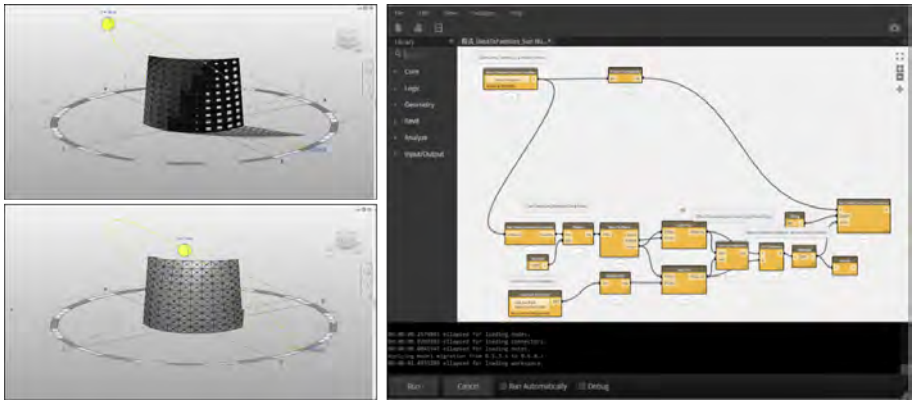


*Figure 1: Left: the simulated results of Revit model; Right: The scenario of higher and lower hierarchical controls in Dynamo engine.*

Dynamo engine is successful for mediating between the photoresistor and Revit model. The next step is to build the connection between the virtual Revit model and the physical PASS model. In this step Dynamo engine de-

livers commands back to the Arduino board to trigger the servo motor. We design the folding structure in each kinetic component. The rotation of servo motor can drive the folding motion to increase or decrease the opening degree. The prototype is developed as Figure 2.

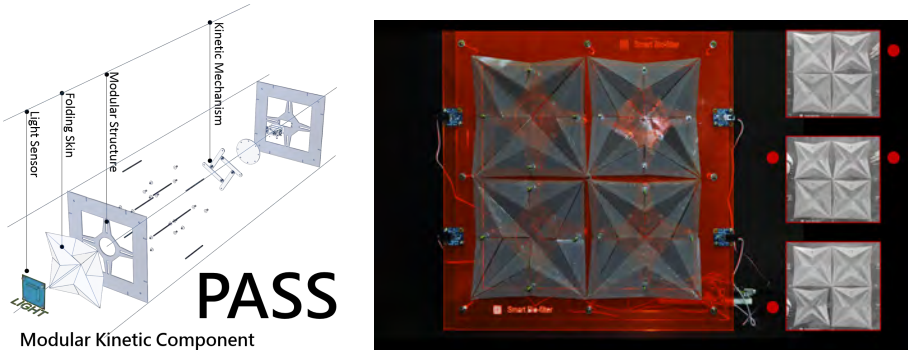



*Figure 2: The folding structure of kinetic component.*

Although the physical PASS model shown is simple in construction, it demonstrates that the workflows is successful in using a real light sensor plus simulated solar terms to drive the interaction of virtual Revit model and physical PASS model.

## 5. Discussion and conclusion

### 5.1. DISCUSSION

The workflow of Dynamo engine demonstrates a method of dynamically repositioning the virtual and physical components in response to an environmental stimulus. So far this paper only focuses on the light parameter. However, as we know, the real world micro-climate conditions have complex influence to building performance analysis. Adding more environmental parameters is the necessary approach in the future. Fortunately, the open structure of Dynamo engine allows the further augment of sensing inputs. In addition, although virtual data from simulation or prediction do not exist in the real world, they also paly the significant role to prevent overreaction of active control system; moreover, the service of precautionary measures or reactions can be triggered according to the simulation or prediction. It provides macro-control scenario for the build operation and management. Therefore, the integration of real light sensor plus simulated solar terms in this paper illustrates the potential picture of BIM-based service for the high building performance.

## 5.2. CONCLUSION

This paper proposes a novel concept and practice to engage the BIM model as a control system of building energy performance service. This issue can be divided into two sub-issues including the development of more eco-friendly façade which can interact with its local environment, and the related active control system which can process the environmental parameters for eco-friendly actions. The Parametric Adaptive Skin System (PASS) engages the dynamic sunlight adaption for higher building performance. PASS consists of kinetic façade components dominated by the BIM-based parametric engine called Dynamo. The Dynamo engine works as the building brain to determine the interactive control scenarios between buildings and surrounding micro-climate conditions. The PASS prototype has been developed and installed in the real field for the pilot study. The light parameters inputted to Dynamo engine include real-time sunlight from physical sensors, and the simulated solar term from Revit. The integration of physical and virtual sunlight parameters ensures that the interaction of PASS can both satisfy instant changes of microclimate and the permanent constraints of season. The PASS prototype demonstrates that the workflows is successful in using a real light sensor plus simulated solar terms to drive the interaction of virtual Revit model and physical PASS model. The further development of PASS will address on the integration of complete micro-climate conditions which also affects the building performance and users

## Acknowledgements

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## 3D PRINTING AND ROBOTIC ASSEMBLIES

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# SPATIAL WIRE CUTTING

## *Cooperative robotic cutting of non-ruled surface geometries for bespoke building components*

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**Abstract.** The research project Spatial Wire Cutting (SWC) investigates a multi-robotic cutting technique that allows for an efficient production of geometrically complex architectural components. Being pursued by the group of Gramazio Kohler Research at ETH Zurich, this approach involves a spatially coordinated movement of two six-axis robotic arms that control the curvature of a hot-wire, which adopts itself against the resistance of the processed material (e.g. polystyrene). In contrast to standard CNC hot-wire cutting processes, in which the cutting medium remains linear, it allows the automated fabrication of non-ruled, doubly curved surfaces. This pursuit includes the development of a custom digital design and robotic control framework that combines computational simulation and manufacturing feedback information. Ultimately, SWC enables a considerably expanded design and fabrication space for complex architectural geometries and their construction through automated robotic technology. This paper addresses the applied workflow and technology 1) such as computational design and simulation, robotic control and adaptive fabrication, 2) results of application within a two-week design and building workshop, and 3) will conclude with further steps of future research.

**Keywords.** Computational design and digital fabrication; feedback-based automated manufacturing; multi-robot control; digital simulation; hot-wire cutting.

## 1. Introduction

Since the beginning of the 1990s advanced computing technologies have led to a substantial architectural design revolution facilitating the graphical representation of complex geometries and shapes (Pottmann et al, 2007). In order to convert these digital data sets into physical reality, digital fabrication technology has become crucial and marked the advent of a "Second Digital Age" (Gramazio et al, 2014). In turn, multiple constraints that come along with computer-controlled manufacturing have also substantially fertilised the field of architectural design and geometry exploration, posing challenging construction-related problems and, ultimately, opening up new architectural research directions for the physical production of complex geometries (Eigensatz et al, 2010). However, a number of commonly used fabrication techniques, such as, for example CNC-milling or 3D printing, are still inefficient and time-consuming (Schipper et al, 2014) when it comes to the manufacturing of bespoke double-curved surfaces. Here, the simplification and post-rationalization of a specific design proposition is often the consequence. In this context particularly digitally-controlled wire-cutting techniques have become very common in the larger fields of architecture, design and construction. However, due to the used linear cutting medium, the range of applicable geometries is narrowed to ruled surfaces (Flöry and Pottmann, 2010).

The research presented in this paper explores a Spatial Wire Cutting (SWC) technique, which is performed by two six-axis lightweight robotic arms that are connected through a single hot-wire, which is attached to their end-effectors (Figure 1). Their coordinated spatial movement allows for cutting configurations in which the hot-wire takes the form of a curve being shaped by the friction of the wire against the processed material (e.g. expanded polystyrene). By escaping in this way from the conventional linearity of the cutting medium, the automated fabrication of non-ruled surfaces, in particular sweep surfaces, which can be geometrically defined by the motion of a changing profile curve along two trajectory curves, becomes possible.

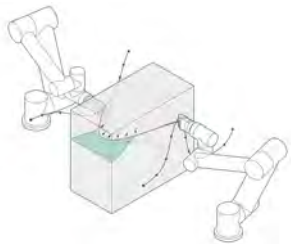


*Figure 1. Illustration of the experimental set-up, featuring two Universal Robots UR5 robotic arms moving on different path curves with a curved wire which is shaped by material resistance.*

However, in order to precisely control the curvature of the wire throughout the multi-robotic cutting process, all relevant material properties and forces that occur during the physical manufacturing process have to be monitored and, if applicable, to be reacted upon, for instance the overall temperature of the wire, the forces acting on the wire, etc. Authoring this complex manufacturing process requires an enhanced robotic control approach that enables to adapt the velocity of the cooperating robotic arms based on feedback acquired online through sensors. Furthermore, the fabrication process-inherent geometrical formulations and constraints have to be integrated in the overall design approach. This clearly demands for a fabrication-informed computational design method, where geometry is directly interlinked with material and manufacturing characteristics. This aligns with the idea of perceiving design and fabrication as a system of recursion, as a dynamic computational composition (Fuller and Matos, 2011), which will change the way complex architectural artefacts are designed, fabricated and constructed.

## 2. State of the art

Digital-controlled wire cutting has become a topic in many research groups (Rippmann and Block, 2011; McGee et al, 2012). It offers a low-cost and flexible production of non-standard volumetric elements for manifold applications (such as bespoke formwork components, prototype construction, etc.) and is fast becoming a mature technology that is ready for larger industrial applications. Here, three-dimensional objects are fabricated via repeated movements of a cutting medium, for instance hot-wire, steel cutting wire, mechanic cutting, stiff or flexible blades (Broek et al, 2002), through a solid material, (predominantly non-metallic, synthetic materials like EPS, EPP, PU, etc., density lower than 60kg/$m^3$). As implemented by a number of architectural research groups, a conventional hot-wire cutting set-up consists of one standard industrial robotic arm with a customised end-effector, where the wire is tightly fixed at two points. The hot-wire is being moved through the material with a predefined velocity that relates to the temperature and vaporises the material just in advance of contact to prevent occurring resistance forces contrary to the moving direction. In contrast to these approaches SWC is based on two robotic arms and operates in transition states between thermal cutting and thermo-mechanical cutting a) to utilize the material resistance contrary to the moving direction and b) to exploit the (individual) robotic velocities at both wire ends to directly manipulate the cutting medium. Most importantly, the resulting curvature of the cutting medium enables the fast and efficient fabrication of non-ruled doubled curved surfac-

es through single cuts, and therefore significantly expands the set of possible hot-wire cutting geometries.

## 3. Design and fabrication methodology

The main inputs for the fabrication procedure that are principally determining the geometry of the evolving surface are the path curves for the robotic arms (along with velocities and the temperature of the wire), respectively their positions along that curves at a given moment in time (Figure 2, left). However, there is a non-transparent relationship between the design of these path curves and the resulting physical cut surface. Therefore, a simulation framework has been developed (and experimentally tested during the Summerschool workshop, see Section 4.), that emulates the wires deformation within the material according to the input curves and the position of the foam block (Figure 2, right). This simulation framework allows to anticipate the surface and is therefore a precondition for the custom integrated design tool.

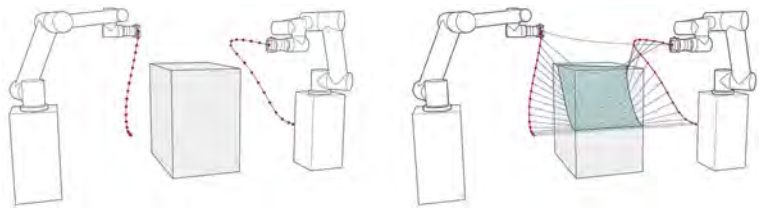


*Figure 2.(Left) Path curves and synchronized positions on that curves; (Right) Simulated hot-wire curves and lofted surface thereof.*

### 3.1. COMPUTATIONAL WIRE SIMULATION

This simulation framework is written in the programming language Python and integrated into the computational design toolkit in Rhinoceros 3D/ Grasshopper. Currently, the wire's shape is simulated by calculating a funicular curve using the non-linear force density method (Malerba, et al., 2012). The wire is discretized into segments by a number of nodes, whereas the wire's end points are the fixed nodes on the path curves. While iteratively stepping along the path curves and taking another pair of fixed nodes, the (differing) forces, consisting of vectors with a defined magnitude, are recalculated on basis of the previously calculated shape. The calculation of these forces define the overall shape of the wire in the simulation and the objective is therefore to match these calculated forces to the physical occurring forces.

Concerning material behaviour and relationships between the parameters guiding the process, this project builds upon previous research on hot-wire cutting conducted in the field of mechanical engineering. A property that is

commonly used is the area specific heat input $Q_{eff}$ [J/m$^2$] (Ahn et al, 2003). It is a means to consider the influence of both the heat input and the cutting velocity. To relate the cutting force $F$[N] in the steady state[1.] to a given $Q_{eff}$ and additionally taking the engaged wire length le[mm] into account (= actual length of wire in the foam) several cuttings tests with different voltage / speed settings have been performed and the forces throughout the procedure were logged. The following exponential model developed by Bain (2011) was used to correlate and match the test measurements in the steady state conditions (where the coefficients[2.] were found by model fitting, see Figure 3, left):

$$F = 3.4115\, l_e\, e^{-0.0015\, Q_{eff}} - 0.4944 \quad (1)$$

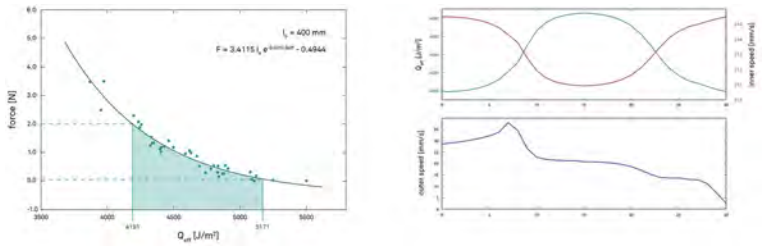



*Figure 3. (Left) Results of material tests, fitted with the model (1) and operating $Q_{eff}$ range; (Right) $Q_{eff}$, inner- and outer speeds calculated from the simulated curves.*

For the SWC procedure, this may not be fully applicable, because the wire is not always in steady state conditions, but constantly changing between transition states and experiencing forces from different directions and magnitudes. Still, this model serves as a first approximation to define the operating domains of the fabrication parameters. On the basis of qualitative observation of over 100 different robotic cutting tests an optimal operating force range was defined (0.7-2.0 N, see Figure 3, left). A certain tension force in the wire has to be kept throughout the cutting process to achieve a corresponding surface quality and, ultimately, to efficiently control the SWC procedure. Based on the simulated curves (Figure 2, left), and the model (1), the speed of the wire within the foam (inner speed) to a given voltage, and subsequently the speeds for the robotic arms (outer speeds) are calculated and used as estimated velocities for the fabrication procedure (Figure 3, right).

## 3.2. ROBOTIC CONTROL AND ADAPTIVE FABRICATION

A custom control software has been developed to precisely execute the fabrication procedure driven by the settings defined by the computational simulation framework (such as path curves, estimated speeds and voltage). With-

in this robotic cutting process, the forces and its direction at the mounting points of the wire are continuously registered (using a custom end-effector, see Figure 5, right), as well as the individual speed variations and positions of the robotic arms, which is all fed back into the robotic controller. Taking the estimated speed at the current position, the online force measurements (process variable) and the desired force (set point) into consideration, new velocities are constantly calculated and sent to the robotic arms (Figure 4).

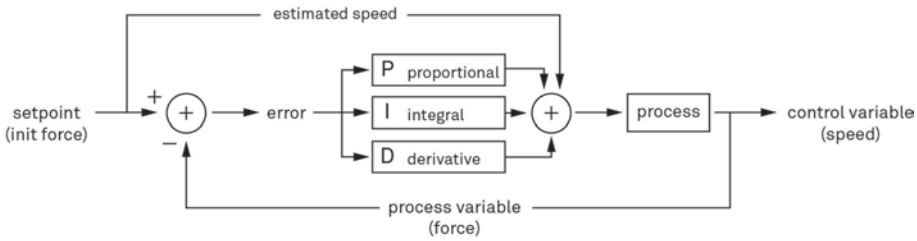



*Figure 4. Combined feed-forward/feed-back control.*

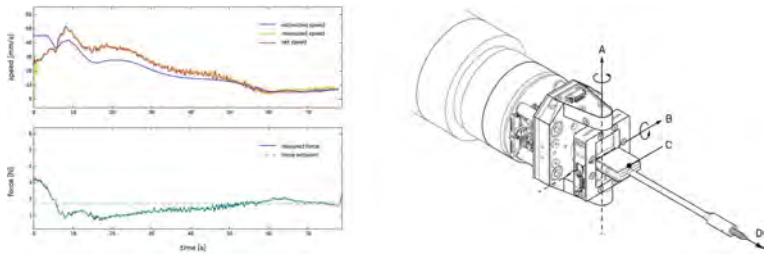


*Figure 5. (Left) Logged data from the process: comparison between estimated and actual speed and force measurements; (Right) Cardan joint end-effector with axes (A, B) rotating towards the direction of the force (D) measured by a force sensor (C).*

## 4. Physical experimentation and validation

To validate the workflow, transferability and application of the proposed SWC design and fabrication methodology, a two-week Swisspearl® Summerschool 2015 (Eternit (Schweiz) AG, 2016) was pursued, focusing on the development of novel façade typologies as experimental test cases while expanding SWC towards the application at an architectural scale.

Within the design and conceptual phase of the workshop, students explored the technique first through a series of manual tests, using a handheld hot-wire cutting device and graphite enhanced expanded polystyrene blocks of 300 x 400 x 600 mm to develop an intuitive understanding of the material and its (coordinated) manipulation. Subsequently, based on the exploration of the typology of individual elements, these manually-derived concepts were transferred into the computational simulation framework (as described

in Section 3.1) to elaborate an overall design concept and parametric model for the aggregation of full scale, robotically-cut prototypes, featuring panel sizes of 1200 x 600 mm. These were then used as moulds for the lamination with the fibre-cement composite Swisspearl® (also known conventionally as Eternit), a well-established manufacturing procedure, that, however, requires substantial manual labour and craftsmanship (Figures 6, 7). The challenge of this unique combination of fully automated SWC and manual lamination was to find the synthesis between two very different material systems each one with his specifically constraint design space.

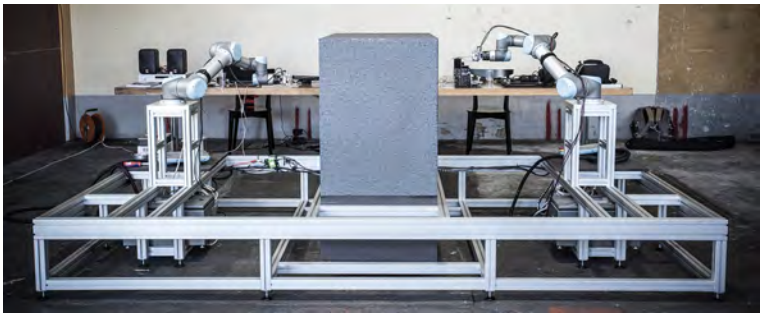


*Figure 6. Employed robotic setup of the Summerschool, consisting of two Universal Robots UR5 robotic arms.*

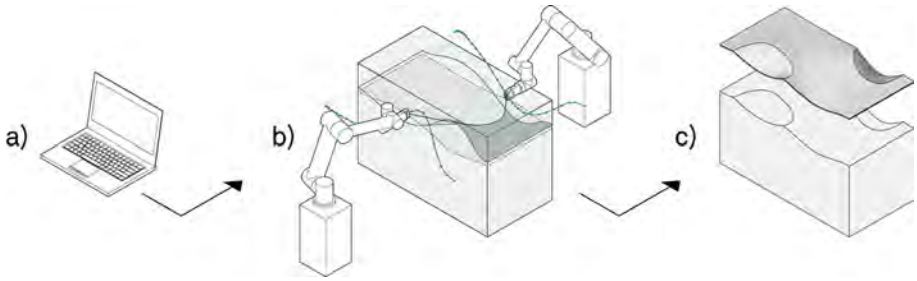



*Figure 7. Workflow: a) design, b) robotic fabrication, c) manual lamination.*

Four different design concepts of four student groups have been developed and demonstrated through full scale prototypes (Figures 8, 9):

- The first group developed the concept of controlling the intersections of two surfaces to produce crest lines as design patterns on the façade. This has been realised by a parametric differentiation of the edge curves (varying heights and positions of the control points), from which the surfaces were generated with the simulation framework (Figure 9, left).
- The second group explored edge curves with alternating combination of sharp peaks and valleys. Combined with the controlled direction of the hot-

wire's movement, the uniqueness of the process was demonstrated expressively in the fabricated surfaces (Figure 9, right).

- The concept of the third group was based on the idea to hide the vertical connections between the panels by using 'waves'. Through empirical testing the maximum range of surface stretch and compression of the cement composite was identified and used as a design constraint for the parametric control of the edge curves, thus pushing the boundaries of the material process.
- The fourth group's concept was to assemble six smaller fabricated pieces into one single mould for the lamination of larger panels. This system, combined with the controlled changing of edge curves to generate ruled surfaces, explored subdivision as strategy to widen the spectrum of possible surfaces.

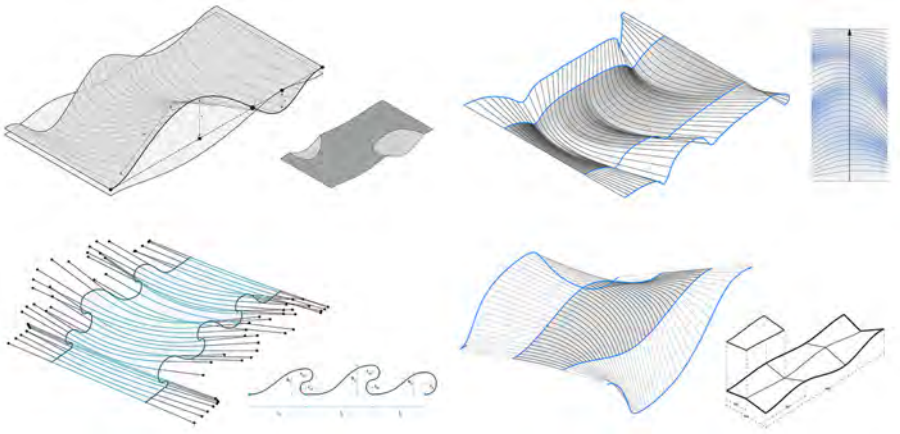


*Figure 8. Conceptual drawings of groups 1 – 4.*



*Figure 9. Final prototypes of group 1 (left) and 2 (right).*

Overall, the pursued physical explorations within the framework of the Summerschool led to a variety of different results, promising interesting avenues for SWC to be used for 1:1 constructive processes (e.g. façade panels or complex concrete formwork elements). The speediness and efficiency of the SWC process and the lamination allowed for a large number of iterative tests and design explorations. As such, a comprehensive investigation into

the architectural potentials of the discussed technique was possible and has clearly proven the viability and application range of SWC. In fact, these studies have successfully shown that a) the developed computational simulation tool (Section 3.1) can be employed for digital design explorations that are coherent with their fabrication and b) in combination with advanced robotic control (Section 3.2) can foster the efficient fabrication of unique and differentiated double-curved surfaces through a synthesis of material system and digital manipulation.

## 5. Conclusion

One of the major challenges regarding the fabrication prior to the start of the workshop was the upscaling from model scale to full architectural scale. Whereas the procedure in terms of scalability of material properties proved to match to the findings in Section 3.1, the limits of the robotic workspaces were reached and therefore required additional path planning. The applied workflow of computational design and simulation, joint with the adaptive fabrication procedure proved to be successful in terms of design strategy and production efficiency. Fabrication related constraints could be identified in early design stages, included into the considerations and the computational model, which was directly linked to the fabrication, requiring no further post-processing. In this current state of research a clear characterization of the geometric discrepancies between the simulated geometry and the resulting materialization can yet not be given in full detail. Further tests and explorations, such as detailed analysis of scanned physical objects for the purpose of optimising and calibrating the digital simulation and fabrication, will be a topic for continuing development. This includes the characterisation of process-inherent geometric formulations and the elaboration of a catalogue of viable SWC-geometries. By reaching beyond the simple linear workflow between design and fabrication, this technology brings forward a novel geometric capability to existing hot-wire-cutting techniques. Thus, this opens up a new perspective to the area of digital fabrication in architecture in general and contributes to the research on material and process informed design methods.

## Endnotes

1. Steady state conditions are reached at constant speed when the temperature and the cutting force level off.
2. The coefficients for this model vary according to the used foam and cutting medium as tested by Bain (2011). The described experiments were performed with the foam swissporLAMBDA Vento (density: 15 kg/m$^3$) and the material for the hot-wire was Kanthal A with a diameter of 0.15 mm.

## Acknowledgements

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# ROBOTIC FORMING

## *Rapidly generating 3D forms and structures through incremental forming*

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**Abstract.** The past years have seen significant developments in the area of robotic design interfaces. Building upon visual programming environments, these interfaces now allow the creative industry to define even complex fabrication processes in an easy, accessible way, while providing instant, production-immanent feedback. However, while these software tools greatly speed up the programming of robotic arms, many processes are still inherently slow: Subtractive processes need to remove a large amount of material with comparably small tools, while additive processes are limited by the speed of the extruder and the properties of the extruded material. In this research we present a new method for incrementally shaping transparent polymer materials with a robotic arm, without requiring heat or dies for deep-drawing, thus allowing us to rapidly fabricate individual panels within a minimum of time.

**Keywords.** Incremental forming; robotic fabrication; visual programming.

## 1. Introduction

Complex geometries in architecture and individual free-form-facades are becoming increasingly prominent in the urban landscape. While new digital tools greatly facilitate the efficient development and segmentation of these complex architectural structures in the design phase, the actual production of free-form-elements is still laborious and expensive. Common methods such as deep-drawing of plastics (e.g. Kunsthalle Graz) or explosion forming of metal (e.g. Hydra Pier, Haarlemmermeer) are based on the fabrication of individual dies for every unique surface geometry (Brell-Cokcan and Braumann, 2013). While dies can be re-used in the serial fabrication of identical elements, relying on such processes for single, individual pieces is highly time consuming and material-intensive.

Therefore, we are exploring the fabrication strategy of Single Point Incremental Forming (SPIF) within the context of individualized production, towards enabling the fabrication of highly customized, transparent elements.

## 2. Investigation

So far, SPIF has mostly been explored in the context of mechanical engineering and material science (Jackson and Alwood, 2009), though more recently also by researchers in architecture, who focused on the development of tools and techniques for the parametric design of prototypical, metal building skins (Kalo and Newsum, 2014). Our investigation into SPIF is focused on the practical applicability of the SPIF process to the working practices of the creative industry and other groups with less experience in automated production planning. Furthermore, we place a special importance on realizing a continuous design to production workflow, utilizing visual programming strategies that are now commonly used in the creative sector. Thus, we implemented the necessary process immanent steps in the digital design environment of Rhino and Grasshopper, allowing us to quickly prototype the process in both physical and virtual space.

While the initial material research was done in the laboratory, our investigations into the practical applicability of such processes involved a series of intensive workshops, where participants intuitively explored material and digital constraints of the process and created a series of exhibition pieces (Fig. 1). Our developed process was also featured as part of the Ars Electronica Festival - one of the world’s most significant digital media festivals - with the goal of demonstrating how industrial machines and industrial processes are no longer exclusive to industrial mass-fabrication, but can be manipulated and re-applied by the creative industry. A Leap Motion 3D-scanner allowed members of the audience to interact in an intuitive way with the par-

ametric design and fabrication model running within Grasshopper. The hand movement detected by the sensor was linked to the design parameters of position, depth and size of the deformation shape, continuously morphing the geometry and fabrication toolpaths in real-time (Fig. 2). As a subsequent step, an agent system explored the generated 3D-surface in the design process creating a spline like pattern that emphasizes the spatial properties of the panel structure (Fig. 2). This pattern was implemented during manufacturing as additional paint layer on one side of the polymer sheet.



*Figure 1. Geometries intuitively generated through SPIF: Haptics of deformation paths (left), twisting of sheet through distinct deformation (middle), double sided deformation (right).*

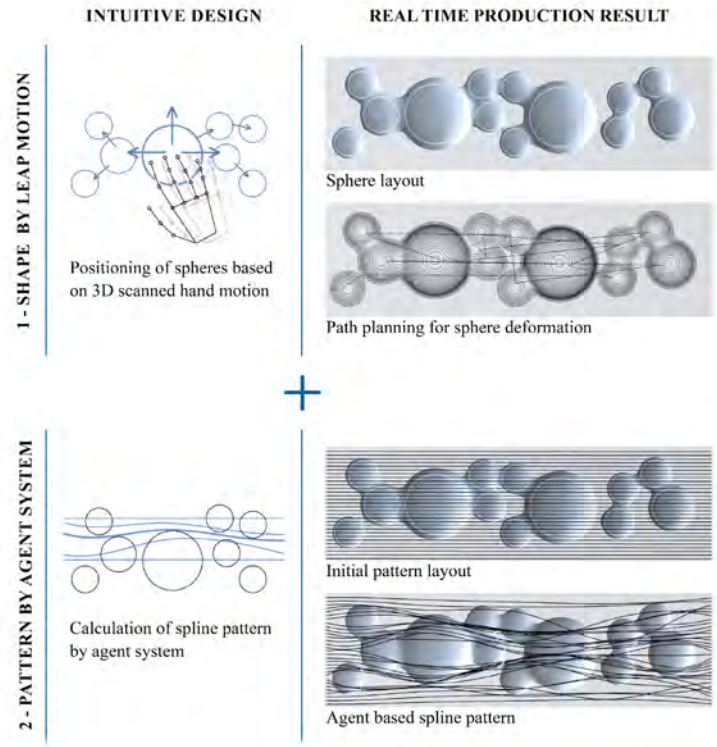



*Figure 2. Intuitive toolpath generation through a combination of leap motion scanning (step 1) and an agent system (step 2).*

## 3. Single point incremental forming of polymer sheets

SPIF is a cold-forming production process which is capable of manufacturing arbitrary free-form-surfaces by gradually pressing sheet material into the desired shape with a spherical tool attached to a robotic arm or CNC machine (Fig. 3). In comparison to commonly used hot-forming processes such as deep drawing, the deformation is achieved in a single production sequence not requiring dies or other preliminaries. Therefore, the application of SPIF is most interesting for the efficient and rapid production of small batch sizes of individual, prototypical items (Tuomi and Lamminen, 2004) or a great number of diverse elements such as façade panels.



*Figure 3. SPIF of a transparent polymer sheet. Stress micro-fractures are visible.*

The technique was initially developed for metal sheets, but has more recently also been applied for polymer sheets (Franzen et al, 2009). Our research is focused on applications of transparent polyethylene terephthalate (PET), which offers a range of benefits for the creative industry. The main advantage is the polymers low yielding strength which leads to a smaller expenditure of force during deformation and thereby to a decreasing process energy consumption. Furthermore the optic behaviour of the transparency panels can be adapted and implemented as a design strategy e.g. via grinding or painting - using the same robotic setup but with different attached tools. Towards the realization and assembly of actual building elements, the light weight of the polymer panels becomes another advantage which greatly facilitates on-site assembly.

## 4. Workshop setup

Our investigation into SPIF was conducted using the depicted setup (Fig. 4) with the main elements being an industrial robot as well as a metal frame holding the polymer sheet. Furthermore, a range of different sizes of tools and sheets were utilized for the different workshops (Table 1). The layout and position of the frame as well as the deployment of robotic arms were chosen in order to offer a variation of the tool angle as well as enable double sided editing of the sheets using only one robot - thereby being able to realize a light-weight, locally flexible and less expansive workspace.




*Figure 4. Low-payload KUKA Agilus robot deforming a transparent PET sheet (left). Section of double sided deformation setup (1-Frame, 2-Sheet, 3+4-One robot deforming both sides one after the other , 5-End effector with deformation and painting tool).*

TABLE 1. Combinations of tool, material, and machine.

| | W 1 | W 2 | W3 |
|---|---|---|---|
| Robot | Kuka Agilu (6kg payload)s | Kuka Agilus (6kg payload) | Kuka KR16-2 (16kg payload) |
| Sheet Size | 250 x 250 mm | 300 x 300 mm | 400 x 1250 mm |
| Tool Size | Ø 8 mm | Ø 8 mm | Ø 10 mm |
| Special Effects | Shading via grinding, drilling | Shading via grinding, illumination | Paint application, illumination, connection to 3D-capturing device |

The double sided editing enables the production of complex forms within a single process step without changing the main setup e.g. through turning over the sheet, and without the need for supporting systems. Additionally, the combination of design strategies and visual properties allows a more complex arrangement of fore- and background or the superimposition of form and pattern or the application of post processing work on both sides of the sheet.

## 5. Process analysis

### 5.1. DESIGN AND PRODUCTION WORKFLOW

The research as well as the individual workshops started out with intuitively collecting design ideas, patterns and shapes without yet considering the production process. Afterwards, these ideas were transferred to a digital 3D model in Rhino or Grasshopper and finally used to inform tool paths using basic and easily learnable geometric operations with Grasshopper. Afterwards, the design and manufacturing processes were linked by converting the paths into machine code using KUKA|prc and sending the resulting data via Ethernet to the robot (Braumann and Brell-Cokcan, 2014). Finally, the sheets were deformed by the robotic arm.

Each of these steps take up a very short amount of time and can be easily adjusted and fine-tuned by changing the input variables of the parametric definition. Especially, the actual deformation processing time is very low, which coincidently leads to a decreasing energy consumption and a greater economic efficiency of SPIF (Dittrich et al, 2012). With ongoing research and more preset tools within Grasshopper and KUKA|prc, the design and prefabrication planning is further reduced to a minimum of necessary work time consumption, which is one of the important factors for a successful application of the process next.

### 5.2. PATH PLANNING AND SHEET DEFORMATION

Path planning has got a great influence on the haptics of the final shape as well as the production time and general feasibility of forms. During the workshops, two approaches have been favored for path planning - either by slicing the 3D shapes in horizontal segments – similar to subtractive processes such as contour milling with a constant stepdown - or by manipulating the dimensions of linear patterns in 3D-space – alike contour milling with a three-dimensional stepdown according to the shape's deviation (Fig. 5). However, especially when working with polymer sheets, the path planning strategy not only affects the local area immediately next to the forming tool, but also has a significant impact on the global sheet geometry. Our research showed that even small, superficial deformations can generate a twisting of the polymer sheets (Fig. 1, middle). As this effect cannot yet be considered using our current evaluation and simulation tools, the twisting effect creates an increasing difference between the digital model and the physical panel that can cause unpredictable collisions. Still, these effects can also be used on purpose as a design strategy in order to create new geometric panel shapes with a minimum of deformation action.

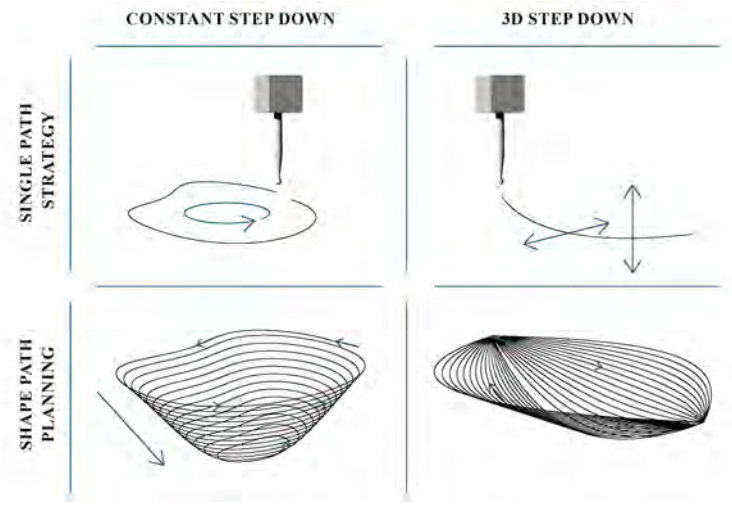



*Figure 5. Different path-planning strategies for incremental sheet forming.*

## 5.3. CONTINOUS DESIGN

Due to the short manufacturing cycle, SPIF is most suitable for rapid design-to-production workflows (Tuomi and Lamminen, 2004), to which parametric and adaptive planning as well as rapid learning and improvement techniques can be seamlessly added. The depicted process confirms the application of a closed, at any time digitally controllable workflow from the design idea to the final product. Through the constant evaluation of the gained elements, prompt optimization can be added to the process procedure. Accordingly, an increase in the efficiency of the building industry - including designers, engineers and prefabrication specialist – can be achieved.

More than that, SPIF is capable of expanding its application to the whole lifecycle of the produced (building) element, which is caused by the deformation process itself. Since no additional help (heat, dies) other than the pressure of the tool is necessary to generate the shape, the polymer sheets can be restructured at any time. Accordingly, a total reshaping to the original state of a planar sheet was already experimentally proven with SPIF of metal sheets (Takano et al., 2008) and will be further examined for polymer sheets in future research.

Thus, there is no final state of neither the element nor to the manufacturing procedure. Overall, this fact is reinventing the design thinking and making to be crucially relevant at all planning and utilization stages to the products very final end of life - experiencing initial design concepts, as well as designing for reshaping, reusing and recirculation of each object. However, the ongoing design and fabrication work is not bound to certain skilled per-

sonnel but to any involved person during the products life cycle on account of the relative simplicity of the SPIF procedure. Therefore, the contemporary interest in intuitively fabricating products with individual, adaptable character is not only a prelaminar decision but still inextricably inherit and long lastingly embedded in the physical status of the element itself.

## 6. Product outlook

### 6.1. TRANSPARENCY OF MATERIAL

Working with transparent material opens up new challenges in regards to the surface finish, but also leads to entirely new effects, such as the intricate light patterns (Fig. 6) created by the reflected and refracted light shining through 3D surfaces. The computational design of caustics is already being researched (Kieser et al, 2012) but needs to be adjusted for this specific production process. We see a wide range of applications for such panels, from interior design to entire façade structures with additional organic solar cell systems or integrated, individualized shading structures.

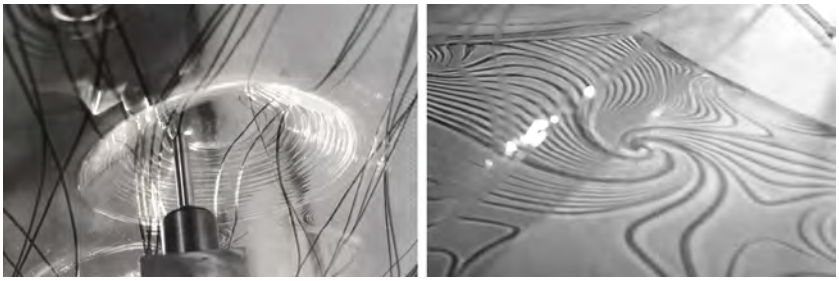


*Figure 6. Light-patterns: Combination of deformation and paint pattern (left) and pattern like shade only through deformation (right).*

### 6.2. SCALABILITY

For a widespread application of any manufacturing procedure within the architectural context, the scalability of the product and process is mandatory in order to react on the different needs of design and planning stages – model, building element and building. For verification, the SPIF process was applied to different sizes of experimental setups including differences in the machinery as well as the size of polymer sheets (Table 1).

These results show that the process is inherently scalable, using robots with higher payload and greater range enables the processing of larger, thicker PET panels. Due to the parametric nature of our code, we can rapidly adjust the process to new material and mechanic constraints, adapting the

toolpaths to fit the particular combination of machine and material. The required tools are also mechanically simple, consisting only of a metal pin with a (semi)-circular tip mounted on a bearing system. Thus, even the haptics of the toolpath are easily scalable by quickly replacing the tools.

### 6.3. MATERIAL CHALLENGES

Due to the material characteristic of polymer sheets, the sheet was prone to spring back during deformation, which as a result negatively influenced the accuracy of the designed shapes (Franzen et al, 2008). Although this might have interesting aesthetic effects, the path planning needs to be globally adjusted according to the individual behavior of different polymers and their specific spring back factor in order to meet the legal requirements of tolerances in the building sector. Considering that, research was undertaken for various metal deformation (Behera et al, 2012) as well as simple geometric shapes of polymer sheets (Le, 2009). The next step is to adapt these research results to be able to calculate most diverse irregular forms of polymer sheets for manifold application.

## 7. Conclusion

Today, multi-functional robotic arms and visual programming strategies allow architects and designers to develop entirely new fabrication strategies within a comparably short timeframe, creating new products and workflows that are optimized for the requirements of the creative industry.

Our research shows the potential of the incremental forming of transparent polymer sheets as a highly flexible, scalable fabrication process that can be used for large-scale architectural applications. We see particular promise in the emerged topic of illumination effects, towards using SPIF made façade panels for light guidance and targeted shading. Therefore, experiments on optics, refraction and light control are upcoming.

Moreover, we believe that the continuous design approach of SPIF allows for an efficient customization of building elements in full 1:1 scale. Thus, future research will focus on the potentials and constraints of implementing the procedure onto building sites. We expect that the on-site, just in time fabrication of panels, can allow us to individually minimize building tolerances. Furthermore, the process as well as the design of the façade panels can be adjusted according to on-site detected changes in constraints or other environmental influences.

On a broader outlook, research on alternative fabrication processes such as SPIF contribute to the implementation of new strategies for the integration of design and production during the whole lifecycle of building elements and

thereby strengthen the longevity and environmental impact of buildings in general, although the underlying building materials are not yet classified as sustainable.

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# PARAMETRIC CUSTOMISATION OF A 3D CONCRETE PRINTED PAVILION

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**Abstract.** Advances in 3D printing technology have reached architectural scales with 3D concrete printing, a digitally controlled fabrication process in which fibre-reinforced concrete is deposited layer-by-layer to fabricate building elements. In this paper we present a brief overview of key concrete 3D printing related research development efforts, followed by a report on a research project into the parametric online customisation and fabrication of small 3D concrete printed pavilions. The research project is set in, and addresses possibilities and constraints of, the developing local Chinese construction context.

**Keywords.** 3D concrete printing; parametric design; digital fabrication; online customisation; China.

## 1. Background

For more than three decades, the Chinese construction boom has resulted in the placement of unheard-of quantities of concrete. Smil (2014, p. 91) illustrates the scale of this transformation with the observation that Chinese construction between 2009 and 2011 consumed 5.5 gigatonnes of cement, while the USA consumed a mere 4.56 gigatonnes of cement in the entire twentieth century. Collateral environmental impacts result, besides other factors, from the import and production of iron ore for reinforcement steel, from the depletion of river sands to be used as aggregate, and from the waste of large quantities of discarded formwork. This developmental push forward is bound to remain in effect for decades to come. At the same time, large-scale urbanisation, the opening of markets, the emergence of a new urban middle class, and the gradual de-regulation of family structures in China give rise to an increasing demand for variety in built form. Despite these

changes, dominant methods and typical forms of concrete construction in China have not changed significantly for decades, and digital automation technologies in particular have remained largely out of reach for China as well as other developing countries. Key reasons for the persistence of concrete construction methods include the lack of skill in labour force as well as challenges of introducing automation at building scale. While low-skilled human labour can be expected to dominate concrete construction in China for the foreseeable future, recent advances in 3D printing based construction automation are now showing promise.

With this paper, we aim to connect recent initial advances to introduce 3D concrete printing technology into the local Chinese construction context with the more advanced possibilities offered by advanced parametric modelling. The research project outlined in the second half of this paper is based on the authors' collaboration with three undergraduate students of architecture over one summer. The scope of the work comprises primarily the set-up of a parametric model that takes into account local material and construction technology constraints in the fabrication of 3D printed concrete and can be operated through an online user interface.

## 2. 3D printing at the scale of buildings

In parallel to recent advances in more familiar desktop 3D printing and rapid prototyping technologies, larger-scale 3D concrete printing, currently still in the early stages of its technological development, has progressed significantly over the past few years. Van der Zee et al (2014) distinguish two types of process in in building scale 3D printing: Additive layered depositing, and selective sintering. Among a variety of potential materials, concrete has emerged as one of the most promising materials for automated layered depositing fabrication at the building scale. This approach uses robot arms or, more typically, gantry cranes as large-scale Cartesian robots for the computer-controlled deposition of concrete, and is currently explored at an experimental and early demonstration stage.

The Contour Crafting process, developed by Behrokh Khoshnevis at the University of Southern California (Leach et al, 2012), is an additive layered depositing process. Layers of a concrete mix are extruded and deposited robotically to form building elements, typically walls stabilised by an internally corrugated structure, without the need for traditional formwork. A layered 3D concrete printing process for the manufacturing of building components has also been developed at Loughborough University (Buswell et al, 2007; Lim et al, 2012). This initiative focuses on reinforcement techniques, material science, and the development of robotics for material

placement. The Loughborough group has manufactured prototypes for building elements that are complex in shape and require precise manufacturing, such as doubly-curved cladding panels. In contrast to the previous two approaches, which use a layered depositing approach, the work of Dini of D-Shape Enterprises (Dehue, 2013) employs the selective sintering approach, which requires printed objects to be dug out of a mass of substrate after printing is finished. In collaboration with Kushner Studios, Dini is currently aiming to print a large house in Gardiner, New York (Myall, 2015a).

## 3. Recent developments in 3D concrete printing in China

While so far most 3D concrete printing research efforts are taking place in academic contexts, with a focus on technology development and small prototypes, the Suzhou, China based company WinSun has made headlines in recent years by producing a series of full-scale 3D printed buildings. WinSun has adopted the recipe for its concrete mix (called "ink" and kept secret by WinSun), along with its layered printing technology and internal wall corrugation construction method (figure 1, left), from those developed by the Contour Crafting group – under controversial circumstances (Sheehan, 2015). Starting from producing ten small pavilion-like structures within 24 hours in 2014, the company has proceeded to unveil two larger record-setting prototypes on their company grounds in early 2015: A large two-floor villa as well as a five-floor building (figure 1, right).



*Figure 1. Deposited layers of "ink": 3D concrete printed object by WinSun (left), five-floor experimental building by WinSun (right).*

While their presentation as "3D printed" suggests that these larger structures are completely 3D-concrete printed, they are in fact based on a hybrid construction method in which vertical compression-loaded elements (i.e. walls and columns) are 3D printed, while floor slabs are in-situ cast by conventional means. The ink mix used by WinSun consists, besides recycled construction waste, of cement and a binder that takes 24 hours to dry (Sun, 2015), as well as structural reinforcement in the form of glass or polymer

fibre. The fibre gives the ink some tensile strength within each deposited layer, but little tensile strength between layers where little or no continuity of fibre is present due to the extrusion-based depositing method. This results in weaknesses under tensile stresses, while compressive strength of structures made from ink lie at the lower end of the range of compressive strengths of conventional types of concrete. For these reasons WinSun typically embeds steel reinforcement in larger 3D printed structures, effectively employing the 3D printed concrete elements as lost formwork for an internal conventional reinforced concrete structure. While this strategy supports higher reliability of a new material with not yet well understood structural behaviour, it also renders such building elements heavy and primarily usable as walls and columns. WinSun has recently extended this limited architectural repertoire with large-scale 3D concrete printed structures comprising also horizontal building elements for the Museum of the Future project in Dubai, in collaboration with well-known international architecture and engineering firms Gensler, Thornton Thomasetti and Syska Hennessy (Myall, 2015b).

The 3D concrete printing research initiatives outlined in section 2 above are characterised by different motivations. While Koshnevis expects that future on-site production of buildings will make low-cost but high-quality housing construction possible (Sun, 2015), the Loughborough University team focuses on high precision fabrication of building components for complex geometries. Dini and Kushner, meanwhile, are working towards the automated construction of entire buildings featuring complex shapes (Myall, 2015a). The WinSun company takes a yet different approach in aiming for the prefabrication of simple building elements that cut construction costs by reducing labour cost and construction time. With this aim, WinSun continues to push forward with achieving and announcing new records regarding speed, efficiency and economy, but currently pays less attention to new architectural possibilities, spatial qualities or high quality detail design.

Besides the automation and form giving opportunities they offer, WinSun's and similar 3D concrete printing technologies show potential with regards to sustainability. Not only does WinSun claim that their ink contains a significant proportion of recycled construction waste, which would reduce the demand for "fresh" aggregate as well as for landfill space; there is also a significant potential to reduce the demand for river sand in concrete construction. A factor that contributes considerably to the demand for river sand is the corrosive effect of salt and chloride contained in other (ocean, desert) sands on rebar steel. Abundantly available and cheap ocean and desert sands are however suitable for 3D printed concrete elements whose glass or polymer fibre contents are sufficient to deal with physical stresses,

and which hence require no steel reinforcement. To deal with tensile stresses in its larger scale structures, WinSun typically embeds rebar in river sand-based concrete added within cavities left in the corrugated interiors of 3D printed extrusions, to ensure cohesion between 3D printed layers. When embedded in this way, rebar steel does not get into contact with corrosive, ocean or desert sand based ink elements. If this construction technique could reduce the demand for river sand even by modest proportions, given the above-mentioned gigantic volume of concrete production in China, the overall environmental and economic effects could be considerable. The economic effect may well offer viable returns on the investments necessary for the development efforts required to bring 3D concrete printing to maturity.

3D concrete printing allows, within some constraints, the production of unique, one-off shapes. It is hence highly suitable for, and easily related to, digital and parametric form giving approaches. The following sections of this paper outline a project in the intersection between parametric form finding and 3D concrete printing. With this project, we aim to explore possibilities for academic and industrial research collaborations, to extend the use of digital parametric modeling, as well as to address a lack of attention towards architectural quality. For a discussion of the general characteristics and possibilities of parametric design have been discussed in other contexts, and will therefore not be reviewed in this paper. Readers interested in this aspect of the background of this study are referred to Jabi (2013), Woodburry (2010) and Herr (2011).

## 4. Customisation platform and fabrication

The project discussed here was conducted jointly by a team of undergraduate architecture students and faculty members at the Department of Architecture at Xi'an Jiaotong-Liverpool University (XJTLU) within the framework of a novel summer undergraduate research fellowship programme. The research students were invited to explore and evaluate possibilities of customising 3D concrete printed pavilions, and to investigate the potential of 3D printing for online parametric mass customisation (Gilmore and Pine, 1997; Herr and Fischer, 2015) of small concrete buildings to address varying client needs and site contexts. More specifically, the students developed an architectural form language that mediates between the possibilities of simple web-based interfaces and the constraints of 3D concrete printing as currently practiced by WinSun, and implemented a demonstration platform that bridges these technologies. In this manner, the project is related to recent studies exploring

how advanced digital design can be implemented with basic means in projects constructed in developing countries.

Methodologically, the project has adopted a research-through-design approach that has also served to explore possibilities for industrial collaboration with WinSun. The research process took the form of alternating cycles of design exploration and synthesis, informed by sketching, model making, experimental coding, data collection and expert feedback focused on material, fabrication, transportation and construction constraints, functional aspects, and structural evaluation. Outcomes and findings include a form language suitable to the material and fabrication process, a parametric customisation approach, a set of structural design and construction constraints, and a rage of pavilion designs generated with the system. The research-through-design approach allowed the evaluation of results on a continuous basis, and may lead to the realisation of one pavilion prototype.

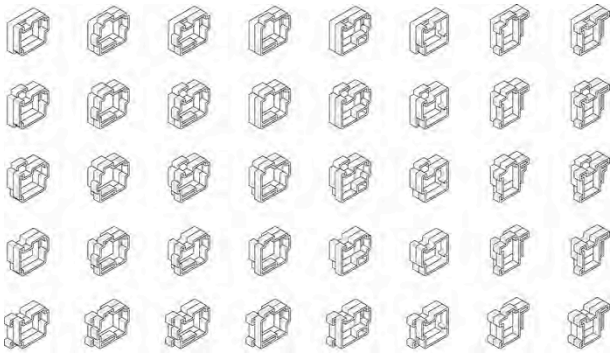


*Figure 2. Possible combinations of sections in the library (partial view).*

The architectural form language developed for this project (figure 2) responds to current possibilities and limitations of 3D concrete printing on the scale of buildings, related material properties and structural performance criteria. It recognises the need to print larger, heavier elements in straight vertical stacks without overhangs that could produce curves in section. To achieve enclosing shapes, the form language hence requires the printing of closed vertical section shapes including floor, walls and ceiling on a flat horizontal surface, and the result to be turned on its side after the concrete mixture has hardened – typically after 24 hours. The form language developed in this project was inspired in part by a precedent project investigating online parametric pavilion customisation (Rüdenauer, 2005). Functional aspects of use, ergonomics as well as fabrication, including the integration of an electrical system, and transportation and assembly constraints were considered.

The online customisation interface (figure 3) offers access to elements of the form language and some of their attributes via an extendable library of segment cross-section profiles, allowing for their recombination and parametric dimensioning. The system is implemented in Python/CGI via an Apache web server driving a parametric Rhino3D model and Grasshopper setup (see figure 4). It permits the exploration of a broad variety of different yet structurally and aesthetically coherent pavilion structures.

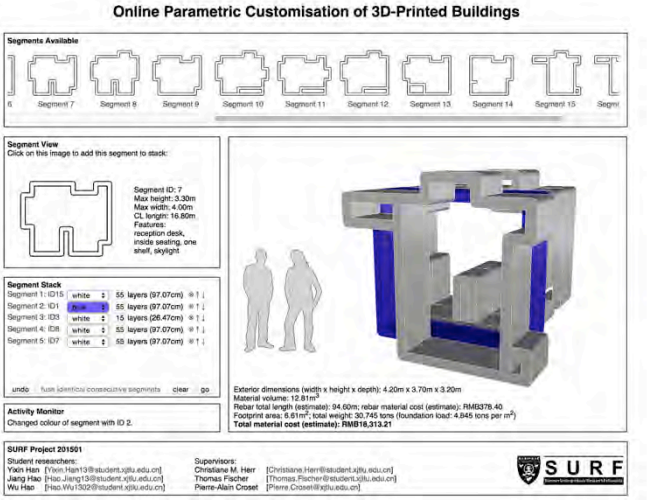



*Figure 3. Online customisation interface.*

Users can select cross section profiles from a cross section library and add them to a stack. The interface offers several functions to sort, edit and process stacks or cross sections. Each cross-section in a stack can be altered parametrically in terms of its depth, concrete pigment colour, and position within the stack. CGI scripts and Grasshopper are interfaced via file system based data exchange, which requires the Grasshopper setup to operate in an error state (indicated by red and orange coloured elements in figure 4) when idle and to enter error-free operation when input data becomes available momentarily.

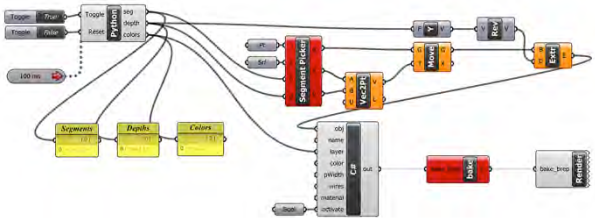



*Figure 4. Grasshopper setup.*

Of the vast variety of pavilions that can be generated using this platform, the research students chose one (shown in figure 5) for in-depth analysis and implementation.



*Figure 5. Rendering of the pavilion selected for production.*

The structural performance of the pavilion selected for implementation was evaluated in collaboration with XJTLU's Department of Civil Engineering using Finite Element Method (FEM) in ANSYS (see figure 6).

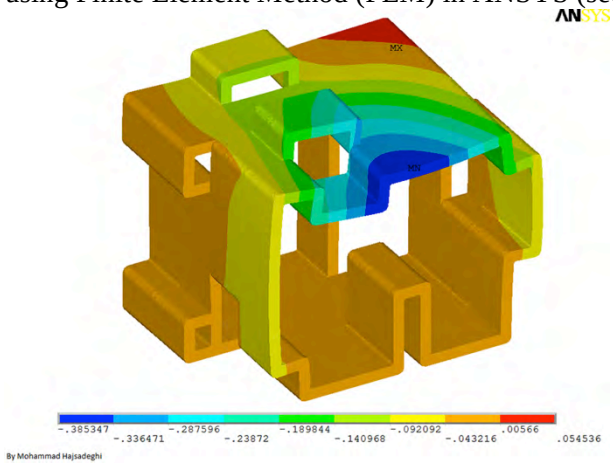



*Figure 6. FEM-based simulation of deformation (displayed disproportionally) under dead load in ANSYS.*

The structure of the selected pavilion was simulated assuming the structural properties of conventional, non-reinforced concrete, and found to be capable of supporting its own weight within a margin of safety of 150%. However, greater stresses than dead load support must be expected,

especially during handling, transport and assembly of individual segments. In addition, as the structural characteristics of the ink material are not yet fully understood, they were unavailable for simulation purposes. For these reasons it was decided to embed steel reinforcements both within the printing plane (at an interval of ±10 printing layers) and perpendicularly to the printing plane to ensure the connections between printing layers as well as the connections between pavilion segments.

This project allowed extending the scope of previous parametric design related research (Fischer and Herr, 2015) to investigate architectural (functional, aesthetic, structural, economic) aspects of 3D concrete printing within the framework of parametric design. It also extends previous research on integrating advanced digital design methods with local Chinese construction practice (Herr and Fischer, 2013; Herr and Fischer, 2014). The study focuses on a specific building type, a specific fabrication method, a specific material, one form language, and a particular recombinatorial and parametric customisation approach. Alternative approaches and form languages are possible and may be addressed in future research. The FEM analysis could potentially be integrated into the Grasshopper definition in a further development of this research. Findings achieved in this project are expected to inform future 3D concrete printing practice, as well as further research into related materials, technologies, form languages and customisation strategies.

## 5. Conclusions

With the described proof-of-concept implementation, we have demonstrated how users and clients can be enabled to conduct or to participate in building customisation via an online interface. We have further shown how digitally supported fabrication of such customised buildings through 3D printing can take into account possibilities and constraints of current 3D concrete printing technology and materials locally available in China. This was achieved through the coordinated design of the described online interface, the described form language, and a suitable backend setup. Further development of the presented work will be subject to all involved partners' readiness to engage in collaborative partnership.

## Acknowledgements

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# ROBOTIC PRODUCTION OF INDIVIDUALISED WOOD JOINTS

*Fabricating an Info Point Structure for the WCTE*

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**Abstract.** Modern modular constructions can consist of highly individualised elements that are produced at nearly the same efficiency as serial manufacturing. This paper focuses on the project "WoodWaves" an Info-Point for the conference World Congress of Timber Engineering, which was designed with this new conception of modularity. The process utilises a robotically operated milling cutter to form blockboard panels out of spruce, which make up the multifunctional information point. The entire object is produced with only sliding dovetail joints. Parametric design methods were developed to automatically adjust each joint to fit the individual conditions. New CAD/CAM interfaces, linking design directly with fabrication, enabled the serial production of 108 different shaped elements with a 6-axis robotic arm.

**Keywords.** Computational design; robotic production; digital fabrication; wood joints; info-point.

## 1. Introduction

The aim of the project was to design an Info-Point for the World Conference on Timber Engineering, acting as a recognizable landmark while also providing information to attendees. The design of the object should emphasise the innovation and high performance of wood-based constructions, while the temporary nature of the event required quick assembly and disassembly, the

reusability of elements and versatile usage of the space. Wooden blockboard was provided by a commercial partner and incorporated as an important design parameter from the beginning.

We started a student competition at the department of Timber Engineering to find a design that would represent the university. 17 students took part, resulting in a total of 12 projects. After a 5-week planning period the project “WoodWaves” was selected by the jury for realisation (Figure 1). The project was chosen due its flexibility in design and the feasibility of a digital production process. Due to the fact that all single elements had a unique shape, a computer aided manufacturing machine would be required. By engraving information into the wood, the winning project was able to incorporate the WCTE-relevant information as part of the elements without adding additional information devices such as flatscreens.

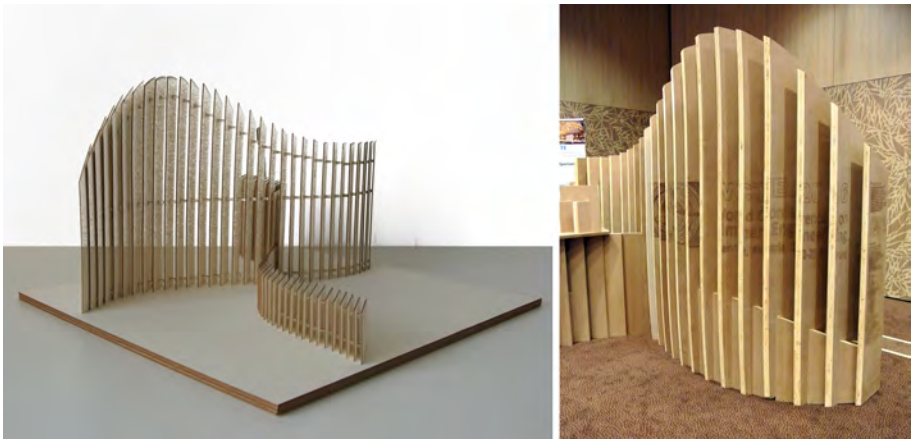


*Figure 1. Initial WoodWaves concept model (left), final WoodWaves structure with engraved information (right).*

## 2. Design idea and process

The fluent design of the multifunctional Info-Point leads to its unique appearance. Its shape is defined by two different curves, which overlap asymmetrically. The main curve defines the information panels while the other curve defines the table and bench. Only these initial curves are sketched by the designer within the CAD environment Rhinoceros - the resulting form, location and size of panels are then automatically defined through generative design methods in the second step, e.g. shaping the doubly curved edges of the panels using two sinusoids. While the panels are placed nearly parallel to each other, their spacing gradually varies.

## 3. Detailing & materialising

Our goal was to be able to set up the object with tight fitting joints to avoid using any screws or glue, so that it can be assembled and disassembled multiple times over its lifespan. In the initial design the main panels were fixed at three points with smaller elements (Figure 1, left). The disadvantage of this solution was the high amount of joining elements and having to produce individual grooves in the main panels. A further disadvantage of multiple joints was a reduction in space available for the information area within the main panels plus a lack of stability in the overall structure.

The subsequent design added a second layer of panels of lower height (41-75 cm) with free formed edges to the main panels to stabilise lower structure. Orthogonally to the direction of the main structure a second curved row of elements with the same construction principle as described above was added to stabilise the overall structure.

The detail for the panel connections was developed as a variation of the "sliding dovetail" woodworking joint. Usually, the sliding dovetail is a method of joining two boards at right angles. However, due to the non-rectangular arrangement of panels, the joints had to be generated dynamically in order to realise the given shape. Thus, each and every single tail is designed and produced with a different angle (placed on the small connection panels). The slightly tapered sockets are designed with a right angle and are located on both sides of the main panels (Figure 2).



*Figure 2. Sliding Dovetail: Initial concept model (left), final fabricated elements (right).*

The entire object uses a single type of blockboard with 5 layers, called "BACO MDF Triple Core" (Spruce), and produced by Schweighofer. In or-

der to be able to mill the socket on both sides of the panel, the required thickness of the panel was calculated to be 34 mm. While the 3 inner layers consist of spruce, the outer layers are covered with 2mm MDF panels.

## 4. Implementation

The final model of the Info-Point required 108 individually-shaped parts. 21 main panels define the appearance of the object and are engraved with brief information about the WCTE conference. A further 13 panels with a length of 450 mm form a bench and 8 panel with a length of 1100 mm form a bar table. The remaining 66 plates are connection elements.

### 4.1. DIGITAL DATA

While the general, global shape of the structure is relatively easy to generate, actually fabricating the structure required a much more precise detailing. In collaboration with the wood-engineers we developed a construction logic that would allow us to easily assemble and disassemble the entire structure, while also keeping close to the original design-intent. This construction logic was then implemented using Grasshopper, a [modular] visual programming environment (Davis et al, 2011).

Commonly, CAM software such as HyperMill would be used for preparing the milling data for each panel. However, this proved to be impractical due to the large number of elements that had to be processed, with every panel having its own, unique geometry. While current CAM software is optimised to deal with a certain amount of variable parameters, such as varying whole diameters, the complex, changing shapes of the panels would have required a manual setup of each individual component.

So rather than relying on preexisting fabrication strategies in commercial CAM software, we created a new, parametric definition within Grasshopper that would allow us to fabricate each panel, simply by referencing the main geometric features such as edge curves. Since every panel is topologically similar, this enabled us to perform the more complex milling strategies for the connection elements, as well as the engraving of the information layer, within a single workflow. However, after the initial definition of the fabrication strategy, the entire fabrication had to be adapted to the local fabrication setup. Due to the complexity of the geometry, we had to use a milling machine with at least five axes, as only that amount of kinematic flexibility would allow us to fabricate the non-vertical edges of each element. However, as five-axis CNC machines with a sufficiently large workspace are very rare, we instead decided to use a six-axis robot that was set up with the explicit goal of being used for wood fabrication.

While a six-axis robot provides even greater kinematic flexibility than the previously mentioned CNC machines, we had to carefully consider the workspace of the machine. Unlike CNC machines that are commonly built "around" the workpiece, the robot stands within its own workspace, making an accurate prediction of reachability difficult.

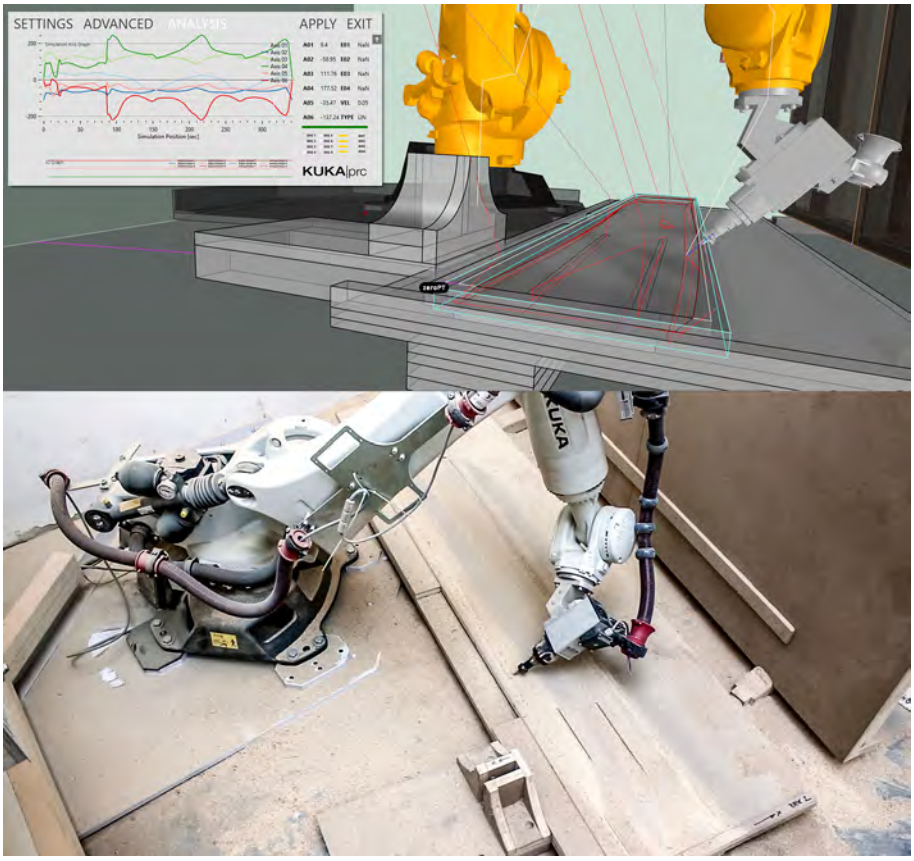



*Figure 3. Checking the reachability of the KUKA robot with KUKA|prc - the axis movement of the robot is graphed in a separate window (above). Physical fabrication with challenging shallow angles (below).*

Rather than experimenting on-site, we decided to use KUKA|prc (parametric robot control) – an accessible software tool that allows the user to control industrial robots from within the visual programming environment (Brell-Cokcan, Braumann, 2010). Coupling KUKA|prc with the existing parametric toolpath definition allowed us to immediately check every panel for reachability and to adjust it accordingly (Figure 3, top).

It also showed us potential problematic areas, especially on long pieces with very shallow angles at the edges (Figure 3, below). While the robot was able to easily reach the position, the angles were so shallow that the tool-holder would have collided with the ground. In the end this issue was solved “physically” by simply using longer milling tools. For the workflow we chose not to automatically generate all robot control data files in advance, but to prepare each subsequent file while the predecessor was being produced. This allowed us to quickly react to new challenges, such as insufficiently stable workpiece holders that than had to be enlarged.

The main challenge of the digital workflow proved to be the version control between the people who supervised the programming, resulting in people working with outdated or simply wrong calibration data, thus making the simulation unreliable.

### 4.2. PHYSICAL FABRCATON

For the production of all panels we used a 6-axis robotic arm, a KUKA Quantec KR120 R2500 with 120kg maximum payload and a reach of 2.5m. The production took place in three steps and with three different kinds of milling cutters, which are operated by a spindle with a maximum rotational speed of 16000rpm.

At the first stage of production a 14 mm thick /110 mm long milling cutter is used to cut the double-curved edges of the main panels and to mill the sockets for the joints. Following that, the more compact connection elements are milled vertically to use the workspace of the robot more efficiently. Finally, the edges are cut mitre with a right angle and the tails for the joints shaped without bevel. At the second stage of production a router cutter completed the final geometry of the elements. The sockets of the main panels and the tails of the connection elements are milled with the final bevel. During the last stage of the production the logo and important information regarding the WCTE conference are engraved on the surfaces of the main panels.

The main panels are fixed above the zero plane on a pedestal with a smaller dimension, so that the complex edges can be cut all the way through, without colliding with the underlying structure. For the connection elements we constructed a jig to hold them vertically. While this mounting strategy increased vibrations, it offered the best accessibility for the robot, thus avoiding costly collisions. Finally, all parts are marked with different position numbers, in order to facilitate a quick assembly.

## 4.3. CHALLENGES

In order to interlock the parts smoothly, the sockets and the tails for the connections have been designed and produced with a tolerance of 0.5 mm. Despite this tolerance we realised that the sockets and the tails did not fit precisely after the production process. We measured a deviation along the longitudinal edge of the tails up to 1 mm.

As described in chapter 4.2, the connection elements were produced vertically to provide the best accessibility for the robot. The working pieces were clamped 20 cm deep between two panels. Additionally, a standing plate was installed crosswise, to the working piece, in order to minimise the vibrations during the milling process (Figure 4). The working piece was fixed to the jig at two points and with one screw along the edge of the crosswise plate.



*Figure 4. The holder of the connecting elements has been reinforced to reduce vibrations and thus increase accuracy (left), robot path planning (right).*

This kind of jig caused two problems. The connection elements had to be prepared 20 cm longer than needed and afterwards the plates were cut to the correct length, leading to an unnecessary waste of material. Secondly during the milling, the mechanical power transmission between the robotic arm and working piece was high enough to cause vibrations in the working piece, causing the slight deviation along the longitudinal edges. The amount of deviation gets bigger with the increasing length of the connection elements. The smaller elements up to 50 cm remained within the tolerance limit of 0,5 mm and could be connected without any issues. However, connection elements with a length of more than 50 cm had to be reworked.

This vibration problem did not affect the production process of the main panels as the working pieces were milled on top of a large support. All sockets were produced without appreciable deviation along longitudinal edges.

### 4.4. ASSEMBLY

Every single element was checked against its neighbors while still at the woodshop, sanding each tail and socket. Each main panel was placed horizontally so that the connecting elements could be easily pushed into its sockets. Afterwards the partially assembled elements were repositioned vertically. This process was repeated for each group (main panel plus connection elements), sequentially combining those into a single object (Figure 5). Three people assembled the whole object within 90 minutes.




*Figure 5. Final, assembled WoodWaves Info Point.*

## 5. Related work

Since 2010 several experimental projects with wooden joints were realised using industrial robots. Some of them were developed and realised by Menges, Schwinn and Robeller. They use dovetail and finger joints for wood to wood connection. The robotic fabrication allows for the efficient fabrication of performative finger joint connections even at extreme angles.

In the project of Menges and Schwinn the contact surface of the pins and tails are arranged orthogonally to the edge. (Schwinn et al, 2012). Robeller's dovetail joint tails and pins were milled with a fold angle of 167,2° (Robeller et al, 2014).

In a common dovetail joint many pins and tails run alternately along the edges, while with a sliding dovetail joint – as in the WoodWaves project -

there is just one socket and tail. The socket runs along the surface and the tail is placed on along the edge (Figure 6).




*Figure 6 Assembling of the panels and joint detail (left), connection elements with different angles by the edges (right)*

The stability of this type of connection depends heavily on the precise and congruous production of the socket and tails. Due to the organic form of the object all panels are connected with different angles, which vary from 26,7° to 66,5° (Figure 6). The sockets and tails are formed as if they were a common right angle connection, but the tails are connected to the edges at varying angle. Using this methodology even extreme angles can be produced without breaking edges.

Industry commonly uses 5 axis joinery machines for dovetail joints. However, these machines are very voluminous and expensive, so that only large wood fabricators specialised in mass production can afford them. The most frequent industrial use for dovetail joints are beam to beam connections, which can be produced by joinery machines with different angles.

Thus, joinery machines are optimised for the manufacturing methodology of the carpenter, so that standard applications can be programmed rather easily and are then performed with great speed and accuracy. Problems only arise once nonstandard solutions are required. The programming difficult geometry is time consuming and not as flexible as with a robot arm. While robots – due to their kinematic layout – cannot compete with specialised machines in regards to total accuracy and speed, these machines represent a new an affordable way towards making complex joinery technologies available to smaller companies and even individual carpenters, that were previously only accessible to high-end industry.

## 6. Conclusion

The results of this project represent the first step of investigation for a research program, which compares digital fabrication techniques with common

carpenter production methods. Instead of having to rely on mass-fabricated elements, today's digital and mechanic tools allow us to create designs that consist of individualised building parts. However, to cope with the complexity of the high number of digital shapes, it is not sufficient to solely draw a 2D plan or even a 3D model. Instead, contemporary architectural design methods require the use of digital parametric design tools and knowledge of programming (Agkathidis, 2009).

Combining such high-end digital processes with the high-end, ecological material wood can now create new, sustainable designs with the same efficiency as mass-production.

New interfaces enable a direct communication between 3D modelling software and complex machines such as robotic arms. This allows designers and architects to develop entire manufacturing methods by themselves, and gives them to control over all aspects of a design, from sketch to fabrication (Brell-Cokcan and Braumann, 2012).

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# DEVELOPING THE TERMITE PLUG-IN

## *Abstracting operations to link 5-axis CNC routers with parametric CAAD tools*

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**Abstract.** Since the turn of the millennium, architects and designers have used greater access to Computer Aided Manufacturing (CAM) machines to explore links between design and fabrication. This trend is recently manifested in plug-ins for CAD software packages, which enable designers to program industrial robots and additive manufacturing machines. However, amongst the array of contemporary tools, few connect CAD packages to commercial 5-axis routers and, as a result, designers are forced to use complex CAM software to operate these machines with limited exploration of the interface with design. This paper reports on the development of a CAD plug-in for driving such routers and targeted at designers. It discusses key aspects in the conception of the software libraries for an alpha release of the tool, a plug-in for *McNeel Grasshopper* named *Termite*. Primary considerations for the development team include the areas and extent of flexibility offered in order to enable non-expert users of such machines to use them to in an effective and efficient manner. Key elements of the tools are discussed, including the definition of machining tools, the creation of generic toolpaths and the subsequent writing machine-code files. A set of example pieces are presented to demonstrate the proposed approach for flank-milling, patterning and connecting timber components at a furniture scale. These are compared to plug-ins for industrial robot with similar technical knowledge and experience amongst the target audience.

**Keywords.** Digital fabrication; parametric design; architectural prototypes; digital material.

## 1. Introduction

Gaps between design and fabrication are being shrunk as technology for CNC fabrication becomes increasingly cheap and ubiquitous (The Economist, 2012). Amongst the hype around this technological expansion are a number of assumptions about the skill required to operate machines in a manner that is effective, efficient and safe. At an extreme, it is assumed that Computer Numeric Control (CNC) machines remove all requirements for skilled operators, a conception which has been historically shown to be naïve and costly (Moe, 2010). The reality is that specific user groups have specific demands in flexibility of operation and accuracy of finish. This paper presents the conception and alpha version of *Termite*, a plug-in targeted at designers for the operation of panel routing machines. The development of this software demands the careful consideration of the target audience, their skill levels and the functionality they will require. Designers are not commonly experts in details of CNC machine operation and are not engaged to finesse details or optimise process for high volume efficiencies. It is therefore important to provide a flexible but simple interface between design and machining. Where designers are producing material artefacts as part of an iterative design process, these are often to relatively low dimensional tolerances. For example in the construction industry +/- 1mm is more accurate than conventional building trades and presents emerging challenges and opportunities (Sheil, 2013).

## 2. Background

### 2.1. TARGET AUDIENCE AND CHALLENGES WITH CAM PROGRAMS

Rather than being closely aligned with the tasks of contemporary designer, CAM has conventionally been a separate task, undertaken using software packages operated by specialist users. This reflects a deep set of knowledge required for using CNC and other fabrication machines. However, contemporary interest of the so-called maker movement and businesses promoting amateur users are challenging this divide.

Some tasks such as the 3-axis operations of machines like laser-cutters are generally quickly learnt. However, for machines with more degrees of freedom, the complexity of programming and operation increases steeply. To drive machines with 5 and more axes, typically a standalone CAM program is used, a common example in industry being *DelCam PowerMill*. This program exposes the user to over 17 dialogue windows for every toolpath, with numerous parameters and settings within each, allowing accurate and opti-

mised programming for a broad number of machines. The complexity of this software and the detailed inputs required is such that regular use is necessary to efficiently operate a machine.

### 2.2. CAM PLUG-INS FOR DESIGNERS USING ROBOTS

Recently, software plug-ins to CAD platforms have become available which offer the programming of industrial robot arms. These have claimed attention by providing a relatively simple interface between design and fabrication. The simple interface provides access to basic functionality of a machine and enables rapid feedback iterations between digital design versions and material prototypes, without confusing the process with too many details related to machining. Amongst a number of tools, two plug-ins for parametric design platform Grasshopper for *McNeel Rhinoceros* - KUKA|prc and HAL – are exemplars. Users with relatively little experience in machine programming, can generate files for *Kuka*, *ABB* and *Universal* robots.

Industrial robot arms have been described as “universal fabrication machines” (Bonwetsch, 2013) for their flexibility of tool and geometry. The plug-ins mentioned here provide universal functionality – placing a tool point in a specified position. Much of industry, however, utilises Computer Numeric Controlled (CNC) machines which are designed for specific tasks. These machines are more efficient than universal robots, offering higher accuracy, as well as more consistent and faster cutting speeds. CAD plug-ins similar to those for robots, however, have not been developed for these machines, and so novice users have little opportunity to use them.

## 3. Key aspects of Termite

*Termite*, currently built as a plug-in for the parametric modelling platform *Grasshopper* within *McNeel Rhinoceros* seeks to be an easy extension to a design workflow. Panel routing machines have a very broad set of input parameters. As a tool for non-expert users, the plug-in schema presented here provides only limited options to the user in order to minimise problems, increase speed and ease of use.

*Termite* development has initially focussed on aspects of panel machining that cannot be achieved with 3-axis machines such as flank milling, compound saw cuts and angled drilling. The low computational requirements of these operations also make them well suited to near real-time manipulation in a parametric design environment, a critical aspect for the plug-in’s functionality. ‘Surfacing’ which is more computationally intensive presents specific challenges and is covered briefly by parallel finishing and spiral finishing components.

The process to create a machine code output file is broken into five steps – tool definition, geometry definition, cutting operation definition, machine definition and file generation (Figure 1). Outside of these is a 'parser' component, which generates the machine preview directly from the output code. This last component allows for existing machine files can be read into grasshopper as geometry, which provides a convenient way of checking files, without needing navigate someone else's parametric definition. These key components can be modified and deconstructed in greater detail with additional components.

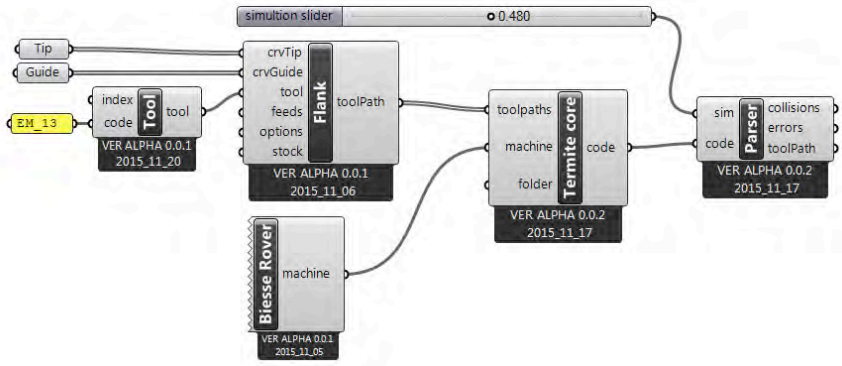



*Figure 1. A basic Termite definition consisting of: Tool, Toolpath, Machine, Core and Parser. Note that not all options require user input. Default toolpath feeds and speeds are extracted from tool properties, stock size is defined from input geometry bounding box, and options are set to sensible default values for each toolpath type.*

## 3.1. 'CORE' COMPONENT

The core component: Allows key folders to be referenced; ensures the correct document units system; post-processes toolpaths into machine code, and contains all the code classes, which are centralised for ease of maintenance

The source code to *Termite* is exposed within each component, making is possible for others to extend and modify functionality. Users can create their own scripted components using termite datatypes if a specific function doesn't exist. All *Termite* datatypes can also be deconstructed into generic and native Rhinoceros types including lines, points, vectors, numbers, strings and booleans. This approach contrasts with the other packages mentioned above.

## 3.2. 'TOOL' CLASS AND COMPONENTS

Tools can be defined by a user or alternatively generated directly from tool data file stored on the machine. This latter approach enables easy mainte-

nance of keeping tool library in *Termite*, updated by simply locating a copy of the tool data.asc file from a machine backup.

This machine-managed tool definition contains limits for the tool feeds, speeds, depths, useable length, whether it can cut with it's end, side or both. For example, if a saw blade manufacturer requires that the blade rpm not exceed 4500 and if a termite tool path spindle speed exceeds this limit, it will throw an error. A similar error message is raised if a user tries to use a drill bit rather than a milling bit for a milling operation.

This difference between tool types is a common mistake among novice machine users. Restrictions in the software are essential where the novice programmer is very unlikely to be aware of any restrictions on the tools or machine. This enables those with design skill, but not necessarily CAM knowledge to integrate CAM into their workflows.

### 3.3. 'TOOLPATH' CLASS AND COMPONENTS

Toolpaths in *Termite* are defined as lists of a generic point and vector format (x,y,z,i,j,k), accompanied by a feedrate. This definition is not machine specific and can readily be fed to different machine post processors, as well as some simple machines and CAM softwares. For example *Termite* toolpaths could be used to create robot toolpaths in *HAL* or *Kuka|prc*, allows our plugin to work alongside other CAM plugins.

Many of the possible attributes of a toolpath are not exposed on the toolpath components. A toolpath settings component is available to provide more detailed controls where necessary, however the default values are intended to cover most scenarios.

Lead-ins, the process of a tool entering a material stock, are an essential part of toolpaths. These are always created as a default of defining a toolpath. There are three main strategies: plunge – directly along a tool axis; ramp – in an oblique direction towards the first point; and spiral – movement in a circular, ramping motion. Lead-ins typically occur at a lower speed. Further detail of a toolpath is needed to accurately and safely define a strategy for cutting ruled surfaces (Figure 2). Many common methods used to generate these surfaces are unsuitable for milling as a tool is designed to cut in a specific direction, typically either parallel to a trajectory or tangential to the direction of cut.

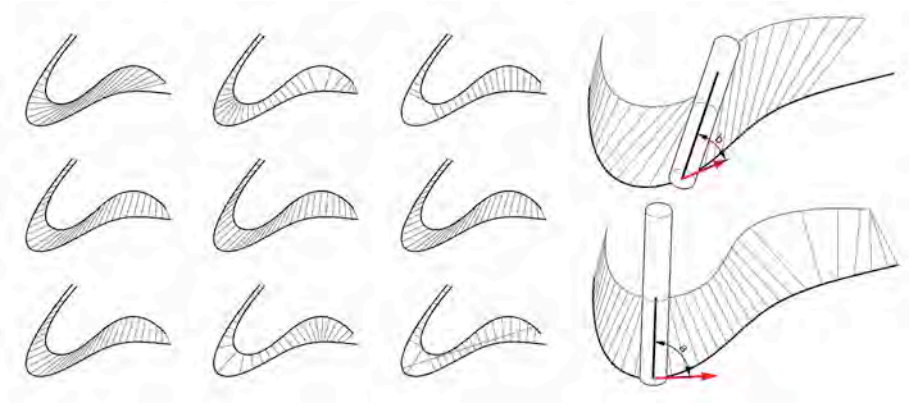


*Figure 2. There a many methods to convert pairs of curves into ruled surfaces (small images), however many of them cause problematic tool axis directions (top right)*

### 3.4. 'MACHINE' COMPONENTS

The machine component defines the capabilities of the machine, such as it's bed size, spindle limits, and additional command code formats if available such as chip blower, extractor hood position and clamping/vacuum controls. These ancillary functions can be added as inputs to an extensible component. The machine component also contains an instance of the 'post' class, which defines the format specification of machine instructions, as well as headers, footers and tool change routines all of this information is needed to translate the geometry into machine code. This is the point at which close coordination of machine specific syntax is required to interact with more generic toolpath definitions.

### 3.5. 'PARSER' COMPONENTS

The toolpath preview is generated directly from the post-processed output file by means of a parser component. This component uses the format specification of the writer component to read the toolpath back into grasshopper. This helps ensure that the writing component has written in the correct format. Essentially this allows students to create machine files on their own using termite, then staff to check the output by using only parser and preview components. The parser also retrieves the tool from the tool database.

## 4. Example case studies using alpha software tool

The alpha release of *Termite* plugin includes one fully developed machine library for a *Biesse Rover* 5-axis machine. A series of common tasks are presented as examples for the functionality of the library. The software is cur-

rently being used by workshop staff who operate this machine. This is an audience with range of experience on the machine, some having used it previously and others new to CNC operations. The examples below are common tasks which these staff must undertake.

### 4.1. FLANK MILLING

A common prototyping challenge is fabricating flat panels with many uniquely mitred edges, either as planar faces or ruled surfaces (Figure 3). *Termite* can streamline this process by connecting data from the design model to machine code. The existing on-machine solution proved to be laborious, requiring detailed operator input and unwieldy conversions between file formats. This made the prospect of mass customisation both labour intensive and prone to human error. This ultimately stifled the design process by forcing iterations to be locked down early, increasing cost of change (Davis, 2011).

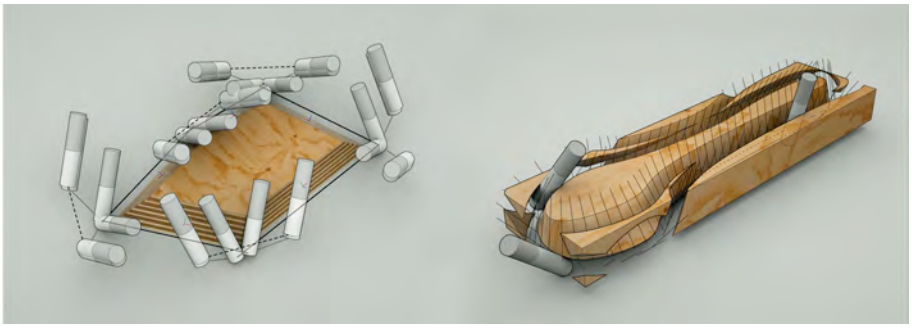


*Figure 3. Flank milling: angled mitres (left) and curved 'spoon' example (right)*

To use the flank-milling component, polylines representing both the top and bottom outlines (tool tip and tool guide) of the panels are selected. Each discretized tool-tip point is paired with a relative guide segment. These segments are then extended and adjusted to ensure the tool cuts perpendicular to the direction of travel.

Lead-ins and rapid paths linking cutting operations are also added. The core converts the tool positions to the machine NC format, writing the file and previewing the tool position at each line of code. This can be scrubbed back and forth through the use of a slider, enabling a user to make a visual check for errors, before loading the file onto the machine. Flat panel collision checking allows us to visualize if the tool shank or tool holder intersect with the stock (Figure 4). In the curved 'spoon' example a preview mesh of the form is generated from toolpaths. This representation allows the designer

to know if a design change causes a collision or a tool limit to be breached in-situ.

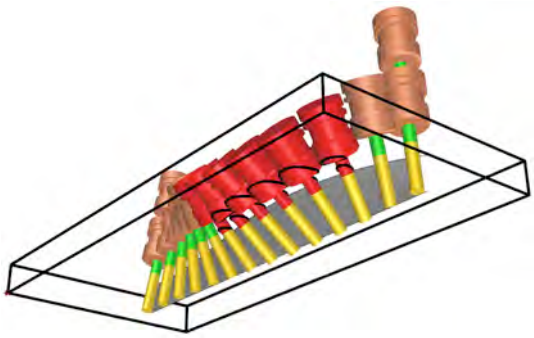


*Figure 4. Tool preview and collisions with panel*

## 4.2. DRILLING AND COMPOUND CUTS

More simple examples are the linear motions which are required for drilling operations and compound cutting (Figure 5). These can be defined by simple, linear set-out geometry. Common problems amongst operators have been attempts to create drilling operations from non-linear curves and compound cuts from non-planar curves. These problems are avoided by the components ignoring incompatible geometry, and notifying the user which geometry indices have been skipped and for which reason.

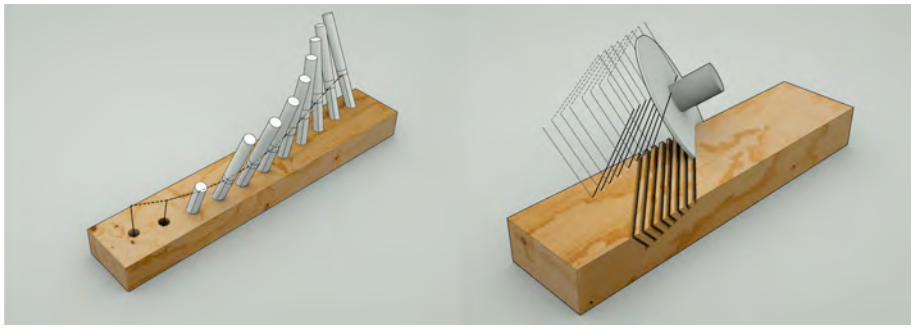


*Figure 5. Angled drilling and compound saw cut examples*

## 4.3. SURFACE MILLING

A given mesh or B-Rep form can treated as a form for milling through a series of basic strategies. For such an operation, the toolpath component can be specified to generate either a spiral, parallel or algorithmically generated.

Accurate surfacing presents challenges through managing tooltip compensation with reasonable calculation time.

## 5. Alpha release as part of the Rhino/Grasshopper ecosystem

With such a focus to this plugin, a number of key contrasts in functionality can be seen between *Termite* and other CAM plug-ins for Rhinoceros (Table 1*). KUKA|prc* and *HAL* are general purpose platforms for the control of robot arms. As these are highly generic machines the software does not impose limitations on toolpath strategies allowing the rotation and travel of a head in a freer set of movements. As discussed previously, this freedom is not desirable to panel routers and so toolpath movement becomes part of a network of constraints in a parametric design schema. The time and effort required for straightforward tasks can be further improved by the development of more, common default settings to components.

Table 1. Comparison of functionality and features of other CAM plugins for Rhinoceros.

| | RhinoCam | KUKA\|prc | HAL | Woodpecker | Termite |
|---|---|---|---|---|---|
| 5-Axis | ● | ● | ● | ● | ● |
| Parametric | | ● | ● | ● | ● |
| Fank milling | ● | | | ● | ● |
| Drilling | ● | | | ● | ● |
| Saw cuts | | | | ● | ● |
| Machines | >300 | <20 | <100 | external | 1 |
| Tool limits | ● | | | | ● |
| Machine code | ● | ● | ● | | ● |

As a contrasting package, *RhinoCam* provides extensive functionality typical to a CAM software package. This allows an experienced user to specify machining details, however, at the cost of more complex user interface, poorly suited to designers. Furthermore, as a standalone CAM plugin, it is disconnected from the parametric design schema and therefore less easily influence design decisions. Early feedback from users is that *Termite* has great benefits in ease of processing common tasks.

## 6. Conclusion and next steps

This paper has reported on the development of a plugin to connect parametric design with panel routers. This plugin is aimed to fill a gap between CAM packages currently used for programming these machines, and the parametric schemas developed for design. A closer coupling of these two el-

ements provides the potential for the fabrication constraints to inform conceptual design work.

Further development is necessary for a broader release of the plugin. This includes the development of libraries for other machines, firstly 3-axis panel routers to complement the existing 5-axis capabilities. The toolpath definition will include redundant information of a vertical tool angle, however, this is considered a small expense when considered in the broader context of the plugin's flexibility.

Beyond this, ease of programming is a priority and workflows for generating toolpaths will be improved through substantiated feedback from users. Assumptions regarding common mistakes and preferences for default settings will be reviewed. Beyond this, of immediate interest is improvement to surface milling functionality. The toolpaths here can require a large amount of detail and slow, iterative adjustment by a user in order to achieve desirable results.

## Acknowledgements

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# CLAY ROBOTICS

*Tool making and sculpting of clay with a six-axis robot*

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**Abstract.** The objective of the project is to design a reproducible clay sculpting process with an industrial robotic arm using parametric control to directly translate mesh geometry from Computer Aided Design (CAD) environment into a lump of clay. This is accomplished through an algorithmic design process developed in Grasshopper using the C# programming language. The design process is enabled by our robotics modelling and simulation library which provides tools for kinematics modelling, motion planning, visual simulation and networked communication with the robotic system. Our process generates robot joint axis angle instructions through inverse kinematics which results into linear tool paths realised in physical space. Unlike common subtractive processes such as Computer Numeric Control (CNC) milling where solid material is often pulverised during machining operations, our process employs a carving technique to remove material by displacement and deposition due to the soft and self-adhesive nature of the clay material. Optimisation of self-cleaning paths are implemented and integrated into the sculpting process to increase pathing efficiency and end product quality. This paper documents the process developed, the obstacles faced in motion planning of the robotic system and discusses the potential for creative applications in digital fabrication using advanced machines that in certain terms exceed human capability yet in others are unable to reach the quality of handmade works of art.

**Keywords.** Design computation; digital fabrication; architectural robotics.

## 1. Introduction

The rapid evolution of Computer Aided Design and Manufacturing (CAD & CAM) in parallel with digital fabrication technologies, in particular industri-

al robotics (UNESCE, 2005), has influenced design research work in the field of architecture in the recent years. Robotic technologies have been employed in the past for a wide range of applications (Siciliano and Khatib, 2008) including automation of on-site building construction (Cousineau and Miura, 1998; Gambao el al, 2000). Recently, robots have been deployed for creative investigations of the capabilities of design and fabrication processes that are beyond human aptitude. Robots have been used for both additive processes such as assembling brick walls (Gramazio and Kohler, 2008; Willmann et al, 2012) and extrusion 3D printing (Leach et al, 2012; Jokic et al, 2012; Peters, 2013; Van Herpt, 2014; Sun et al, 2014); subtractive applications such as machining material stock (Brell-Cokcan et al, 2009; Schwinn et al 2012; Dritsas and Goulthorpe, 2013); and forming processes such as folding (Lavelle et al, 2011; Pigram and McGee, 2011).

Amongst those fabrication processes, the work presented in the paper may be classified as forming and/or subtractive. In particular the use of wet clay in our project is closer to such traditional processes of carving and sculpting where material is both imprinted, displaced and deposited. The objective of the project is to experiment and explore the possibilities and limitation of applying advanced fabrication technologies to traditional, culturally loaded and environmentally sustainable material.

## 2. Digital and physical process overview

The preliminary goals of the still ongoing study are to design and produce a large scale ceramic artefact using a computational strategy informed by the material and robotic fabrication processes. The project is thus organized in the following research and design tasks: (a) Understanding the Material, (b) Tool-Building for Clay, (c) Parametric Computation Geometry Design, (d) Motion Planning for Robotic Fabrication, (e) Ceramic Firing and Assembly.

### 2.1. UNDERSTANDING THE MATERIAL

Clay has numerous advantages in term of material properties such as its low embodied energy in unfired form; it is readily available at a low cost in a wide variety of mineral compositions and colours due to its abundant natural sourcing; it exhibits certain desirable mechanical characteristics such as high compressive strength in fired form which is typical to ceramics; as well as excellent weathering resistance attributes which are desirable for outdoor building applications. However, clay has also both material property limitations such as high density, porosity and fragility well as some severe fabrication challenges due to its wet processing pre-fired, shrinkage due to firing

and hardness after firing, inconsistent composition, even though more controllable compared to other natural material resources such as timber.

In addition, we note that clay is extremely sensitive to physical damage during processing, characteristic of soft types of materials such as foam (Figure 1). Its self-adhesive properties further complicate shaping as there is the need for careful planning of material debris extraction in order to achieve high quality surface finish. Therefore, the process is unlike milling where the subtracted material is typically chipped, pulverized and evacuated from the work piece by the tool shape and external extraction systems. We therefore embarked on a custom tooling design and development process with the starting point being, the techniques and tools used in traditional pottery.



*Figure 1. Initial prototypes of robotic clay sculpting demonstrates the difficulty of material.*

## 2.2. TOOL-BUILDING FOR CLAY

We developed prototype tools by adapting traditional wheel throwing clay hand-tools purchased off-the-shelf as the robot's end-effector. The design was a clamping mechanism to accommodate various tool handle shapes and cutting edge profiles. It was fabricated using laser cutting plywood and featured details for mechanical fastening and support of the cantilevering tool (Figure 2). While the interchangeable characteristics of the end effector allowed for quick tool centre point (TCP) offset calibration and rapid prototyping with various tool shapes, it proved limiting in terms of overall stiffness. Robotics generally is less stiff or positionally accurate compared to CNC mills. Extended tool lengths tend to produce vibration-induced imprints on the work piece. Nevertheless, with this study it became evident that these traditional hand tools are designed for two armed sculptors with one hand available to collect excess material before it reattaches to the artefact. We thus moved to CNC-inspired reinterpretation and redesign of our tool set.

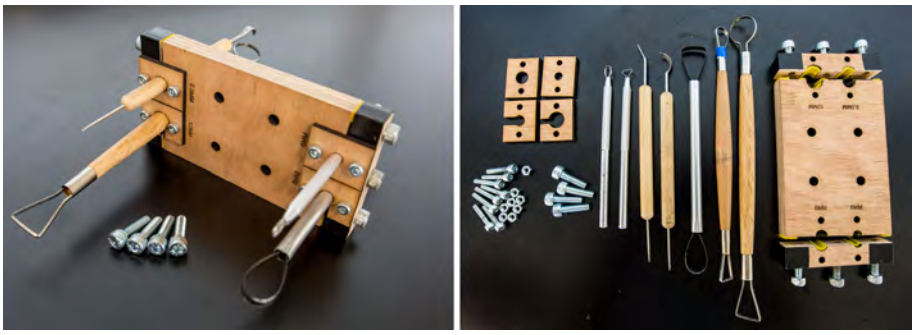


*Figure 2. First iteration of robotic end effector based on traditional clay hand tools.*

For the second tool design iteration, we used waterjet cutting to fabricate a stiffer clamp from aluminium sheet metal. The tool holder was designed as an interlocking set of plates centred directly axially above the Z-axis of the robot's flange with shorter protruding tools of various edge profiles. This allowed for both easy tool changes as well as faster calibration of the TCP offsets. Even though the performance of the second generation tooling greatly improved, we observed that hollow tipped tools were difficult to use because residual clay tended to block the cavity. Clay parts would thus fall directly behind the processed part, encumbering the cleaning process. Solid tipped tools designed in the third iteration were more predictable as they laterally displaced material that was scooped by a follow up cleaning pass. In addition, we experimented with techniques used in machining and turning where small bevels and tapers are ground into the tool's side edge to assist material guidance evaluation. The benefits of these were nominal (Figure 3).

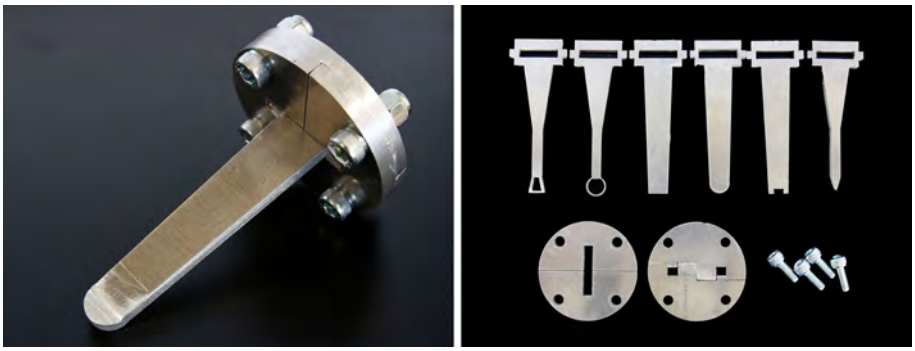


*Figure 3. Second and third iteration of robotic end effector made of aluminium.*

## 2.3. PARAMETRIC COMPUTATIONAL GEOMETRY DESIGN

The design objective for the large scale prototype was to create a decorative tiled surface with a regular layout and parametrically varied interior pattern; something desirably reminiscent of traditional ceramic wall tiling qualities but revisited with computational geometric and digital fabrication techniques.

The initial intent was to inform the design pattern from the sequence of tiles sculpted such that material continuously displaced towards the edges of the wall and ensured end product finish clarity. We used regular triangulation to organise and segment the design into manageable sizes for fabrication. To achieve visiting each part of the triangulation once in centre-out fashion, we employed graph analysis, namely the breadth first search sequencing (BFS). Furthermore to minimize the travel length of the robot tool, we employed a shortest path logic embedded in Dijkstra's path finding algorithm. The result of the analysis produced an outward centripetal tree structure which we then classified such that tree edges would become the conduits of displaced clay from the interior triangles discharged to the artwork's boundary (Figure 4).

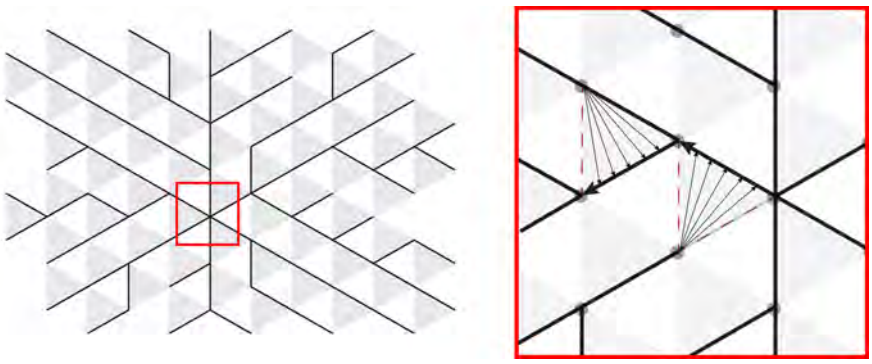


*Figure 4. Overall tiling pattern and detail of material displacement pathing.*

Individual triangular faces were shaped using a fan-shaped geometric pattern with gradient characteristics identifiably produced by computational methods (Figure 5). The desired outcome was to create a wall surface with haptic, visual and lighting characteristics due to varied three-dimensional texturing.

The parametric geometry was developed in Grasshopper using components created in C# programming language. The graph analysis and optimization methods were based on the Jeneratiff library which is being developed by the team and is currently available online for download.

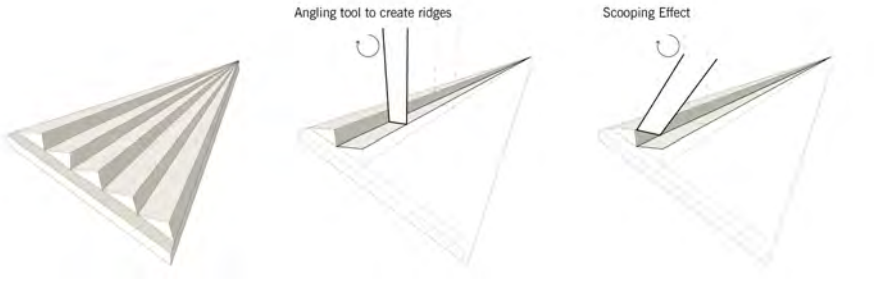



Figure 5. Triangular face material removal pathing and finished geometry.

## 2.4. MOTION PLANNING FOR ROBOTIC FABRICATION

The project was developed with the Universal Robot (UR10) in combination with the Jeneratiff digital fabrication library developed by our team that enables translation of geometry from CAD to the Pythonesque programming language understood by the machine. The benefits of this approach is the integration of the design modelling, simulation and direct over the network communication with the robot, which enables rapid experimentation cycles by eliminating technical details that demand time away from understanding the design, material and the formation process (Figure 6).

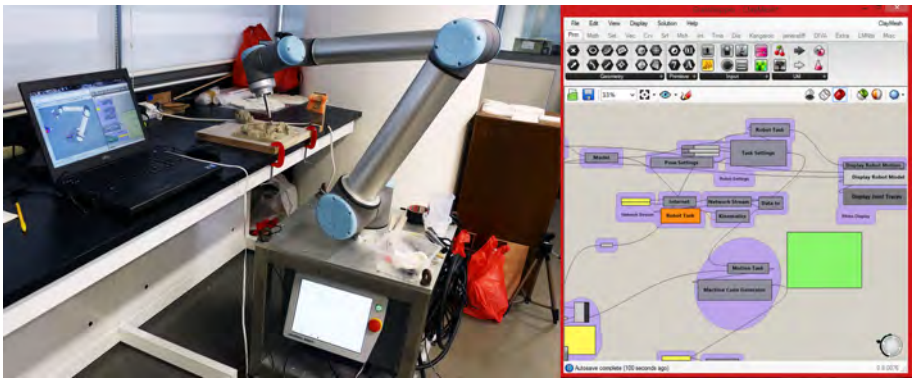


*Figure 6. Robot programming and control interface based on visual programming.*

Motion planning for robotic clay fabrication process includes translating design geometry to machine operations taking into account such properties as machine acceleration, travel speed and breaking which are relevant to the rate of material extraction and quality of surface finish. In addition, the main challenge was to define pathing such that residual material would be com-

pletely removed from the processed surface without reattaching onto the part.

The first iteration attempted a conventional machining inspired strategy of multi-pass processing which included a roughing phase that removed the majority of material followed by a surface finishing phase at lower speeds. To overcome the vibration of tool due to robotic stiffness issue explained as well as ensure sufficient time for the trapezoidal speed profile, we used also a strategy originating in machining, namely extended paths at the entry and exit points of the workpiece. The results were somewhat successful yet the remaining parts of material required multiple additional finishing passes.

The second iteration adapted the above logic to the material behaviour by introducing interim tool cleaning operations. Initially approached with the amusement of having the robot clean itself periodically; the idea proved to be effective in that it actually reduced the total fabrication time compared to extensive processing (Figure 7). The logic was finally fused with the design using the pathing conduits for material evacuation within the pattern and the sequencing of triangular fan indentations was organized such that subsequent passes would always push the material towards the edge gutter.



*Figure 7. Damp sponge cleaning apparatus experiment improved surface finish.*

## 2.5. CERAMIC FIRING AND ASSEMBLY

As we have not concluded the project, we have only some initial insights of the firing and assembly process. The selection of the clay material used was made with the kind advice of the local Chinese pottery gild master such that it would not require temperatures too far above 1000°C to achieve minimal shrinkage due to vitrification of clay particles. The initially fired parts did however shrink and as such these results will inform the upstream design segmentation and detailing logic. This will direct the approach to creating an interface for assembling the parts into a bigger wall which is currently based

on applying a uniformly imprinted roughing pattern on the back side of the tiles using a textured mat such that mortar or engineered adhesives can create mechanical attachment to a substrate.

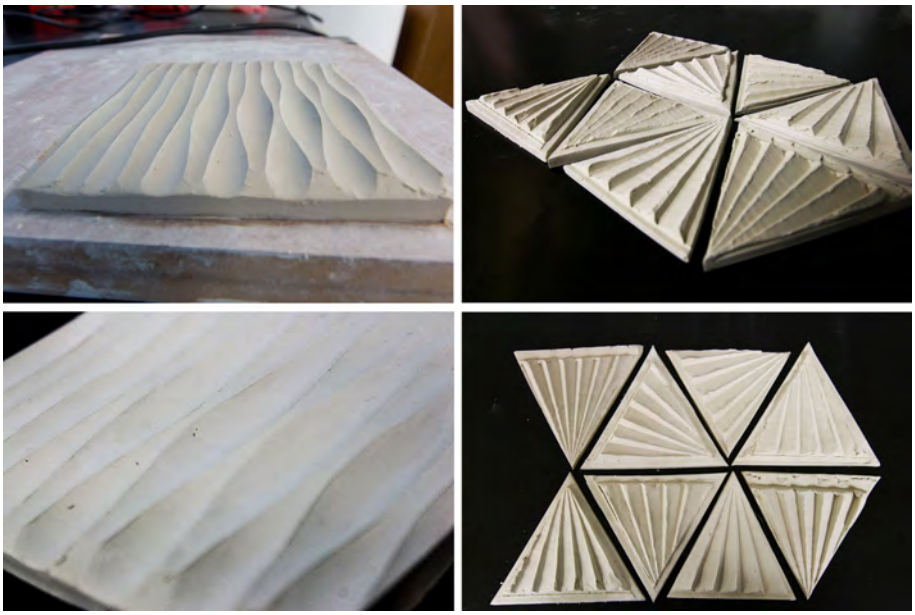


*Figure 8. Final results of prototypes prior to firing process.*

## 3. Conclusions

The characteristics of artisan operation upon material are driven by cycles of skilled hand operation, acute visual evaluation and dynamic adaptation of planned actions towards end goals. In contrast, the process studied here is a computational approach that is virtually modelled and then executed off-line on top of material domain without direct or online understanding of actions and reactions of the material or feedback mechanisms.

In this fashion, it is evident that there is a qualitatively fundamentally different approach and aesthetic in the both the process and end products which should not be confused as an attempt of replacing or even simulating human action. Nevertheless, we had trouble convincing otherwise the Chinese pottery gild master as he was evidently upset when he realized the artefacts he fired for us were made by a robot. In popular culture, robotics are often perceived as immensely more capable compared to humans even though in reality we can only achieve modest results such as those presented. Arguably there is room for advanced digital fabrication for cultural heritage conserva-

tion we explored in the past (Dritsas and Yeo, 2013) especially in the light of the extinction of artisan techniques due to modernity.

Perhaps robotics can be deployed for capturing and reproducing human behaviour using vision systems and advanced closed loop control algorithms. Yet for the purposes of attempting to expand the realm of digital design and fabrication it is questionable if this would make sense or there are more fruitful opportunities for exploring the singularity points of machine capability and aesthetic.

## Acknowledgements

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# TRANSLATING DIGITAL TO PHYSICAL GRADIENTS

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**Abstract.** As the practice of using notations to translate from two to three-dimensions is becoming superseded by the direct relaying of building information digitally, the separation between designing and building is diminishing. A key aspect in lessening further this division, is heterogeneous materiality that supersedes component thinking and effectively tectonics. Being an embodiment of the redundancies of tectonic assembly, a curtain wall detail has been redesigned with a heterogeneous and continuous multi-material using CFD. The main research problem following this redesign has been the conversion of material data from the CFD program into a 3D-printable format and in order to achieve a closer linkage between design and building. This has been pursued by initially converting the fused material parameters into fluid weight data and eventually into RGB colour values. The resulting configuration was output initially as a multi-colour print and effectively fabricated in a multi-material.

**Keywords.** Multi-materials; CFD; 3D-printing; autography.

## 1. Introduction

### 1.1. ALLOGRAPHY VS. AUTOGRAPHY

When describing the changes brought about in architecture during 20th century modernism, Carpo (2011) states that a main shift has been in architectural authorship that has transitioned from a condition of autography to one of allography. This shift can be traced as far back as the Renaissance and early Humanism, with Alberti being the first to "claim that architects should be not makers but designers." After a few centennials, this divide is according to Carpo appearing to come to an end, with digital technologies enabling a reverting back to a premodern, autographic status in architecture. Being closer to artisanal making, there is no longer the need for translations from

two to three dimensions, intervening between the design of a building and its physical manifestation. This is because: "a coherent object on a computer screen is automatically measured and built informationally- and the computer can actually fabricate the same object for good, if necessary, via a suitable 3D printer" (Carpo, 2011).

This statement, although suggesting a fundamental change in the way building information is 'transmitted', at the same time it still carries with it a modernist leftover. The modular object as the elementary unit that can be aggregated digitally to form a larger virtual construct and consequently fabricated and assembled to form a building, is still intrinsically linked to the aforementioned allographic status of architecture. This is because tectonic assemblage is the applied end result of a design process conceived as and consisting of, component objects that can be easily numbered, catalogued and retrieved in the building site, in many cases without the mediation of an architect. In addition, the practice of breaking down architecture in parts has been going hand in hand with a conventional and familiar material practice based on uniformity and invariability, the traces of which go as far back as the 19th century. For instance:

> "While naturally occurring metals contain all kinds of impurities that change their mechanical behaviour in different ways, steel and other industrial metals have undergone in the last two hundred years an intense process of uniformation and homogenization in both their chemical composition and their physical structure. The rationale behind this process was partly based on questions of reliability and quality control, but it had also a social component: both human workers and the materials they used needed to be disciplined and their behaviour made predictable. Only then the full efficiencies and economies of scale of mass production techniques could be realized." (Gordon, 1988)

Two hundred years later, these methods still remain the same, while "[…] if we look at construction and manufacturing, there are major inefficiencies, energy consumption and excessive labour techniques" (Zolfagharifard, 2013). This seems to be the case as there is one parameter of the digital shift that up until now has remained largely underutilised. That is heterogeneous materiality.

## 1.2. RESEARCH BACKGROUND

In fields adjacent to architecture such as aerospace (the scale of construction being to a very large extent similar to architecture), the necessity for invention is something that exists intrinsically due to the extremity of the environments that any constructs will be placed in. This has effectively resulted

in research being conducted towards material fusion, in which the complementing properties of different materials can be combined together into one continuous multi- or functionally graded material (FGM) volume. The high thermal resistance of ceramic can be combined with the structural integrity of steel for example, in order to cope with extreme temperature fluctuations during spaceflight.

This multi-material paradigm is currently also making its way into architecture, at the moment through the fabrication of small scale representational multi-materials, with research however, already conducted towards a much wider application of FGM in the building industry in the near future. This is due to the radical implications that multi-materiality can have on the aforementioned constructional redundancies, as "aside from developments in self-assembly, multi-material 3D printing aims to address inefficiencies by reducing the number of manufacturing steps for one object. Compared with single material 3D printing, it allows a functional product to be created with different properties without the need to bring together components" (Zolfagharifard, 2013). Departing therefore from allography and tectonics, an initial claim of the paper is that *fusing* is the appropriate technique linked to 21st century autography.

## 2. Continuous Design

Additionally, responding to the call for "interrogating the notion of continuity" and "continuous designing" and following up from Carpo's description of a seamless transition between conception, design and materialisation, the following will address continuity in a twofold manner. Firstly, methodologically i.e. in terms of design process and workflow and secondly, physically i.e. materially.

### 2.1. RESEARCH QUESTION

Regarding process, a new methodology is briefly described that is based on CFD simulations to compute the fusion of materials in their liquid state. This is in order to redesign a typical cladding panel connection of a glazing pane to its surrounding aluminium frame, through a continuous multi-material consisting of glass, alumina and aluminium. Research has shown that these materials exhibit fusion compatibility and already exist as manufactured FGM (Mahboob et al, 2008; Yu et al, 2007). Following this initial description, the objective has ultimately been to research into ways that the aforementioned autographic workflow can be completed and the CFD design output physically. It is useful to mention at this point that there exist software platforms such as Monolith that have embedded multi-material 3D-printing

capabilities. The departure from these, however, is that the graded material design has been generated in a simulation as opposed to a voxel environment. Effectively, the main question that the paper will be discussing is how can the CFD designed multi-material part be physically fabricated?

## 2.2. SIMULATING FUSION

Research presented previously (Grigoriadis, 2015) argues that material simulation is of primary importance when designing with FGM, as material behaviour takes precedence over component and shape thinking. As particle systems are by virtue of their computational structure made to resemble physical phenomena and in this case material behaviour, the software platform RealFlow was utilised to compute fusion. Effectively, six particle emitters in total (two each for aluminium, alumina and glass) were placed on either side of a containing geometry within which the particle materials were made to fuse together. The corresponding values, such as melted glass viscosity of approx. 1 $m^2 \cdot s^{-1}$, were attributed for each of them and a vortex daemon commensurate with the centrifugal force acting upon materials during FGM manufacturing added to the scene. A unified mesh was then applied on the simulated particle blend, which effectively formed a "three dimensional representation of the outmost particles of […] [the] emitters" ("Nodes – Meshes", 2014). Multi-materiality was imprinted on this mesh skin as colour graded boundaries in-between the main material areas (represented by different colours) of the volume (Figure 1).

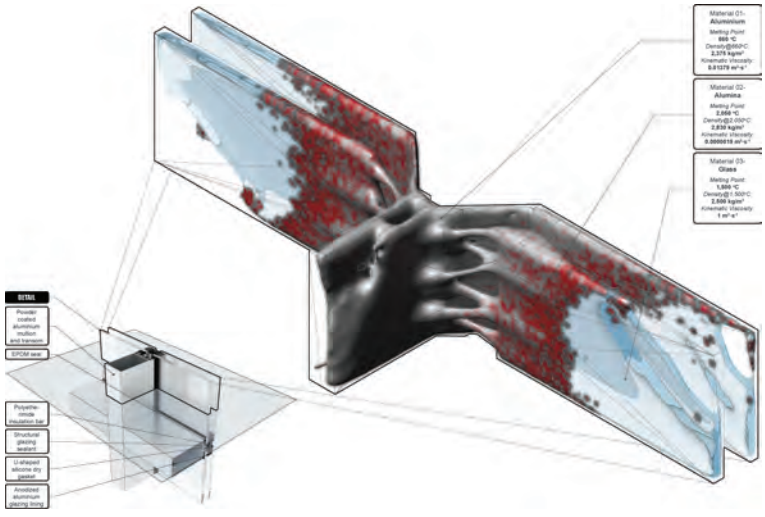


*Figure 1. The multi-materially designed curtain wall detail. Original curtain wall materials are on the bottom left and graded materials on the top right.*

### 2.3. TRANSLATING DIGITAL TO PHYSICAL GRADIENTS–PROBLEM DEFINITION

The main problem in this instance was that although colouration that represented graded materiality was visible in the simulation software, exporting it to a 3D-printable file format was not possible. This was the case because from all file formats that could be output from the software, none preserved the material/colour values. To generate the necessary bridging between simulation and fabrication, the gradients had to be converted into numerical values that could then be imported into a commercial 3D-modelling application in order to output a readable file format for 3D-printing.

## 3. Translating digital to physical gradients–computational workflow

### 3.1. FLUID WEIGHT DATA

The first attempt towards this conversion was to utilise the per-vertex weight of each particle emitter that can be retrieved as a decimal. The value denotes the degree of influence that the individual particle emitters have on the colouration of each of the vertices of the mesh. The Python script utilised to perform this operation was the following:

```
for i in range (0, total number of mesh vertices):
    vertexWeight= ParticleMesh.getFluidsWeightAtVertex(i)
        file.write (str(vertexWeight))
```
(1)

A first run of the script resulted in outputting all weight data in this format: [(‘01_Aluminium_Fill_Object’, 0.0), (‘02_Alumina_Fill_Object’, 0.0), (‘03_Glass_Fill_Object’, 0.0), (‘04_Aluminium_Fill_Object’, 0.0), (‘05_Alumina_Fill_Object’, 0.0), (‘06_Glass_Fill_Object’, 1.0)], which in this case indicated that the specific vertex colouration would be 100% influenced by particle emitter 06.

At another index of the data list corresponding to a different mesh vertex, the output would be: [(‘01_Aluminium_Fill_Object’, 0.0), (‘02_Alumina_Fill_Object’, 0.0), (‘03_Glass_Fill_Object’, 0.0), (‘04_Aluminium_Fill_Object’, 0.27106717228889465), (‘05_Alumina_Fill_Object’,0.20003880560398102), (‘06_Glass_Fill_Object’, 0.52889406681060791)], indicating that the specific vertex is influenced by three particle systems with the addition of the numbers amounting to 1.

When data values were then output and saved in a .doc file, a striking fact would be the very large volume of the file size, which for a total of 297,651 vertices would be 68.1 MB, with the overall word count being 3,411,613

words over 17,576 pages. This would have an impact on file handling times and processing power needed to manage and retrieve the data. Removing the preceding ‘x_x_Fill_Object’ before each of the numerical values reduced the file size down to 14.2 MB, 1,785,906 words and 6,581 pages.

A sequential correspondence between the fluid data and the mesh vertices meant that in principle, a direct colouration of the imported mesh vertices would be possible. The main problem, however, was that when the data were converted into RGB values although being accurate in terms of the distribution of gradients, the colours themselves were different to the ones of the particle mesh. This was due to the fact that the weight data were an indication of the influence of each sub-colour in the overall pigmentation of the vertex rather than a direct colour value. Colouration would be quite straight forward in the case of a 0.0, 0.0, 0.0, 0.0, 0.0, 1.0 output, as the only influence would be of particle system 06 with an RGB value of (178, 216, 239). The complications would arise when the aforementioned 0.0, 0.0, 0.0, 0.27106717228889465, 0.20003880560398102, 0.52889406681060791 output would correspond to the influence of particle systems 04, 05 and 06, each with a different RGB colour of (87, 87, 87), (133, 13, 83) and (178, 216, 239) respectively (Figure 2).

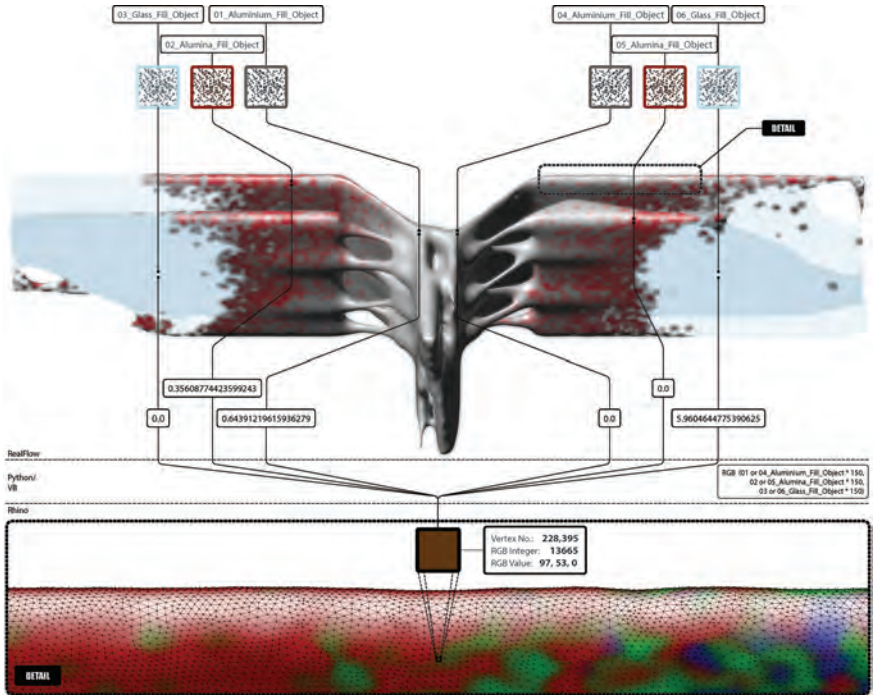



*Figure 2. The fluid weight data workflow leading to incorrect colouration.*

The initial response to this was to convert each RGB value to an integer and multiply that by the weight data value. RGB (87,87,87) for instance would become 5723991 and then 5723991*0.27106717228889465≈ 154547757. The idea would then be to perform this operation for the other two remaining particle systems and eventually add together the resulting figures in order to acquire the appropriate colour value. This was of course not possible and in retrospect taking into account that an RGB integer stems from this formula: RGB Integer= Red + (Green * 256) + (Blue * 256 * 256) an alternative approach would be to multiply each RGB value by the fluid data value: 87 * 0.27106717228889465= 23.58284398913383 and convert the results to an integer by applying the results to the formula above: RGB value= 23.58284398913383 + (23.58284398913383 * 256) + (23.58284398913383 * 256 * 256). The problem, however, would still lie in the averaging out of the numbers of the other two particle systems in order to obtain the correct colour.

### 3.2. RGB COLOURS

Eventually, the complexity of this routine was abandoned in favour of a Python script that would output RGB values from the simulation software directly, developed in collaboration with Next Limit Technologies. With a much more manageable file size of 10.3MB, the output text file would contain 3 values for R, G and B, which would be converted from arithmetic into Digital 8-bit per channel values using the following formula: RGB (Vertex R Value (0 to 1) * 255, Vertex G Value (0 to 1) * 255, Vertex B Value (0 to 1) * 255). This enabled the direct transferring of data from one software into another and was tested out by generating a multi-colour sandstone 3D-print, coloured according to the RGB data list. The distribution and colouring of gradients were visually identical to the ones generated in the simulation (Figure 3), however, the objective as mentioned earlier would be to achieve direct multi-material correspondence as opposed to one that is representational.



*Figure 3. The multi-colour sandstone print.*

## 4. Translating digital to physical gradients–fabrication

When attempting to translate the computer generated material gradients into ones that are physical, the main problem to take into account is that the 3D-printing of gradients is not yet possible. The relevant fabrication methods work with singular materials that are combined to form a larger multi-material entity. The continuously coloured mesh described above would therefore have to be discretised by converting the initially continuous, into step-wise material structures. This conversion would affect some of the attributes of the part, while leaving others intact.

Change of properties would naturally be the case when designing with sub-materials that are computationally different to the ones physically fabricated. At the same time shifting to stepwise distribution would have an effect on the structural behaviour within the multi-material itself, as there would be the problem of additional forces developing on the sub-material segment boundaries. Visually and aesthetically speaking on the other hand, there would be no evident difference between the continuous and the stepwise. This is because the material selection from the glazed area towards the alumina and aluminium part could be made optically incremental, therefore still maintaining the effect of transitioning gradually from opacity to transparency. Lastly, regarding the structural characteristics of each sub-material, further research is necessary in order to evaluate the pros and cons of replacing glass with transparent plastic and of aluminium with a Polyjet rigid plastic material.

Consequently, this additional operation of converting the continuous to the step-wise was performed by running a VB script on the graded colour mesh and isolating similar-colour mesh faces. A fact about mesh colouration, however, is that it occurs on face vertices and not on the mesh faces themselves. The RGB colour of each of the three vertices corresponding to a mesh face therefore had to be retrieved, indexed in an array and stored together with the face itself. The stored per-face vertex values would then be tested against an input colour value and if the two would equate, all faces within the same colour range removed from the overall mesh topology and placed on a separate layer. Performing the routine with a different input colour value each time, eventually isolated all similar-colour families into different layers.

An additional observation at this point would be that the fineness of each of the colour layers would dependent on two parameters. The first was the size of the polygons that the overall mesh would be made of and the second, the degree of deviation of the average mesh face colour to the input colour value. Smaller polygon sizes resulting in a larger number of mesh faces, as

well as a smaller deviation of face to input colour value would mean that the overall mesh would be cut down in very fine, almost imperceptibly small segments that would give a better impression of gradation. The flipside to this would be more sub-material boundaries within the larger mesh topology affecting structural behaviour, as well as the available Polyjet materials not being enough to correspond to the large number of sub-materials. Eventually, the script was run for a total number of 9 sub-materials that were corresponding to the original gradients as closely as possible, given the multi-material 3D-printing sub-material availability, mesh subdivision limitations and target colour range (Figure 4).

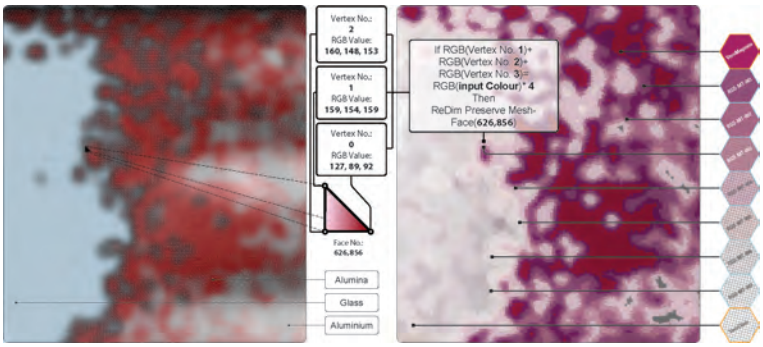



*Figure 4. Digital to physical gradient conversion workflow. The palette on the right shows the maximum of nine consecutive materials that can be used to achieve a smooth gradient.*

Having followed the above workflow, the mesh having been discretised and corresponding materials applied to each segment, a further problem was that the mesh skin pieces had to have a minimum thickness for the multi-material printing purposes. When this minimum of 0.4mm was applied, some of the segments would intersect with their neighbouring ones, which resulted in the materials cancelling each other out (Figure 5). Research is being conducted at the moment with offsetting and clash avoidance routines in order to be able to successfully 3D-print the part.



*Figure 5. One of the multi-material 3D-print tests. The nine initial sub-materials became four, due to offset mesh material overrides.*

## 5. Conclusion and discussion

At the moment "there is nothing out there that can do true multi-material manufacturing" (Zolfagharifard, 2013), but at the same time "real innovations will happen in the research world. Multi-material is the next evolution in the technology… you're probably looking at a 5–10 year timescale to see real multi-material integration" (Zolfagharifard, 2013). As 3D-printing technology is rapidly advancing towards this integration, translating digital to physical gradients is expected to become increasingly apropos as a research subject.

At the same time, achieving complete autography is a process that is still in its nascent stages and as it has been presented, a degree of mediation still remains the case. Fused materials had to be translated into gradient colours that were then converted into numbers, which were converted back into gradient colours, discretised into singular colour groups and output as materials, which, however, had different properties to the ones originally computed. It is a matter of time until direct autography takes over, but until then it is to be hoped that research as the one presented will form a contributing step towards it.

## Acknowledgements

Special thanks to Alex Ribao from Next Limit Technologies for his invaluable help in mesh colour data exporting in Python. Also to Adam Bloomfield and David Morris from Industrial Plastic Fabrications Ltd. for their consistent perseverance when trying to resolve the various problems with fabrication, on the multi-material printing end of the whole process.

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# ARCHITECTS AND DIGITAL DESIGNING TECHNIQUES FRONTIERS

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**Abstract.** Recently digital-design techniques have influenced the way architects think and design. This extends to impact architectural education by drawing new boundary lines. Therefore, it is desirable for architectural educators and students to consider these lines and to know how to establish them within these technological trends. This will be through raising their knowledge and skills in three aspects, which are algorithms and geometry characteristics, authorship, and fabrication in digital architecture.

**Keywords.** Algorithms; authorship; fabrication; education; digital.

## 1. Introduction

With the emergence of the developing digital-design techniques, architectural educators and students are facing some difficulties and complexity. These difficulties are manifested in algorithms, authorship, and fabrication in digital architecture design. While utilizing the significant role of computers and fabrication machines, architectural designers need to manage using algorithms and, at the same time, remain the central operators and thinkers in the design processes. This paper argues that the frontiers between architects and digital-design techniques come in four aspects. First, architectural educators and students need to be knowledgeable, qualified and skilled to access the computational capacity to get the most out of it. Second, they are still the decision makers who are developing the design process. Third, they are the authors of the design, and are thus controlling the design most of the time or, potentially, co-authors at some stages. Fourth, they need to be aware and updated in terms of the new and prevalent fabrication techniques and machines.

In terms of using algorithms in architectural design, the paper argues that architectural educators and students need to appreciate the new relationship

between design, computation, and algorithms, and also to use them within particular aspects of the digital. Using algorithms in architectural design means formalizing the design process as procedures and instructions.

To use algorithms, architectural educators and students need to understand, write and design them. Designers therefore need to control and utilize the algorithms to undertake the design process. Designing the design is a procedural issue controlled by the individual designer. Hence, there are steps to (re)define the design process as integrated design systems. It thus poses design itself as a significant problem where architects engage with broad cultural and technological discussions between scripting as both an 'open' and a 'closed' system.

Furthermore, the paper also argues that despite the fundamental shift in design processes, architects remain the author(s) of the design and/or co-authors some times. They are playing crucial roles in almost all the design processes, even if there is a need some times for other disciplines (e.g. programming, mechanical, environmental, electrical, etc.). They are also in control in all design stages from setting up the initial ideas, writing the code, judging, evaluating and decision making, and fabricating materials and techniques. However, they have less or no control in the stage where computers run the code.

Finally, the paper suggests that gaining knowledge in relation to fabrication and its materials and machines is one of these frontiers that architectural educators and students should consider. It is important to know the current digital fabrication techniques and machines to be able to transform a digital model to reality, right from the initial design idea. This imposes a shift in the design process to consider fabrication materials, structure, and generated forms.

## 2. Algorithms and geometric characteristics

In terms of algorithms and geometric characteristics, architectural educators and students now need to understand the relationship between architectural design, computation and algorithms, and to be able to use them to serve their design goals and objectives. An algorithm, according to Burry and Burry:

> "is a very specific set of instructions for carrying out a procedure that generally includes an instruction to stop. It may be long or very short". (2010, p. 252)

In computing, algorithms are procedures to transform inputs into outputs. In addition, in architecture algorithms are used to formalize the design process as procedures and instructions to produce geometries. Thus, the importance of algorithms manifests itself in its power to create functions and

instructions; it is also a very crucial part of the geometric traits. When architects want to create a computational geometry it is better for them to know its algorithms, even if it is ready to use as a function on the software interface. As a result, sufficient knowledge is desirable in fields such as catenary models, cellular automation, curvature, developable surfaces, dynamic relaxation, elliptical geometry, emergence, fluid dynamic, fractals, hyperbolic geometry, immersion, inversion, Lindenmayer systems, minimal surfaces, non-Euclidean geometry, non-linearity, Non-Uniform Rational B-splines NURBS, recursion, system dynamics, topological transformation, topology models, and a voronoi diagram. To understand the algorithms and geometry architectural educators and students need to look at their mathematical and logical composition before using them.

Burry & Burry (2010, p. 7) argue that the mathematical processing of the algorithms is usually overlooked or deliberately concealed within the commercial design software. For example, using this software is actually a series of mouse clicks and keyboard strokes; but behind that there are very fast complex mathematical operations undertaken. Using algorithms and computation in architecture allows the producing of more options (forms) resulting from a range of constraints. Within this process the algorithms are driven to meet the designer intentions to eventually find the final form. At the same time, it follows the geometric constraints that require strong understandings of the relationship between design, computation and algorithms. This relation may be shown in the examples presented in Burry & Burry's book, such as mathematical surfaces and seriality, chaos, complexity, emergence, packing, tiling, and topology. This is to show the ways to understand and use these mathematical and geometrical concepts through computation. Consequently, this will help finding new and unique solutions.

Architectural educators and students are required to know that using these techniques are more than simply a set of formal software ready to use commands/icons. They need also to know that there are a new range of emerging terms of algorithms and geometry that are in use now within the digital architecture circles. Moreover, they need to know that the design processes and techniques are shifted towards generative, self-organization, and optimization, which are different from the traditional concepts and techniques (but, this does not mean omitting the traditional techniques). This shift is defined when the architects add the possibilities of scripting (generative techniques such as multi-agent systems or genetic algorithms). This imposes a significant shift from the traditional top-down forms of control to more fluid possibilities of a bottom-up approach. However, this shift is usually permeated with hardship, mistakes, errors, and frustration especially at the beginning.

As we all know, using algorithms and geometric properties in scripting is a new knowledge that architectural educators and students need to obtain. To break it down, they need to be skilled in using algorithms, geometric calculations, and scripting languages and logic. According to S. Nassir (2015, per comms., 3rd Sep) learning programming skills requires different knowledge compared to what architects are doing. This will move architects from an architectural design environment to a programming environment, and this will be very hard. It is like doing two disciplines at the same time. Thus, architects need to learn how to master using the commercial software plus using their programming languages. For example, they need to learn how to use Rhino and Python or Maya and Maya Script.

One of the challenges of using algorithms and geometries is in combining designing and scripting abilities. To overcome that, architects need to look at, understand and learn from some famous buildings which are designed using these digital techniques. In other words, they need to look at and learn from famous precedence. Moreover, the other challenge may be the algorithmic activities, based on parameters and rules that allow design strategies which are different from the conventional design strategies (Lee, Gu & Williams 2014).

### 3. Are architects the authors or the co-authors

What do we need to know to answer this question? Architectural educators and architecture students should know that using digital-design techniques will permit them to be either the authors or the co-authors of the design. In the 1970s the role of computers changed towards creating an intelligent assistance system. But, today, computers are significantly involved in the design process, from drafting and modelling to intelligent systems and processing architectural information. Now it is important to ask: who designs? (Terzidis & Vakalo 1992, p. 5). It is important to know that digital-design techniques are no longer threatening the architects' authorial role. They are driven by the designer decisions, and their outcomes are also subjected to the designer's interpretation and understanding. This contradicts what Burry is arguing for. He suggests (2014, p. 388) that scripting is threatening design authorship richness, e.g. dilution of ideas, too much external agency, or just being straitjacketed through code.

Architectural educators and students need to know the difference between the design process when either using or not using computers to generate design. They need to know the difference between the explicit and implicit design process. In the explicit design the designer inputs affect directly the resulting output, whereas in the implicit design the designer decisions are

embedded in the logic of the script, which form an algorithmic layer between the designer input and the resulting output (Marble 2012, p. 44). This layer is where the designer has less control over the running script and as a result he/she becomes a co-author.

According to Oxman (2006, p. 242), architects now interact with generative, performative processes and mechanisms, using information as a new material. The designer becomes a tool builder, which means designers need to improve their computational skills to be able to deal with this new architectural trend. Moreover, Oxman (2006, pp. 242-243) puts forward four components of digital design, namely: representation, generation, evaluation, and performance. Generation includes the process where algorithms are involved to create geometry. This imposes a shift – and restrictions – in the authorial role of the designer. In other words, the historical architecture designer's role has been shifted; he is no longer the sole author of the design. According to Marble (2012, p. 8), the author or creator role of architects is replaced with semi-autonomous, algorithmically-driven design workflows within a collective digital communication infrastructure.

Controlling the design process is desirable for architects when using digital-design techniques. Computers are not always aware of their environment, therefore architects believe that the mental processes of design are conceived, envisioned, and processed in the human mind. Thus computers are just calculation, organization, productivity, and presentation tools (Terzidis 2006, pp. 20-21). Because of that the algorithmic outcome must be referred to human minds, i.e. the programmer or the designer. Therefore, critiquing the algorithms' outcome is always directed to the designer who uses the algorithms. In other words, the designer is responsible and will be blamed for the final outcome, not the algorithms that help him/her to produce it (Terzidis 2006, p. 23).

Traditionally, the designer maintains full control and intellectual property over their design; therefore he/she owns the idea. With algorithms and computation the outcome is not always under the control of their author. This suggests: (a) that the author of the script may not necessarily be the only author of the final outcome, and may not determine all the final characteristics of it (Carpo 2011, p. 5); (b) that if a discrepancy (between the original idea and the actual result) has happened, therefore the designer is not the author of the generated design (Terzidis 2006, p. 20); and (c) that the algorithms and computation imposes randomness, probability, unpredictability, and emergence, which are external and foreign to the human mind (Terzidis 2006, pp. 27, 55). However, all of these factors may be pre-considered by the designer and want them to happen while computers are running the given script. This happens if the designer has used computer to perform tasks that

cannot be done manually (in a conventional way). At this time (when the computer is processing the given script) he/she will be at the co-author position until the computer finish processing. Then he/she will be again at the author position.

To be the author or the co-author of the design, architects need to be connected to the predictability of these techniques' outcomes. Thus, the absence of the designer control shifts the authorship of the algorithmic process to computers (Terzidis 2006, p. 20). Here the authorship will be shared between the author and the computer. To maintain this authorship, architects need to develop an input logic and behaviour of generative process through scripting and algorithms, and evaluating and dispensing among the resulting options (Marble 2012, p. 203). They need also to be the author of the design rules. This includes establishing the logic, guidance, and setting up of the design problem, and being the manager of design data. This includes setting up clear and well-designed organizational strategies (Marble 2012, p. 249).

According to Burry (2014, p. 405) the majority views among scholars show designers as the driver of the design process, regardless of the tools in their hands. That could mean that algorithms should be written, designed and controlled by an architect. This is what (Terzidis 2006, p. 20) claiming, architect programmer must compose the algorithms which then generate forms and he/she must be in control of the outcome and the idea. Finally, the designer who wants to be in control of the result should be in control of the process. To be in control of the process the designer must be in control of the tools. The tools are computational, therefore a designer who wants to be in control must also be a scripter (Burry 2014, p. 405). This will be one of these frontiers that architectural educators and students need to consider.

## 4. Digital fabrication and its materials and machines

As one of these frontiers, fabrication plays an important role in digital design with deep connection to industries, technologies and materials. While fabrication materials constitute the idea of 'building', fabrication machines are devices that can automatically transfer digital objects from the design world into material realization (Mitchell 2004, p. 78). With fabrication technologies, architects shift design processes from form-making to form development, together with material and structure. According to Oxman and Oxman (2014, p. 302) with fabrication, the design sequence has changed from form-structure-material to material-structure-form. However, what are the most popular fabrication technologies?

Hensel, Menges and Architectural Association (2006, pp. 37-38) declare that in the 1950s the US military introduced numerical control (NC) as a ma-

chine of metalwork to break the limitation of mass production. In the following decades, the computer numerical control (CNC) was introduced to produce a wider range of material and scales. This happened with the increase usage of CAD applications. With that, Hensel, Menges and Architectural Association (2006, p. 38) uphold that once the potential of CNC is understood as a key aspect, the integration of materialization and form-generation becomes clear and essential. This suggests merging constructing constraints with the use of materials and the assembly logics to allow more exploration.

A three dimensional digital model of building can easily be cut by the CNC machine. This machine requires less control and it can create millions of copies of identical and non-identical elements. The functionalities of CNC machines can be grouped into three categories: cutting, subtractive, and additive (Kolarevic 2004, pp. 34-37; Krauel, Noden & George 2010, pp. 12-13). Usually, cutting happens with two-dimensional elements. A sheet of almost any material can be cut, and the common cutting technologies are laser, water-jet and plasma. Subtraction pertains to the removal of layers of the volume of the material to create a form. The removal could be mechanical or chemical, but it also depends on the freedom of the milling tool. For example, four or five axis tools make forms that are more complex. Additive, or as it is known by different names like 3D printing, is a way of adding modelling material layer-by-layer, and the only limitation of this technology was scale as it cannot create big objects. But now 3D printing is used to create large objects such as cars and houses.

Most of the recent studies and buildings have focused on the transformation and/or realization of digital models to physical prototypes. Add to that the consideration of function and materiality in relation to manufacturing and production. As a result, some fabrication and designing techniques appeared as a response to these technologies. These, for example, include – but are not limited to – the following: cross segmentation, accumulation, frameworks, loops, folding, twisting, lofting, triangulation, drilling, and knotting (Agkathidis 2012; Agkathidis et al. 2010). (Figure 1).




*Figure 1. Architectural forms and techniques examples.*

These techniques and others give an indication of their widespread use, for they now became available and affordable; they are no longer expensive, and are more efficient than traditional techniques. In fact, each time a new fabrication technology is invented and becomes available, a new architecture style/approach will appear and make its impact. Thus, it is hard to deny that the new designing and production technologies are making irreversible impact on the development of architecture practice today, and will continue to do so (Agkathidis 2012, p. 6). But what is interesting is how architects look at them? Architects, and especially students of architecture, are often fascinated and curious about what technology can do rather than architecture itself (Bettum & Frankfurt 2010, p. 122).

## 5. Conclusion

To crossover these three frontiers, architectural educators and students need to be aware of them. In terms of algorithms and geometry, the need to know first the algorithms' importance, the way they work, and their relation to architectural design and computation. Second, they need to be aware of and understand the new algorithmic terminology. Third, they need to know that algorithms impose a shift that moves architectural design toward generation, self-organization and optimization. Fourth, they need to know that using algorithms requires extra knowledge and skills such as programming languages. This suggests combining two skills or more, i.e. design, scripting and algorithmic activities.

In terms of the authorship rights, they need to know that computers are devices made by humans, but computers do not need humans to complete a given task. Usually tasks (script) are designed and written by humans, but then they pass them to computers to run them. After that computers produce an outcome that humans can judge, evaluate or re-process. Once the computer processing starts, the human role is dispensed. They cannot intervene until the computer finishes processing and here the architects will be in the co-author position. As a result, architects are not always in full control of the design, but they will be responsible and blamed for the outcome.

Moreover, in terms of fabrication they need to think about how to convert a design idea to a real building or physical model. That requires architects to link design with material, structure and fabrication from the very start. Digital-design techniques suggest an evolution and transformation of the current architecture. Therefore, architectural educators and students need to think about how architecture will be, what role they will play, and what extra skills and knowledge they need to be included.

## Endnotes

1. This research is aiming to highlight three important frontiers that architects, architectural educators and students need to put in to account when intending to use the digital-design techniques.
2. This research could be an introductory lesson to those who do not know anything about the role of algorithms, geometry, computation, scripting and fabrication in architectural design.
3. Addressing these three frontiers does not mean ignoring the other aspects of digital design, but, because they are the most obvious and affective ones, we need to start with architectural education.
4. This research is reflecting the author's perspective. Thinking about introducing digital-design techniques to architectural educators and students, focusing on algorithms, geometry, authorship rights, and digital fabrication.

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# AN ADVANCED PARAMETRIC MODELLING LIBRARY FOR ARCHITECTURAL AND ENGINEERING DESIGN

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**Abstract.** This paper presents a design computation system supporting scientific computing methods relevant to architectural and engineering design under the paradigm of visual programming. The objective of this research work is to expand and advance the palette of methods employed in academic and professional design environments. The tools contain methods for linear algebra, non-linear solvers, network analysis and algorithms for classical operational research problems such as cutting and packing, clustering and routing. A few decades ago the idea that computing would become so pervasive in the realm of architecture and engineering as it is today was confronted with deep scepticism. The thesis of this paper is that while it may be equally implausible that such methods are relevant today it may be the next natural evolution in the direction of design computation. The current state of the presented software package is still in early alpha version and it is available online for evaluation.

**Keywords.** Design computation; parametric modelling; visual programming.

## 1. Introduction

In the past decades the process of reinventing the traditional Computer Aided Design and Manufacturing (CAD/CAM) tool-chain moving away from design/drafting and towards design/computing gave rise to innovation by the adoption of computational methods for design such as the Processing by Casey Reas and Ben Fry (2014), which offered low overhead foundations for visual design using the Java programming language (2001); novel parametric modelling such as Generative Components and Design Script by Robert Aish (2005, 2013) introduced graph-based top-down parametric modelling

better aligned with architectural design thinking, in contrast to bottom-up part-assembly design; and visual programming systems such as Grasshopper by David Rutten lowered the steep learning curve barrier to entry into design computation offering an explicit graphical black box modelling approach to parametric process definition.

Even though there have been already at least two decades of research and practice within new generation digital media, ignoring for the moment the pioneering work in design computation from as early as the 60s (Rocha, 2004), our mental paradigm is still heavily form orientated. Design computation systems such as the aforementioned offer the means for conceptual design with computation but nevertheless the primary medium of design is graphics even though it is operated using computation constructs such as data types, containers and transformations. A positive yet perhaps modest direction forward is found in new systems for virtualizing design-for-construction practices which aim to push the building industry in the age of information, namely Building Information Modelling. The introduction of other units of measurement beyond spatial/meters offers the opportunity for insight in the other less popular dimensions spanned by design artefacts. Yet BIM is also heavily influenced by the notion of modelling as an improved version of rather traditional design processes and representations augmented by non-geometric metadata.

Those developments are nevertheless very valuable but one may inquire about the next steps in the evolution of architectural computing, for both the sake of advancing the state of the art in research and design as well as for addressing practice challenges. If computation is a valuable design thinking process rather than an infrastructural technology to support design actions such as automation, then perhaps it is useful to investigate how it can be further conceptually expanded.

## 2. Computational modelling

A key notion identified in this work is that of modelling. But we need first to eliminate preconceptions about the term itself. Instead of modelling for design generation purposes, constructing design intent through logical relationships and procedural representations or automated representation production as an improved medium compared to drawing, we may consider the idea of a model in the sense closer to what we find sciences. The distinction implied here is best captured by the notion of normative versus descriptive thinking by Peter Rowe (1986) extended to the realm of model making. A central concern in science models is foremost to understand complex phenomena, then to capture and organise their behaviours in functional constructs, only

thereafter to analytically evaluate results, derive predictions, support decisions and exercise control. A model is thus a thought construct of understanding as well as a medium for experimentation and operations/production rather than a mathematical or geometric representation itself. Nevertheless we need to be cognisant that design models are fundamentally normative as they objective is to prescribe rather than describe the world.

The presented work is motivated by the observation that there are certain recurring patterns in creating complex models for spatial design, namely (a) the escalation of complexity in terms of mental capacity to retain numerous interacting primitives and relationships, (b) the difficulty to retain the procedural representation aligned to mental understanding and construction mechanics of the model, and (c) recurrence of classical intractable type of problems such as combinatorial assignment which are found both in architectural studies of spatial configuration as well as in construction sizing and scheduling, known in computer science as non-polynomial hard (Hartmanis and Stearns, 1965; Garey and Johnson, 1979). The assumption in this work is that learning may occur either in forward manner from theory to practice or alternatively backwards on per-need basis moving from specific instances of practical problems to understanding the broader theoretical fabric.

There are two avenues available for investigation: delve into the fundamentals notions of computational modelling, for instance questioning how computer languages or visual programing systems can be improved to support thinking by creating new interfaces to computation; and/or alternatively bring advanced methods of computational modelling already used in such fields such as mathematics, computer science, operational research in the design realm. The approach presented here pivot heavier in the later direction with intent to address complexity with the introduction of advanced computational methods compacted in black-box manner. Those may improve cognitive characteristics of modelling by introducing higher level notions, that is instead of black-boxing fundamental arithmetic and geometric operations, offer abstract modelling primitives such as user-defined data types, mathematical graphs, general matrices and operations such as computationally involved in both development and runtime analysis and optimisation tools.

Many of those tools are already available and widely used in scientific computing packages such as MatLab, Mathematica and Sage as well as software libraries such as NumPy and SciPy. What is interesting about those systems is their ability to allow for rapid and terse model development by hiding computational nuances of advanced algorithms. In this spirit the presented work aims at offering a similar perspective to design modelling in a compatible mode of current practices based on visual programming.

## 3. Library design

The library contains a large number of components organised externally in tool palettes (Figure 1) and internally in two packages: (a) Core Algorithms and (b) Presentation Engine. The model/view approach was employed as a design paradigm for separating computing logic of core algorithms from graphical presentation interface and visualisation.

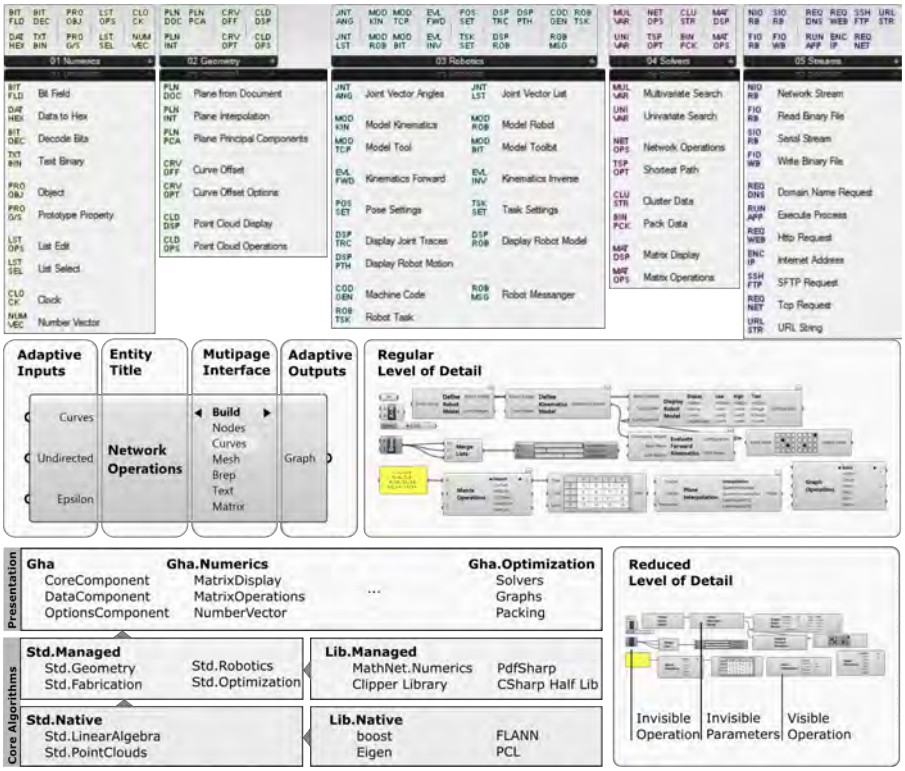



*Figure 1. External structure of the library (top) and internal in algorithms and presentation.*

Even though there are was effort made for non-overlapping dependencies there are unavoidable influences in the design of algorithms to afford interactivity. Numerical solvers by driving input parameters violate the directed acyclic graph models by introducing feedback relationships. Similar requirements are encountered in simulating kinematics as well as network communications where asynchronous events counteract the steady-state logic of the modelling graph. Using graph based modellers for dynamic event data handling is not uncommon as it is already a paradigm employed in sig-

nal processing software products such as LabView (National Instruments, 2015) and SimuLink (Mathworks, 2015).

### 3.1. CORE ALGORITHMS

The data structures and algorithms were developed by the author over many years of research targeting applied design problems. Those we generalised for wider use in architecture, engineering and construction applications. The system incorporates open source libraries for numerical computation, advanced data structure modelling, computational geometry and file transactions. Algorithms are implementations of published research in computer science, graphics, engineering and operations research, acknowledgements thereof are included in the documentation.

### 3.2. PRESENTATION FRAMEWORK

Visual programming is less succinct and inefficient compared to document-based programming. However, it is much more accessible to design audiences. The end-user's goal is often not in developing production grade software but design experimentations and as such visual programming is an excellent medium. A key challenge in visual programming is the unavoidable clutter produced by complex directed acyclic graphs of numerous nodes and edges. In developing libraries for visual programming this problem is greatly exaggerated with the potential clutter of the component palette with numerous nodes of similar functionality only with slightly different input or output parameters.

To maximise functionality in the smallest possible visual footprint: (a) we developed a visual style such that overall design logic remains accessible at different graph viewing scales, such that when node/edge saturation inevitably occurs it is possible to parse high-level logical relationships; (b) created custom representation components for such non-visual concepts as bit-fields and data maps; (c) integrated functional and visual options (enumerated types and bit flags) within node types as well as multipage nodes with optional input and output fields to compress numerous functions (Figure 1: bottom right).

## 4. Functional component organisation

### 4.1 PRIMITIVES

Primitives aim for data-type definition beyond the currently supported entities. The category contains components for intrinsic data types and containers thereof. The Prototype Object component offers a thought experiment on

user-defined data type definition, closely related to record types of pre-object-oriented programming languages (Figure 2). This is highly desirable as there are no options for modelling structured heteronomous data arrangements beyond lists and trees which are formally containers rather than types. There are conceptual challenges to achieve method encapsulation using this approach because those are contained in the document space. Nevertheless, the available capability for object augmentation with properties offers prototype inheritance commonly found in programming languages such as javascript. The Prototype Property component enables field selection, even with heterogeneous types, which is symmetrical to the Prototype Object's compositional logic. The direction of this experimental modelling process aims towards a declarative and/or functional approach to visual programming where complex high-level queries can be performed on sequences of data.

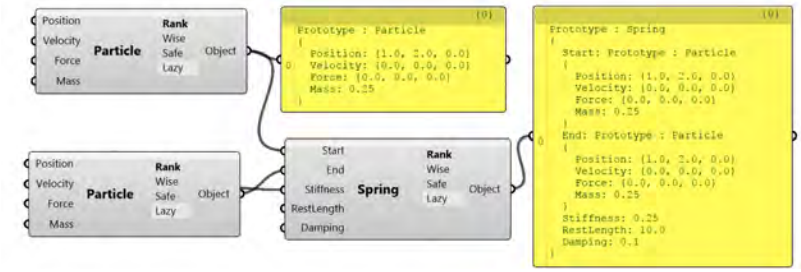



*Figure 2. Structured user-defined data type definition using the Prototype Object.*

## 4.2 GEOMETRY

The current set of geometric extensions is limited adding components that are useful in digital fabrication such as plane interpolation for kinematic model definition and pathing; parallel curve offset, polygonisation and clipping for machine pathing; bi-arc curve interpolation for geometry rationalisation such as singly-bent steelwork fabrication; and principal components plane fitting for bounding box alignment in logistical operations such as part packing and point cloud fitting. There are also tools for 3D scanning data visualisation and editing such as large meshes and point clouds loaded from user-defined ASCII databases as well as proprietary formats.

## 4.3 DIGITAL FABRICATION

The digital fabrication package includes tools for kinematics modelling in terms of both the mathematical and visual representation and for simulation of linkages in typical CNC and industrial 6-axis robotic systems (Figure 3). Relevant work in architectural literature of digital fabrication include

(Braumann and Brell-Cokcan, 2012; Pigram and McGee, 2011; Payne, 2012). Models are generated by loading visualisation geometries, axial configuration data stored as construction planes, and angle limit vectors stored as annotation from the CAD document. Two kinematic families are currently supported for ABB, KUKA, Denso and Universal robots; and perhaps other robots but have not been yet tested. In addition there are tools for defining end-effectors such as grippers, welding torches and spindles.

Motion planning captures concepts of machine path generation and overall operation modelling. The main mode of modelling is based on an offline paradigm, where the fabrication process is planned, modelled, simulated, compiled and executed with target equipment. The abstraction model of this is based on Tasks which contain one or more machine Operations, such as motions types or input/output signals. Tasks can be simulated individually and merged into Programs. Advanced task such as pick and place shortcut the process of defining explicitly individual operations.

In online mode the model-graph contains communication components that exchange live information with the machinery via the network. This is to enable use of sensors and actuators to dynamically program, operate and control machines. The goal for online operation is twofold: (a) to unify machine programming instead of using multiple incompatible offline formats, such as UrScript, KRL, Rapid, and G-Code; and (b) to enable experimentation with non-prescriptive modes of operation using vision systems and bespoke effectors. The challenge with dynamic coding is in the static and synchronous or rather strongly stateful logic of parametric models expressed as directed graphs which is conceptually distorted by transient event-driven logic.

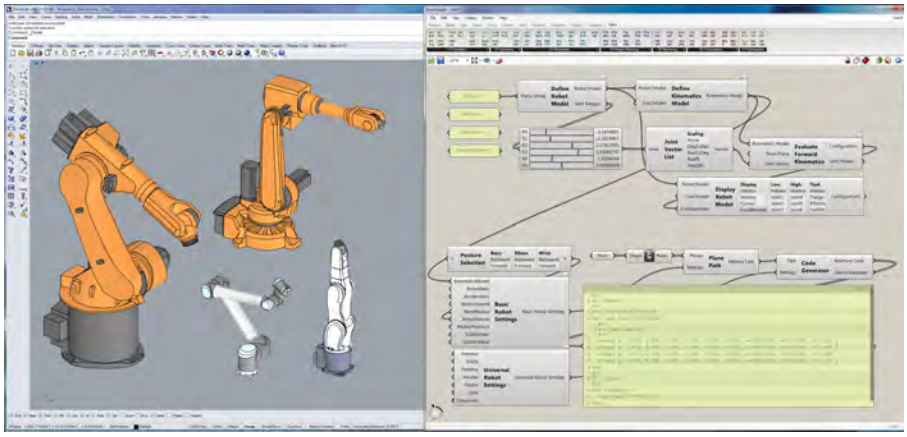


*Figure 3. Overview of robotics models and task-oriented machine programming logic.*

## 4.4 OPTIMISATION ROUTINES

Mathematical modelling primitives and numerical optimisation solvers offer the opportunity to embed advanced computation methods as first class entities that is at the same level of abstraction as with regular components rather than meta-processes. There is a lack of numerical methods in computer aided design tools and while they are extensively used to perform environmental and structural simulations they are seldom exposed as general purpose tools. The motivation is not to replace production certified analysis tools but offer programmable interfaces to the first principles for the purpose of research, rapid prototyping new computation methods and education. The methods available address common design and construction topics organised into:

Iterative numerical solvers for univariate root-finding and multivariate minimisation problems; envisioned to be integrated in the parametric logic to offer alternatives to purely geometric constructions. Mathematical models expressed by numerics often offer simpler formulations in addressing both linear and non-linear problems. The matrix component embeds a linear algebra kernel of approximately forty different functions including: matrix generation and construction from data sources, geometric transformations, and algebraic operations, including factorisations, analysis and matrix characterisation.

Classical information processing methods such as routing, namely solvers for the traveling salesman problem useful for machine planning optimisation (Laporte and Udatta, 2002) such as reducing the time required for CNC machines to travel between contours (Castelino et al, 2003) additive manufacturing (Chou et al, 2008); Data clustering methods for analysis (Jain and Stearns, 1965; MacQueen, 1967; Gonzalez, 1985), such as understanding the range of different parts and dimensional variance in a design and optimizing part typologies (Dritsas 2012); Cutting and packing methods (Dyckhoff, 1990; Martello and Toth, 1990) relevant to digital fabrication for control of material use in machining processes (Dritsas, 2012) and efficient arrangement of 3d prints into build volumes.

Graph or network analysis: contains a range of methods for construction of graphs, analysis of such metrics as various centralities and computation of path finding and tree generation. Graph theory offers advanced set of procedural machinery for such as applications as digital design, such as topology modelling and constraint resolution as well as digital fabrication, such machine pathing but also prominently in urban and circulatory network analysis studies (Turner el al, 2005; Porta et al, 2006; Sevtsuk and Makonnen, 2012) and general signal processing.

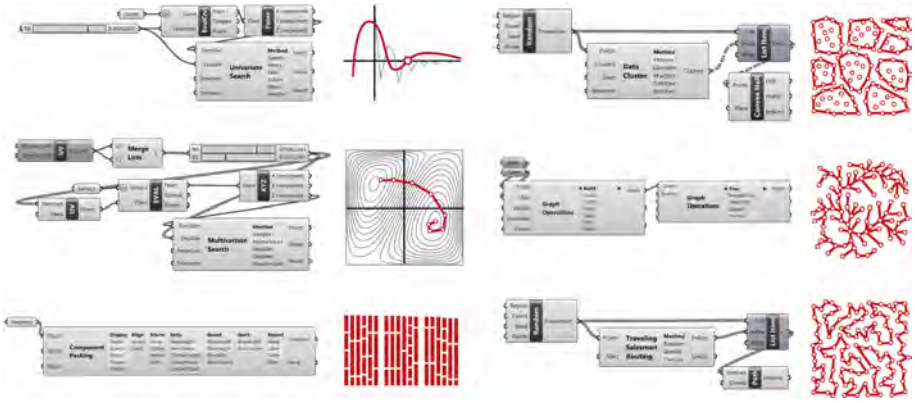


*Figure 4. Overview of supported solvers for mathematical modelling and optimisation.*

## 5. Conclusions

This paper presented an overview of a new design computation library for advanced modelling aiming to integrate scientific computing methods within parametric modelling systems. The topics raised for broader discourse are: (a) The notion of a model as not only virtual machinery of design production but closer to a science ideas and methods may potentially enrich the current modes of thinking and understanding of complex systems; (b) The need of first class analysis and optimisation methods is certainly a topic that requires broader debate as it may address efficient allocation of human and material resources; (c) Embedding advanced methods of analysis and optimisation, such as graphs analysis, data clustering, pathing, routing and packing offers some powerful tools for understanding the implications of early digital design actions to fabrication and construction rather more holistically. Finally, we find that while black-box modelling is inhibiting direct exposure to the theory of the underlying method, the availability of advanced methods can motive learning and understanding and it can effectively solve real world design problems.

## Acknowledgements

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# CULTURAL DIFFERENCE IN COLOUR USAGES FOR BUILDING FAÇADES FOCUSING ON THEME PARK BUILDINGS

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**Abstract.** The notion of globalisation has become widely spread in various fields, and accordingly, it is increasingly more important to take account of indigenous culture characteristics in each field. An aspect of achieving globalisation, globalization with local consideration, is to consider the difference of colour usage between distinct cultures. This study suggests an approach to investigate the colour difference between eastern and western cultures with the case analysis of building façade colours in Disneyland Paris and Tokyo Disneyland. We analysed cultural colour usage characteristics and derived tendencies for both Paris and Tokyo Disneyland building façade colours. To do this, we use image based k-means clustering algorithm and CIELAB colour space distances to explore colour characteristics. Our analysis indicates an overall colour usage tendency that Paris uses more green and bluish colours and Tokyo uses more red and yellowish colours for building façades, based on CIELAB colour space values. The major motivation of this paper was to reflect the atmosphere and the mood of the space that can be easily felt but not readily expressible into a cultural colour palette. Eventually, by finding the characteristics of perceived colours, we hope to create a colour recommendation system for different cultures based on cultural clues.

**Keywords.** Culture; colour usage; colour clustering; building façade; computational approach.

## 1. Introduction

Cultural background plays an integral role in one's way of thinking and behaviour (Nisbett, 2003). According to Nisbett, different environments between eastern and western cultures generate different ability of perceiving and processing information in cultural groups—the cultural power. Hofstede

(1984) first tried to quantify the cultural difference as a form of cultural dimensions. This theory of culture quantification is widely adapted in various fields such as computer-human interaction and social and behavioural sciences (Ishak et al., 2012). Cultural differences can be related to visual design features such as colour preferences in culture groups (Kondratova and Goldfarb, 2009). Kondratova and Goldfarb suggested national colour palette that can be applied to design website interface. However, less work is concerned with architectural colour usage difference between cultures in physical spaces. This study attempts to quantify decisive arrangement of colour choices under the condition of equivalent Disney themes but different cultural circumstances: western and eastern. Disneyland is a representative example of the strategically designed theme parks in the world. Theme park is a place where a wide range of colours, but at the same time, only theme-related colours can be used for architectural façade design. In this condition, theme park designers certainly encounter the process of selecting proper colours for attractions, shops, and restaurants. Moreover, cultural characteristics should not be overlooked to meet glocalisation (Clavé, 2007). However, there has not yet been an extensive research regarding how designers should consider cultural differences in the process of selecting ideal colours. Theme park designers are known to design using concept images and choose colours from them. However, even though it is of same theme such as the Mickey Mouse theme or the Peter Pan theme, there are differences in the overall atmosphere that make up the thematic environment depending on the location where the theme park is situated.

In this paper, we explore ways to incorporate human perception for quantitatively extracting the colours used in theme parks with the aid of computers and compare how much the eastern and western architecture façade colours differ. To do this, we use k-means clustering algorithm (MacQueen, 1967) for image-based colour palette extraction first to guide the surveyors of selecting five representative colours. Then, we evaluated how much the perceived colours differ for eastern and western architecture façades on each axis of the CIELAB colour space, which are blue-yellow, green-red, and lightness. Eventually, by finding the characteristics of perceived colours in theme parks in different countries, we hope to create a colour recommendation system for façade colours or city colours for different cultures that is based on cultural clues.

## 2. Literature review

### 2.1. COLOUR PERCEPTION AND CIELAB COLOUR SPACE

The spectrum of colour is continuous; however, it is widely known that when humans perceive colours, they tend to group discriminable colours into a number of colour categories such as grouping into reds, blues, and greens (Bird et al., 2014; Clifford et al., 2010). Therefore, there is a tendency to merge similar colours or spatially adjacent fragments into one region.

CIELAB colour space is designed to approximate human vision and perception. CIE L* a* b* model (Robertson, 1977) is considered to be more similar to human vision because the way it is represented reflects how humans perceive colour difference. Figure 1 shows the CIELAB colour space. The lightness L*, represents black at L* = 0 and white at L* = 100. The colour channel a* axis represents red-green, with green at negative a* values and red at positive a* values. The b* axis represents blue-yellow, with blue at negative b* values and yellow at positive b* values.

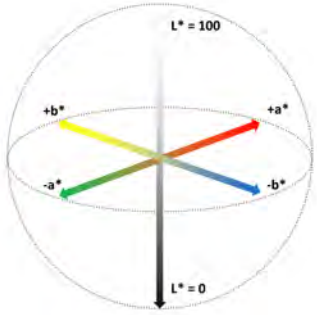



*Figure 1. CIE colour space.*

The Euclidian distance of two colours in CIELAB colour space is generally accepted as the difference between two colours. In this study, the colour distance between two colours is computed based on the CIELAB colour difference equation. The distance between any two-colour locations is typically expressed as,

$$\Delta E^2 = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{1}$$

### 2.2. K-MEANS CLUSTERING

K-means clustering is a method commonly used to partition *n* observations into *k* groups according to the similarity between observations. It proceeds by selecting *k* initial cluster centres and then finds a partition such that the

mean squared error between the cluster centre and each point that belongs to the cluster is minimized. Formally, given a set of $n$ observations $X = \{ x_i \}$, $i = 1, 2, \ldots, n$, where each observation $x_i$ is a $d$-dimensional real vector point to be clustered, k-means finds $k$ cluster centres $\{ m_j \}$, $j = 1, 2, \ldots, k$. The centre $m_j$ of a cluster $M_j$ is defined as the average of observations that belong to that cluster. Given the cluster centres, each observation $x_i$ belongs to closest cluster, where the distance is defined against the cluster centres. K-means works by minimizing the sum of the squared error over all $k$ clusters, given as follows:

$$J(M)=\sum_{j=1}^{k}\sum_{x_i\in M_j}\left\|x_i-m_j\right\|^2, \tag{2}$$

where $m_j$ is the mean of $M_j$.

## 3. Methodology

### 3.1. DATA GATHERING

Building images used in this work are photographs taken at first hand in Paris Disneyland and Tokyo Disneyland with OLYMPUS PEN E-P1 and the size of each original image is 4032*3024. For the comparison of colour usage differences between eastern (Tokyo) and western (Paris) cultures, we have selected three pairs of equivalent Disney themed building images – Mickey Mouse, Peter Pan, and Pinocchio. We extracted clear building shapes from the image by eliminating obstructive factors such as sky, trees, and pedestrians.

### 3.2. MATLAB K-MEANS COLOUR CLUSTERING

We generated 20 theme colour swatches by running k-means clustering on the image in MATLAB (Gonzalez, 2004). Figure 2 shows the example of extracted 20 representative theme colours with three themed buildings that the colours were extracted from: Mickey Mouse theme, Peter Pan theme, and Pinocchio theme from top to below.

The CIELAB colour space is designed to approximate human vision and perception. To incorporate human colour perception, we used CIELAB colour space as our standard space. To this end, we converted every RGB pixel values into CIELAB values by conversion formula provided from a MATLAB library “rgb2lab”.




*Figure 2. Extraction of representative 20 colours through k-means clustering in MATLAB.*

### 3.3. EXPERIMENTAL SETUP

We gathered human extracted theme colours from Amazon Mechanical Turk, which has been widely used in crowdsourcing graphical perception experiments (Heer and Bostock, 2010) and Google Forms survey: (https://www.google.com/forms/about/). We asked surveyors to select their ethnicity (either westerner or easterner at the end of the experiment). In total, we recruited 60 surveyors, including 30 westerners (United States, United Kingdom and Brazil) and 30 easterners (South Korea, India, Mongolia, Japan, China and Hong Kong). We wanted to know if westerners and easterners (as classified according to their nationality) perceive colours in different ways. Each experiment was paid $0.80 and the median time to complete the experiment (total six tasks) was 9.42 minutes.

We followed the experimental setting of Lin and Hanrahan (2013), and asked surveyors to select five theme colours from 20 colour swatches per image for total six images. Each task includes one image on the left and associated colour swatches on the right. They were asked to select five different colours that best describe the image. Figure 3 shows the experiment interface.

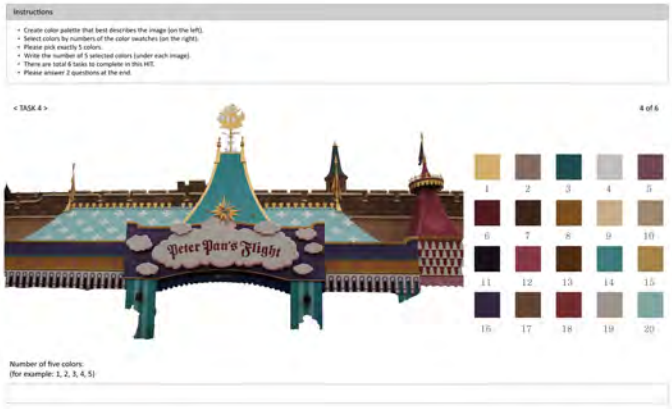



*Figure 3. Experiment interface.*

## 4. Results

### 4.1. DISTRIBUTION ON THE CIELAB SPACE AXES

To evaluate the perceived façade colour differences, we visualized extracted CIELAB colour values on a three-dimensional scatter plot. Tokyo and Paris Disneyland, the two different theme parks situated in eastern and western area showed different trend of façade colour usages. The distribution of points shows how much the colours differ. Figure 4 shows the overall L*, a*, b* values of Tokyo and Paris building façade colours.

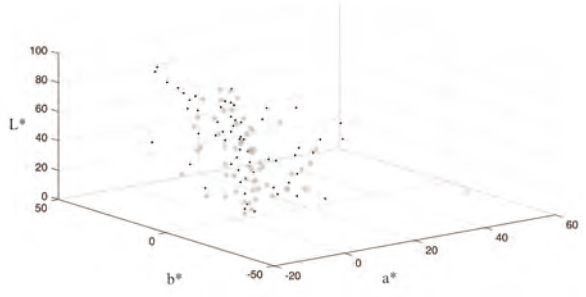



*Figure 4. CIELAB three-dimensional scatter plot of Paris and Tokyo data (asterisk mark represents Paris, dot mark represents Tokyo).*

Figure 5 shows the projection of the Tokyo and Paris building façade colours onto L*, a* and b* axes of the CIELAB colour space. There is little difference in lightness between Paris and Tokyo. However, we found an overall tendency of using more green and blue colours in Paris façade and more red and yellow colours in Tokyo by looking at two-dimensional space.

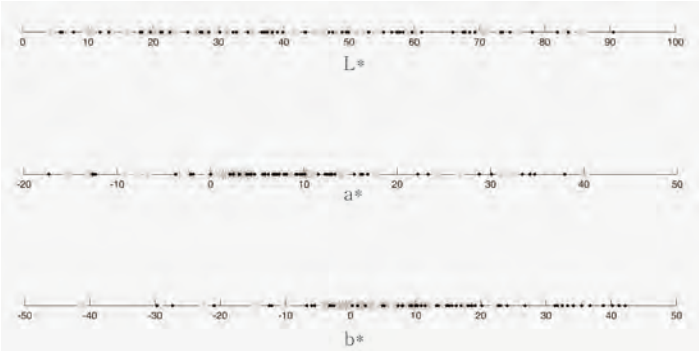



*Figure 5. Colour distribution of eastern and western architecture façades on each axis of the CIELAB colour space (L*: lightness, a*: green-red, b*: yellow-blue, asterisk mark represents Paris, dot mark represents Tokyo).*

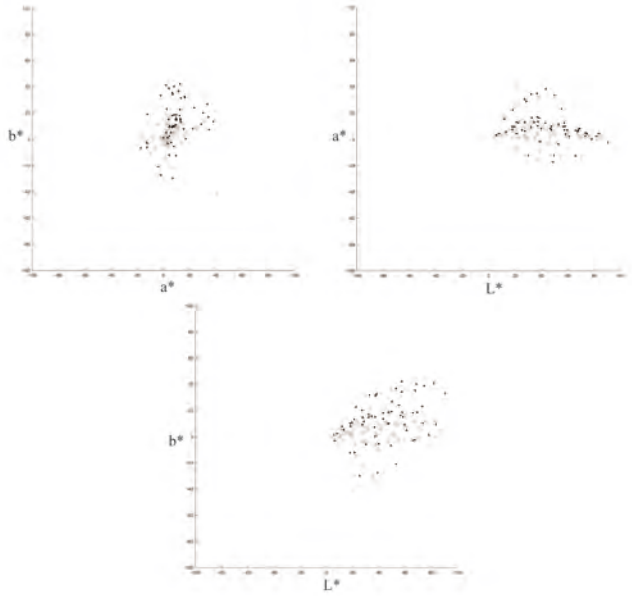



*Figure 6. CIELAB two-dimensional colour space result (left: a* b* relation, right: L* a* relation, middle: L* b* relation, asterisk mark represents Paris, dot mark represents Tokyo).*

Figure 6 shows the result of two-dimensional relation between two axes of CIELAB colour space. It is recognizable that overall trend of Paris and Tokyo colour differs. The right graph of L* and a* relation, Tokyo building façade used more red (higher a* values) colours than Paris. On the contrary, Paris building façades tend to use more greenish (lower a* values) colours for architecture façade designs. According to the middle graph of L* and b* relation, Tokyo building façade used more yellowish (higher b* values) col-

ours than Paris. On the contrary, Paris building façades tend to use more bluish (lower b* values) colours for architecture façade designs.

## 4.2. INSIGHTS FROM RAW DATA

Extraction of 20 theme colours for each image is done by k-means clustering. For each image, we calculated the colour differences among 20 extracted theme colours using the colour difference equation given in (1). Figure 7 shows 20*20 CIELAB colour distance values for each image. According to the calculated colour differences, we could categorize the 20 colours into representative groups of similar colours. We enumerated distance values in an ascending order (lower distance values indicate the more similarity between two colours in human perception) and we found an interesting distance threshold that distinguishes representative colour groups in a way that resembles human colour categorization results. By grouping colours within a CIELAB distance of 15, five to seven theme colours categories are generated, which are reasonably similar to those of human results. For each image, we obtained representative groups of similar colours.

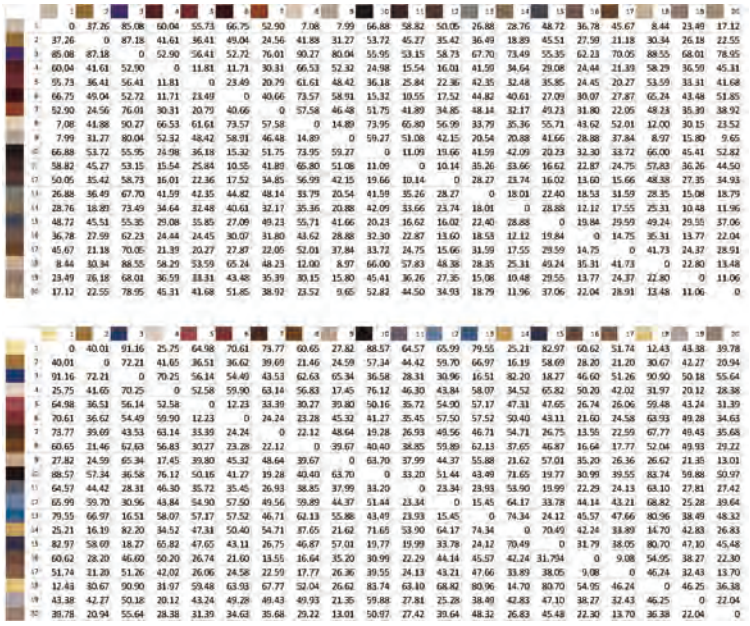


*Figure 7. CIELAB colour distance among the 20 representative colours (top: Paris Mickey Mouse, bottom: Tokyo Mickey Mouse).*

Figure 8 shows the similarity result of five extracted theme colours of total six images. DT indicates the above computational distance threshold ap-

proach of colour grouping result, W indicates westerners' and E indicates easterners' results. We found an interesting insight that westerners tend to choose more theme colours from less salient parts such as back walls of the building, which is located one depth behind the closer salient parts.

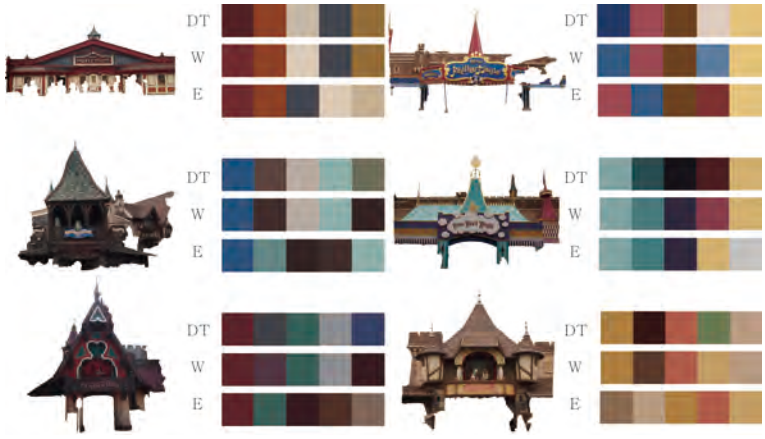



*Figure 8. Building façade images and their associated five theme colours from distance threshold (DT) approach, westerners (W), and easterners (E). From above to below, Mickey Mouse theme, Peter Pan theme, and Pinocchio theme (left: Paris, right: Tokyo).*

## 5. Conclusion and expected contribution

This study suggests an approach to investigate the colour difference between eastern and western cultures with the case analysis of building façade colours in Disneyland Paris and Tokyo Disneyland. We analysed colour usage characteristics and derived tendencies for both Paris and Tokyo. To achieve this, we used image based k-means clustering and CIELAB colour space distances to explore cultural characteristics. We found a difference in the overall colour usage tendency of Paris and Tokyo. That is, Paris uses more green and bluish colours and Tokyo uses more red and yellowish colours for building façades. We also gained insight that westerners tend to focus broader areas such as back walls of the buildings than easterners. Therefore, by considering different tendencies in perception of physical space as well as colour perception, strategical suggestions can be made in the usage of building exterior colours. Based on these cultural clues, we anticipate glocal colour recommendation with local considerations to the theme park designers.

## 6. Discussion and future works

As a first phase of cultural colour study, we wanted to compare same thematic buildings in theme parks located in two different cultural environ-

ments, and the current work may seem to lack data. However, in the next phase, we will improve our approach using a broadened scope of data, such as expressing cultural differences using representative colour palettes of a whole theme park colours or city colours. In addition, it is challenging to get intact building images due to trees or pedestrians in the theme park. Therefore, we expect better results if there is a way to achieve unimpeded images of building façades. The major motivation behind this paper was to reflect the atmosphere and the mood of the space that can be easily felt but not readily expressible into a cultural colour palette. Eventually, by finding the characteristics of perceived colours, we hope to create a colour recommendation system for different cultures based on cultural clues.

## Acknowledgements

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# COMPLEX HUMAN AUDITORY PERCEPTION AND SIMULATED SOUND PERFORMANCE PREDICTION

*A case study for investigating methods of sound performance evaluations and corresponding relationship*

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**Abstract.** This paper reports an investigation into the degree of consistency between three different methods of sound performance evaluation through studying the performance of a built project as a case study. The non-controlled office environment with natural human speech as a source was selected for the subjective experiment and ODEON room acoustics modelling software was applied for digital simulation. The results indicate that although each participant may interpret and perceive sound in a particular way, the simulation can predict this complexity to some extent to help architects in designing acoustically better spaces. Also the results imply that architects can make valid comparative evaluations of their designs in an architecturally intuitive way, using architectural language. The research acknowledges that complicated engineering approaches to subjective analysis and to controlling the test environment and participants is difficult for architects to comprehend and implement.

**Keywords.** Human sound perception; acoustic simulation; experiment and measurement.

## 1. Introduction

The mechanism of receiving signals from the source to the human ear is only the beginning of the sound perception process. Eggermont (2001) elaborated the hierarchal systems which occur between receiving and perceiving the sound. What makes auditory sensation a complicated phenomenon to fully

understand is the interpretation phase in the brain, which is unique for each person. If this is exceptional and complicated process in each person, can architects predict human sound perception at the design stage with the aid of digital simulation? And if so, are the results consistent with post occupancy experimental outcomes? One problem is that acoustics, as a branch of engineering is challenging for architects and is more focused on quantitative rather than subjective analysis. This study aims to provide architects with a better understanding of how to evaluate the sound performance of their design before and after the design fabrication in terms of human perception of the sound.

In recent decades where landscaped plans in offices prevail, sound performance has become a key in architecture design. The database significantly indicates complaints about speech privacy rather than noise level in open plan offices (Jensen and Arens, 2005). Although objective measurement is useful, the human perception of the sound is a determinant of the speech privacy rating in the space. Cavanaugh (1962) found in his experimental research that each subject had his own personal criterion for defining speech privacy in a wide variation of 10 dB. While computer simulations have been widely applied to generate the spatial and temporal data describing the behaviour of sound in space (Stettner and Greenberg, 1989), the degree of compatibility of the simulation with the actual human perception of the sound is still in question.

In doing an experiment with human participants, it is hard to take all parameters into account unless the experiment is implemented in a laboratory, under controlled conditions. Upon doing so, the contradiction is that the environment itself has a great impact on the test participants due to failure to adequately represent the natural situation. Human perception of speech is highly dependent on the eavesdropper's brain interpretation of the sound and it varies from one individual and circumstance to another. An acoustical engineering approach to subjective experiment is well documented in the literature, all carried out in a very controlled conditions; while this methodology is appropriate for outlining the general conclusions and relationships, it may result in investigating impractical conditions (Haapakangas et al, 2014). This research is implemented from an architectural standpoint to test the human auditory performance in the realistic situation of an open plan office.

The significance of this study will be highlighted when it comes to the complicated geometry with articulated surfaces of small-scale spaces where the software is unable to process the data accurately. FabPod, a semi enclosed meeting room located in a large indoor open plan office at the Royal Melbourne Institute of Technology (RMIT) design hub, is an ideal case study of such a complex design. The space has non-rectangular overall ge-

ometry, non-parallel walls and the highly articulated interior surfaces. The aggregate structure, composed of hyperboloid cells with different types of material (Woven image Echopanel, Aluminium and Acrylic) were designed to provide an acoustically live space with better speech intelligibility and privacy (Burry et al, 2012; Williams et al, 2013), (Fig. 1, right).

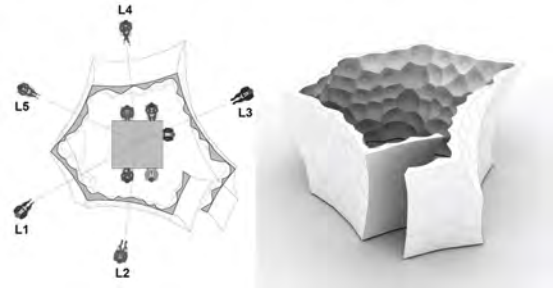



*Figure 1. Experiment plan (left), 3D rendering of the FabPod (right).*

## 2. Subjective experiment and objective measurement

The experiment was designed to assess the human auditory evaluation of the sound field, both inside and outside the FabPod, in a natural situation with controlling neither the environment nor the participants. The study frame can be considered an exploratory cross-sectional research and does not aim to test a statistically significant sample of participant experiences.

### 2.1. EXPERIMENT METHOD AND SETUP

Ten native English speakers, five males and five females, without any reported hearing deficit, participated in the research and were divided into two groups of five according to their age and position.

#### *2.1.1. Procedure*

The process started with a brief introduction to the experiment along with signing the consent forms. One group held a meeting inside the FabPod on a general topic of their own choice with their natural sound level, while the other group was listening to the conversation outside the FabPod in five different locations, specified before the test. ISO 3382-3 (2012) was applied to layout the listeners' locations approximately 1.5 m from the walls of the FabPod and all in the same distance of 4 m relative to the centre of the pod, where an omnidirectional microphone was installed (Figure 1, left).

The conversation inside the FabPod resembled a real meeting for 15 minutes and the eavesdroppers around the pod were advised to listen to the

conversation as if they were supposed to work at that place. These eavesdroppers were each interviewed immediately afterwards to record their experience of listening. The groups then changed their positions as listeners and speakers and repeated the same procedure for the second round for another 15 minutes. All the participants were given full information about what they were doing.

### *2.1.2. Questionnaire and interview*

The listeners around the FabPod in the open plan office were given a qualitative questionnaire focused on speech privacy and level of distraction after each round of experiment. Participants were asked to rate the speech privacy of the open plan office on a slider range from no privacy to confidential privacy and to identify the conversation topic if it was intelligible. The multiple-choice questions were composed of 5-point scales for describing the level of privacy and distraction, acoustic satisfaction, applicability and effectiveness of the design. The speakers inside the pod were interviewed after the test to share their auditory experiences of intelligibility and sense of privacy while having a meeting inside the pod. They rated the perception of the speech privacy while being inside in addition to intelligibility and clarity.

### *2.1.3. Data analysis*

All participants sitting around the pod were able to distinguish the conversation tone and mood. Seven listeners could hear odd words of the sentences but couldn't make sense of them. Eavesdroppers in location L3, described speech privacy as normal with satisfactory acoustic comfort. Participants in location L2 perceived no privacy at all and could easily get distracted with clearly hearing every word. Locations L5, L4 and L1 stand in between these two respectively with little differences in defining speech privacy. Only one participant could identify the topic of the conversation in location L2.

Table 1. Participants' qualitative description summary

| *Gender Difference* | *50% heard males pitch better* | *50% no difference in gender* |
|---|---|---|
| *Degree of effectiveness* | 90% slightly to strongly effective | 10% Neutral |
| *Degree of applicability* | 90% helpful to extremely helpful design | 10% slightly helpful, hard to notice |
| *Speech privacy comparison* | 90% slightly to reasonable degree of privacy inside the pod | 10% slight degree of privacy in open plan office |

The average speech intelligibility and clarity subjective rating inside the FabPod was 0.90. And the average speech privacy rating outside the FabPod was 0.50. The difference between the speech privacy rating outside the pod and perception of privacy inside the pod is illustrated in Fig. 2 for participants in each location. These differences can be attributed to the visual sense of privacy inside the pod.

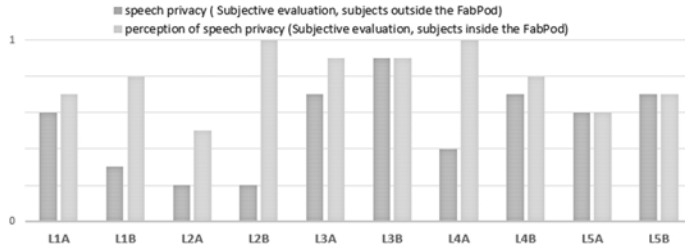



*Figure 2. Difference in rating speech privacy inside and outside the pod.*

## 2.2. OBJECTIVE MEASUREMENT

In the objective evaluation, both un-weighted and A-weighted, were measured. A-weighting is a sound filter which covers the full frequency range of human hearing between 20 Hz and 20 kHz and it has the most identical form to the reaction of the human ear.

The aim was to compare the outcome with the measurement which was implemented before, in a controlled condition with omnidirectional loudspeaker (Qui et al, 2013) instead of natural human conversation as a source. Also the results were compared with human subjective rating and computer simulation as a mean of speech privacy evaluation.

### *2.2.1. Measurement instrumentation and setup*

The background noise was measured by the B&K system comprised of the Hand-held Analyser Type 2270 and microphone Type 4189 with Type ZC 0032 preamplifier. The Sound Pressure Level (SPL) was measured by four NTi systems consisted of an Audio Type XL2 Hands-held Audio and Acoustic Analyser and a Behringer ECM8000 ½'' microphone. The systems were calibrated with a B&K Type 4230 calibrator.

The background noise was measured at 1 position inside (L0) and five different positions outside (L1~L5) the Fabpod when there was no human activity in the open plan office. The measurement positions L0~L5 are shown in Fig. 1 (left), where the microphone is 1.2 m above the floor. The measurement for background noise lasted 60 seconds at each position, which was long enough according to the ISO 1996-1 (Chen et al, 2010).

The SPL was measured at 1 position inside (L0) and 3 different positions outside (L1~L3) the Fabpod simultaneously when the group held a meeting inside. Each round of the SPL measurement was lasting for 15 minutes in accordance to the subjective experiment, during which time the SPL was averaged every 10 seconds, which was long enough according to ISO 140-4 (1998). The SPL was measured in 1/3 octave band from 6.3 Hz to 20000 Hz.

### *2.2.2. Background noise*

The un-weighted and A-weighted total SPLs of background noise inside the Fabpod at the center (L0) and outside around the pod at five different positions (L1 ~ L5) are shown in Table 2. The un-weighted and A-weighted total background noise level inside is about 2 dB and 4 dBA lower than the average value outside the FabPod respectively.

Table 2. A-weighted and un-weighted background noise pressure level in 6 locations

| *Positions* | *L0* | *L1* | *L2* | *L3* | *L4* | *L5* | *Avg.* |
|---|---|---|---|---|---|---|---|
| $L_n$ *(dB)* | 48.3 | 49.8 | 51.1 | 47.2 | 49.1 | 52.7 | 50.4 |
| $L_{nA}$ *(dBA)* | 34.2 | 36.7 | 40.6 | 36.6 | 38 | 39.7 | 38.6 |

### *2.2.3. Sound pressure level*

For the first round of measurement, the SPLs inside are about 14 dB and 18 dB and for the second round 11 dB and 16 dB higher than that outside the FabPod in terms of the un-weighted and A-weighted total SPLs, respectively. The sound pressure level values are summarized in Table 3 and Fig. 3.

Table 3. A-weighted and un-weighted Sound Pressure Level (SPL) for two rounds of experiment in one location inside and 3 locations outside and A-weighted SPL Difference.

| | *Round A* | | | | *Round B* | | | |
|---|---|---|---|---|---|---|---|---|
| *Positions* | *L0* | *L1* | *L2* | *L3* | *L0* | *L1* | *L2* | *L3* |
| $L_p$ (dB) | 68.5 | 54.4 | 54.9 | 53 | 64.4 | 51.7 | 53.7 | 51.9 |
| $L_{pA}$ (dBA) | 64.8 | 48 | 47.8 | 45.2 | 60.1 | 42.1 | 44.9 | 43.8 |
| $L_{pA}$ D (dBA) | -- | 16.8 | 17.0 | 19.6 | -- | 18.0 | 15.2 | 16.3 |

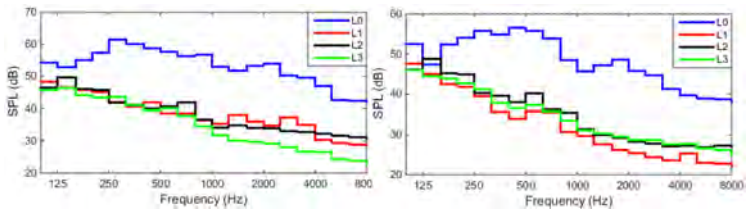



*Figure 3. The sound pressure level in 1/3 octave band round A (left) round B (right).*

## 3. Digital simulation

The main challenge in simulating the FabPod was the extreme irregularity in shape and material. Previous attempts to simulate the FabPod used approximation and simplification of the geometry and materials (Peters et al, 2013; Zhao et al, 2015), however noticing the fact that for making comparisons between human perception of the sound and measurement with digital simulation results comparable conditions were required, we needed to get as close as possible to the actual geometry and materials distribution and absorption coefficients to avoid any possible deviation causes by estimation. 3D visualisation of the simulated pod is shown in Fig. 4. Each hyperboloid was assigned the actual property without generalizing the material distribution, with high mesh resolution and small tolerance for water tightness.

Table 4. Absorption coefficients of the open plan office surfaces.

| *Frequency* | *63* | *125* | *250* | *500* | *1000* | *2000* | *4000* | *8000* |
|---|---|---|---|---|---|---|---|---|
| Ceiling (α) | 0.3 | 0.3 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.97 |
| Wall (α) | 0.1 | 0.1 | 0.05 | 0.06 | 0.07 | 0.09 | 0.08 | 0.08 |
| Glass (α) | 0.18 | 0.18 | 0.06 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 |
| Floor (α) | 0.02 | 0.02 | 0.05 | 0.05 | 0.1 | 0.05 | 0.02 | 0.02 |

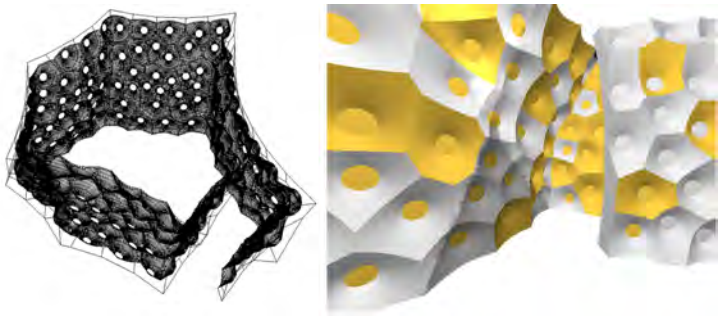


*Figure 4. 3D of imported FabPod in ODEON (left), 3D openGL in ODEON (right).*

### 3.2. SIMULATION ANALYSIS

For analysing the results two main parameters were selected according to the standard 3382-3:2012. ODEON calculated A-weighted sound pressure level (SPLA) and speech transmission index (STI) and the grid map in Fig. 5 indicates the STI for receivers in each 0.25 $m^2$ of the open plan office. STI is the quality of transferred speech from source to receiver (Svensson and Nilsson, 2008) and it is found to be one of the best descriptors for speech privacy and speech intelligibility. With the higher STI, the more intelligibility and con-

sequently less privacy can be achieved in the space. According to ISO 3382-3:2012, the distraction distance starts when the STI falls below 0.5 and the privacy zone has the STI between 0 and 0.2.

The results show that location L3 has less STI (0.24) and more SPLA reduction which implies that this space can be considered more private and less distracting when there is a meeting in the pod. Location L5 would be the next with the STI of 0.28. STI decline at L5 relative to L3 is above the just noticeable difference (JND) range which is 0.03 (Bradley et al, 1999), indicates participants should perceive the difference between speech privacy in L3 and L5. The STI difference between Location L1 and L4 is below JND and it is 0.32 and 0.31 respectively. Therefore, these two locations would stand in the same position in terms of speech privacy. STI for L2 is 0.57.

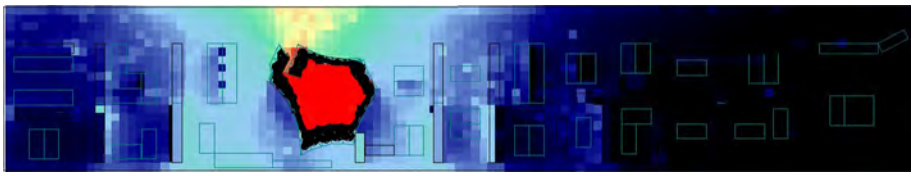


*Figure 5. Calculated STI, grid map of the open plan office at 1.2 m height.*

It is important to notice the limitation of the ODEON software in simulating complex geometry and considering the sound transmission through walls simultaneously. Since the presented simulation is regardless of transmitted sound through structure, currently we are not able to compare the simulated STI with standards, however it is not the focus of this study.

To investigate the effect of the sound transmission through pod's surfaces, we need to simplify the geometry and exclude the impact of the hyperboloids in simulation. The STI will then dramatically increase to 0.59 in L3 and correspondingly to all other locations. The suggested reason for improved speech privacy in spots 3 and 5 is the FabPod's overall geometry with sharp edges in the corners, which provides acoustic shadows at these two locations (Fig. 6).

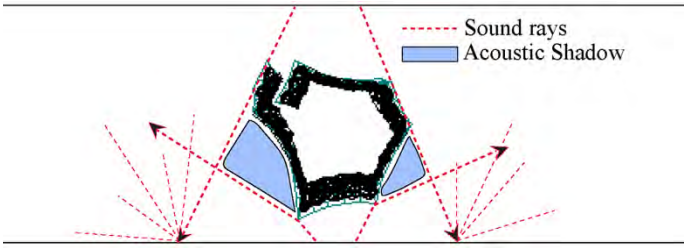



*Figure 6. Acoustic shadows provided by FabPod sharp edges.*

## 4. Results comparison

Theoretically for each location the sound level reduction in both rounds should be the same. One reason for discrepancy in measurement was uncontrolled natural environment of the open plan office. The SPL at each location was not only a transmitted sound from meeting in the FabPod, but also from occupants working at the open plan office at the same time. The second reason was inaccessibility to the multi-channel measurement system at RMIT Acoustic Lab. The measurement results of the four NTi systems might not be synchronized accurately due to manual operations. Also as a result of NTi system noise floor, any SPL measured by the NTi systems lower than 37.5 dBA is unaccountable. Despite these inaccuracies, the average measured sound level reduction is in line with the previous study (17 dBA), carried out in a very controlled situation (Qui et al, 2013). Furthermore, the reverberation time (T20) in simulation (0.27 s) is very close to the post occupancy objective measurement (0.26 s) implemented before (Zhao et al, 2015).

The remarkable consistency between subjective rating, measurement and simulation prediction shows that in all evaluations the best and worst locations in terms of speech privacy are the same. L3 is constantly the best spot in all analysis and L2 with the highest STI and lowest sound level reduction is the most distracting location. Some fluctuations can be seen in the ranking of the other locations due to the complex human perception of the sound and many variables involved in subjective rating, besides the non-controllable situation of the experiment.

## 5. Conclusion

This architectural approach to the research studied the consistency of the simulation prediction with post occupancy subjective judgement of the sound field and measurement in complex geometries. The importance of the results lies in the significance of how architects can predict sound performance regarding human perception and to what extent this prediction can approximates human interpretation of the speech privacy. We observed a high correlation between simulation prediction of speech privacy and human's perception of the privacy, which indicates that architects can predict the acoustic performance of their complex designs especially in small spaces using either simulation techniques before fabricating the full-scale prototype or arranging subjective experiments with scaled prototypes. Second, the consistency between objective measurement, digital simulation and architectural subjective study implies that architects can set up a simple subjective experiments for preliminary testing of sound performance of their design by knowing only the basics of architectural acoustics. This type of experiment

is relatively different from an acoustic engineering approach. However, it can provide continuous feedback for the design before and after fabrication. The STI threshold of privacy and distraction needs further study, specifically for experiments in natural environments, since this research has demonstrated that occupants in the places with STI greater than 0.5 can still be acoustically comfortable doing work with no distraction even though this is above the acoustic threshold suggested in the literature and by the standards.

## Acknowledgment

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# PERFORMATIVE AGENCY OF MATERIALS

## *Matter agency of vernacular African pattern systems*

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**Abstract.** This paper investigates an agency of materials through a design methodology that follows Martin Heidegger's process of "Entbergen" or "unconcealing" as a non-instrumentalist understanding of tools and materials. This investigation takes place through the design of a children's theatre in South Africa where material innovation for architectural components is needed. The research studies vernacular African patterns and their inherent behaviour when transferred to materials. The transference of pattern systems to architectural prototypes is discussed alongside the discussion of their technical and architectural performance criteria. Following Heidegger's theory of "Entbergen" ("unconcealing") the paper will demonstrate how making in this methodology becomes an "unconcealing", which includes both digital and analogue means, linking the four causalities - causa materialis, causa formalis, causa finalis, and causa efficiens – through the agency of material within an integrated process between all four causes. Making becomes a process in which form is generated through interventions within fields of forces and currents of materials, taking cause and agency into account, and standing in opposition to methods that are defined by a premeditated notion of an ideal outcome.

**Keywords.** African patterns, making, design build, design methodology.

## 1. Introduction

John Wood (2007) argues for “brief, local utopias” as a network of connected, pluralized, bottom-up “micro-utopias” that achieve global synergies through design. Such “Micro-Utopias” are more tentative, temporary or truncated versions of the picture book utopias. Within these “Micro-Utopias” design is not just understood as aesthetic, but also as an ethical, social practice to benefit society – building up upon ideas of John Ruskin and William Morris (Burcikova, 2007). Design becomes “metadesign”.

The Guga S'Thebe Children's Theater, located in the Langa community (the oldest township in Cape Town) could be seem as a form “metadesign”, where craft is used to create a physical and cultural environment with lasting impact. This paper reflects upon the design methodology that was used to design different parts of the building with the focus on the design of performative interior elements. This methodology was also used in designing other parts of the building such as the exterior skin. The paper will first – briefly - introduce the project of the Guga S’Thebe theatre and then explain the design methodology and its transference to the design of acoustic absorbers and diffusers for the interior of the theatre.

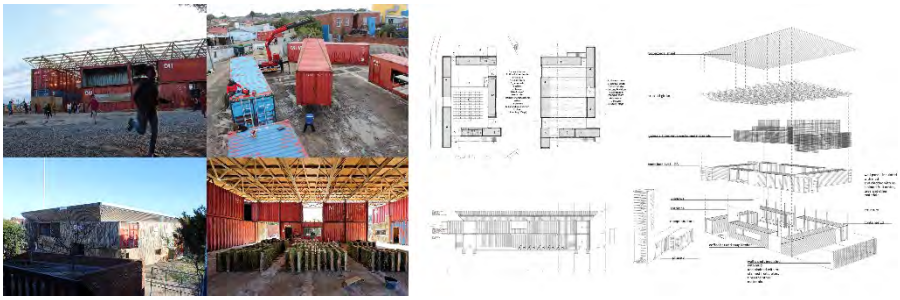


*Figure 1. Children’s Theatre: construction (left), plans (middle), axonometric view (right).*

## 2. Guga S’Thebe children’s theatre

The Arts and Culture Centre Guga S’Thebe attracts local children, adolescents and artists, as well as international tourists. One of its additional programmatic needs is a large multi-purpose space. The new space facilitates local theatrical productions, concerts, church services, marriages and festivals.

The Guga S'Thebe children's theatre is a design build project by multiple international universities working with the local community and practitioners, which creates a cultural "village" through interior and exterior performance spaces. By combining recycled/re-used materials with earth construc-

tions, this project creates affordable and transferable building prototypes, which can be reconstructed easily by inexperienced and shortly trained labourers and adapted to other building typologies. Cape Town, with its big harbour, opens the opportunity to re-use locally found shipping containers. Single shipping containers are used everywhere in the townships to provide safe and inexpensive shelters. Unfortunately, containers perform very poorly climatically. A system of loosely stacked sea freight containers surrounds a central theatre space. The container's structural performance is maximized by minimal modifications. The poche (container walls) incorporates spaces such as backstage areas, a soup kitchen, spectator balconies, a recording studio, an exterior stage and other facilities.

## 3. Methodology

### 3.1. THE FOUR ARISTOTELIAN CAUSES

Aristotle is the first philosopher to introduce the four types of causes for movement or change, which give answers to the "why" questions of: *causa materialis*, *causa formalis*, *causa efficiens*, and causa finalis. Aristotle explains the four causes using different examples for each cause in his book *Metaphysics*:

The causa materialis, the material cause, is "that as the result of whose presence something comes into being",( Aristotle, Metaphysics, 5.1013a) referring to that of which something is made of. Aristotle uses the example of a statue, which is made from bronze. Bronze is the causa materialis for the statue. The causa formalis, is the "form or pattern; that is, the essential formula and the classes which contain it." (Aristotle, Metaphysics, 5.1013a) Aristotle's example is the form of octave, which is determined by the ratio 2:1. The causa efficiens brings something to be by opposing form onto matter or "that which produces is the cause of that which is produced, and that which changes of that which is changed". (Aristotle, Metaphysics, 5.1013a) The causa efficiens of a table is the carpenter or the child's cause is the father. Causa finalis is the "end" or the purpose: health is final purpose of taking a walk. (Aristotle, Metaphysics, 5.1013a)

### 3.2. HEIDEGGER'S CRITIQUE

Heidegger, in "Die Frage nach der Technik" (1954), criticizes this Aristotelian model, which focuses solely on final products and referred to as the *hylomorphic approach*, as purely instrumental. Here the cause is described as an affecting force. Affecting in this context means achieving success. Leaving the *causa efficiens* as determining all other causes. In that context

Heidegger points out that the Greeks know causality as fault, responsibility or indebtness.

Again in response to Aristotle's four examples, Heidegger gives one example - tying all four causes together in one example of the silver chalice.

Matter / *causa materialis*: Silver is the material from which the bowl is made (hyle). Therefore, the silver is indebted to the cause. So the chalice owes the silver that from which it is made.

form / *causa formalis*: Secondly, the silver chalice is indebted for its appearance in terms of its shape and appearance (eidos) of its "chaliceness". Its eidos is a formation of its "chaliceness".

telos / *causa finalis*: But in addition to those causes the silver chalice has been produced to be used - for sanctification and offering. The silver chalice is defined through the boundaries of sanctification requiring a specific performance. A salad bowl or a vase will not do.

*causa efficiens*: The silversmith is complicit in the existence of the silver chalice. His complicity is based not purely on its role as a maker in terms of the effect of making - not as efficient cause.

The silversmith reflects upon and links the first three kinds of indebtness, and brings them into being. The three previous kinds of cause are indebted to the planning of the silversmith, who decides if and how those causes are unconcealed, how their being comes into appearance. The craftsman's responsibility is the poeisis, the bringing forth or revealing (unconcealment) of the object, which was beforehand hidden or not present (Greek : aletheia; Latin : veritas truth).

Heidegger makes two changes to Aristotle's approach: first, there is continuity and resonance between the four causes implied through the example of the silver chalice – one object's event, not four; and secondly, there is a reversal within the order of the causes - *causa finalis* and *causa efficiens* switch places. The *telos* becomes the fourth cause.

In this text Heidegger assigns agency to all contributing causes and clarifies that it is through the interrelating with other causes that the maker becomes co-responsible for emerging design (Bolt 2007).

### 3.3. RESEARCH METHODOLOGY

The presented research and its application to the children's theatre are based on a procedure that tries to incorporate an agency of material where matter, formation, and performance are in conjunction with the maker: a *textility of making* (Ingold 2010).

The materials studied are textiles: Through diagramming, textile systems are transferred to architectural materials. The method proceeds in the follow-

ing 4 phases, in which the maker deploys the four causes in an interrelated process.

Phase I – textile patterns: In this phase textile pattern systems are studied as materials through parametric diagrams and understood in their consequences as material resulting from their process of making. This investigation informs the causa formalis and causa materialis.

Phase II – from 2d to 3d: Through diagramming each textile material system develops into a 3-dimensional configurations or formation.

Phase III – artificial equivalents: Different technological, artificial equivalents with specific performance requirement are proposed and tested. Architectural systems are considered and are constructed in consideration of different scales and scalability linked to the design of the Guga S'Thebe Theatre. This includes performance testing, if needed. Actual materials are considered.

Phase IV – on-site construction: In this last phase students and local workers for the Guga S'Thebe Theatre work on site in South Africa. Instead of one individual maker, the setup of the project is constituted by a diverse team, which operated within a highly constrained time frame.

## 4. Matter agency

In this section two different pattern systems are explored with an account for how the methodology was employed within these examples. The discussion in this section shows design work in preparation for the design build project in South Africa.

### 4.1. ADIRE

Adire - from Yoruba, Nigeria - is an indigo dyed fabric with intricate white figures. The dying process uses the resistance of starch, raffia or thread to prevent the colouring of the certain areas. Two fabrics, 2.5 yards x 1 yard, are sewn together to form customary, patterned women cloth (Horn 1996), which show geometric lines using one or more of the followings elements: dots, circles with varying radii, triangles or rectangles with infill, parallel lines with sometimes variable line thickness, intersections of lines and circles. The special character and beauty of the fabric is created by the strong contrast of the blue and white colour and by the effect by blurring edges.

Five different patterning techniques for indigo-dyed fabrics can be distinguished. The Raffia Resist /Adire Oniko (1) is a technique for tie-dyed fabric using raffia ribbons, which are tied around the fabric in order to stop the fabric from absorbing colour. The blurring effect can be controlled in this technique by supplements such as beans, stones, seeds or other small objects that

are tied inside the fabric during the dying process (Gillow 2003). The Pleat Resist (2) uses pleated cloth that is tied before dying. It is soaked or painted on one side of the pleats to create a stripped pattern. The stitch resist / Adire alabere (3) uses threads as resist. The printed pattern technique (4) applies pattern through stamps. The starch resist / Adire eleko (4) applies starch to resist the dye through a stencil or by hand.

Figure 2 shows an overview of a variety of explorations that start with different patterns and their implied materiality. The diagram then is informed by materiality and allowed to form accordingly, while making and application are simultaneously considered. Within the context of Heidegger we could say that each pattern is unconcealed (Entborgen).

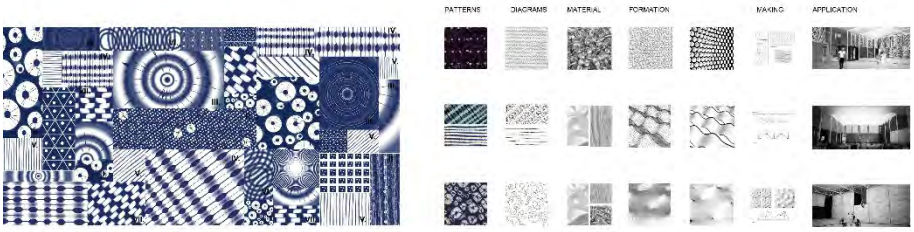



*Figure 2. Adire patterns(left), design develop (right).*

The third option shown in figure 2 was selected for further exploration. In this pattern study circles with varying radii are made by using the raffia resist technique, which blurs the edges, constituting the pattern used in this sample. Through diagramming and scripting the centres of the circles and their radii were transferred to a 3dimensional surface, which reads a small circle as smaller bulge and a larger circle as a bigger bulge. In parallel materials were considered and potential applications proposed. Considering locally available materials and potential re-use of material, the function of an acoustic absorber was explored. Figure 3 shows the material elements involved in the assembly: a wooden frame (15cm), a fabric cover, tensioners, and insulation.

The wooden frame was first built with plywood and later replaced with locally available used pallets from a market. The insulation was initially built using leftover felt. But acoustic calculations showed that the absorption of felt or other re-used waste products would not suffice as absorption for the large performance space. The acoustic calculations showed that the positioning of highly effective absorbers was needed for speech and theatre performance and that there was a need to prevent detrimental reflections from the rear wall, which would to lead to echoes on the stage, if not properly absorbed.

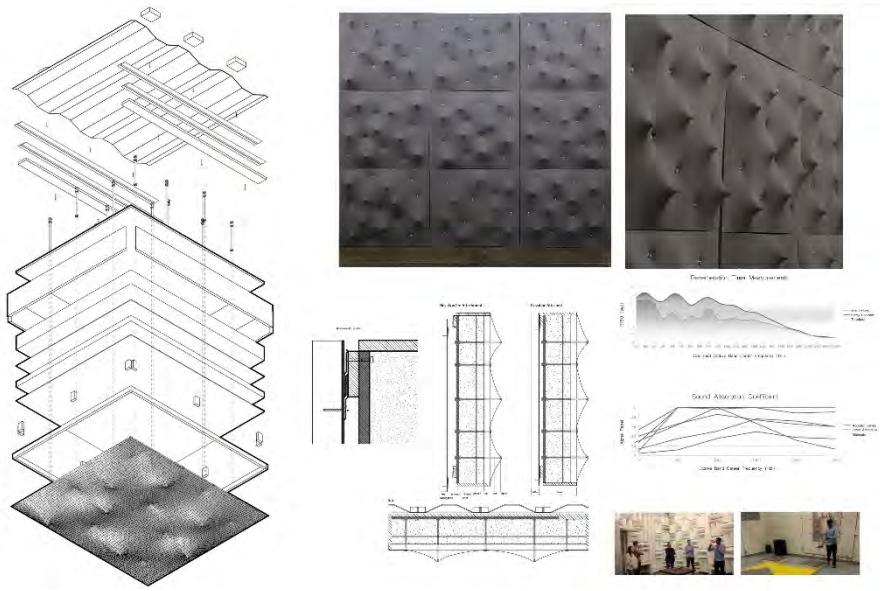


*Figure 3. Prototype for acoustic absorbers.*

Therefore, the following mock-up for the insulation was developed and tested: 10 cm mineral wool, foil (550g/m2), 5cm mineral wool and fabric with a porosity of 35 %. Testing as shown in Figure 3 proved a good acoustic performance. In combination with variable curtain 100 m2 of wall and ceiling surface necessary reverberation times could be provided.

## 4.2. ADRINKRA

The second pattern system studied can be found in Adinkra textiles. Adinkra textiles are a rectangular toga-size cloth that was worn by the Akan people in Ghana and Côte d'Ivoire. As Adrinka originally means goodbye or farewell, those togas decorated with symbols were reserved for spiritual leaders and royalty mourning the dead. Symbols were chosen from a large catalog of graphic figures, each representing a concept or aphorism. Colours used were the darker colours appropriate for mourning. Now, worn by everybody, brighter colours can be found and symbols adapt to incorporate technological developments. Also, contemporary designers have started to use Adrinka symbols for decorating multiple types of objects.

The traditional fabrics were stamped with symbols that carved from Calabash shell onto strips of cloth, which are then sewn together to make large sheets that can be wrapped around the body.

The printer starts by defining a grid 2.7 x 3.6m on the fabric with a bamboo splint dipped into a thick dark sticky substance (a tar from boiled down

babe tree root with iron slag). The next step is to apply a set of rows with different design motifs.

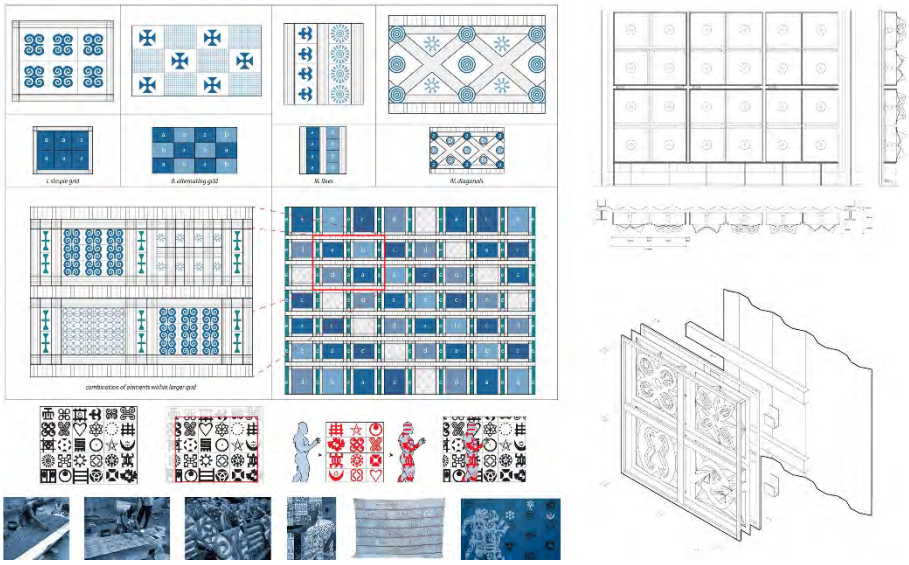


*Figure 4. Adrinka patterns(left), prototype (right).*

We can find a series of different techniques: We can see a simple grid, with one repetitive pattern, an alternating grid of two symbols, bands of symbols, a diagonal grid and combination of grids. The research of the Adrinkra material system revealed that the process of stamping is one of the most characteristic procedures that influence the making of this fabric. Diagramming this procedure as *causa materialis* opened the possibility to explore the behaviour of stamping as a three-dimensional process with digital means. It was assumed that the material, which receives the stamp, is malleable first and can maintain its form afterwards. The project started by three-dimensionally stamping surfaces in Grasshopper and varying the height of the stamp - becoming the *causa formalis*. First material explorations were conducted in concrete and gypsum (powder). The three-dimensional surface of the moulds was cnc-milled out of plywood and a silicon mould was cast from the first mould to be used for the final concrete cast. The potential of this technique was in the possibility for the re-use of the moulds. Problems were encountered by the high weight of the tiles and fine-tuning the pattern's performance aspects to meet acoustic criteria. Façade applications were unreasonable; therefore, interior applications for the theatre space were explored. From an acoustical point of view, the use of shipping containers was already very useful, since the containers exhibit certain diffusivity through

their corrugated exterior. In that sense the interior had already sufficient diffusing surfaces, but unfortunately the diffusion would always break the sound waves in the same way. Difference in diffusion elements was desired. At the same time, it was also a desire to create an interior in which the structure of the shipping container would still be visible and not entirely covered by acoustic absorbers, curtains, illumination elements and other diffusers.

Therefore, the potential for combining performance requirements was explored. Figure 4 shows a wall panel, which diffuses sound with varying angles and performance as light feature within the theatre space. The making is very similar to previous procedure, but the material is changed to a thermo-formable plastic with different colours, which can be used for illumination and sound diffusion simultaneously.



*Figure 5. Prototype (left), fabrication process (right).*

## 5. On-site construction

On-site construction changes the causalities of making drastically. During the construction phase students work with members of the community learning how to deal with different construction materials and their specific applications in South Africa. The methodology provided a framework, in which changes could be made easily without losing the essence of each design. The short time frame of a 3-month construction phase and the constraints within the budget and availability of material provided another input to the design.

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# WORKMANSHIP OF RISK: CONTINUOUS DESIGNING IN DIGITAL FABRICATION

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**Abstract.** Research projects exploring the realm of digital fabrication have shifted in recent years from developing novel techniques and outcomes to the development of tools that are part of the design process. The alignment of material systems with digital fabrication technology and tooling processes have led to new terminology such as 'digital craft' and 'digital making'; both terms imply a relationship between craft and digital design and fabrication. Also implied is an intimate relationship between material production, digital tools and CNC fabrication techniques; critical ingredients in contemporary design processes. David Pye's concept of 'the workmanship of risk' is used extensively in current discourse as a means to qualify digital fabrication as craft production. This reading of digital fabrication as craft is limited because the word craft is used as an analogy to draw parallels between craft production and digital fabrication. There is a gap in the knowledge of what contemporary craft practice can bring to digital fabrication as a discourse or more precisely, the mechanism that allows digital fabrication projects to be read as a form of craft practice. This paper suggests that craft practice is rooted in the relationship between material, tools and technique as an intricate workflow within a project; quantifying risk is just a means to assess this relationship. The workflow however can be considered as autopoietic in nature; it is both self-referential and self-making at the same time as continuously designing.

**Keywords.** Digital craft; digital fabrication; systems theory.

## 1. Introduction

This paper explores the line of inquiry: how does craft practice inform digital fabrication. We do this by examining Pye's concept of the workmanship of risk in craft practice through his book, *the nature and art of workmanship* (1978) and a series of semi-structured interviews with five contemporary craft practitioners based in Australia. With the aim of developing an in depth understanding of the workmanship of risk, the authors have drawn on the reading of Pye's writing to formulate an analytical diagram which acts as a tool to allow the authors to quantify risk in making. The aim of the analytical tool is twofold. Firstly, it allows comparison of different making activities, allowing practitioners to judge and quantify the level of risk in making. We argue that it is important to quantify risk in making and relate it to the type of making and the context of making. The model outlines a framework for understanding the relationship between tools, materials and techniques.

The textual reading is supported by a series of semi-structured interviews with contemporary craft practitioners. These case studies provide a cross sectional view of contemporary craft practices and examine how practitioners deploy and invent novel tools for making as well as techniques to develop their material production. These practices define the context of craft in this paper; by craft, we refers to material production which are bespoke and original in design with small or limited production run which are typically customizable. Here, the authors starts to develop a theoretical framework around an understanding of making as an active design agent or process; the formation of repertoire in craft practice, to borrow a term coined by one of the craft practitioners from the case studies.

Making is often categorised as tacit knowledge instead of explicit knowledge (McCollough 1998; Sennett 2009), which can be difficult to capture. Initially, the research aims to develop a methodology of analysis that allows the risk in making to be made quantifiable; risk such as level of control or consistency in the making process. Kolarevic (2008) suggests this as positive design opportunity. However, what emerges from this research is an understanding of the interdependent relationship of materials, tools and techniques in the making process; the nature of the relationship and how it is affected by its context. These relationships explored through systems theory reveals how craft practice is a continuous 'designing' method. Through this, the authors suggest that there are deeper understandings of craft practice which can be used to inform the way we practice digital fabrication.

The contribution of this paper is to review the current theoretical framework of craft in digital fabrication (McCollough 1998; Kolarevic 2008; Marble 2010) and highlight future areas of research into how craft practice

can continue to inform digital fabrication and design as material production. The paper addresses the conference theme of continuous designing through examining making as a way of generating design knowledge in the process.

## 2. Background

### 2.1. DEFINING RISK IN MAKING

The key reason for a number of authors to align digital fabrication with David Pye's writing is because Pye is foremost a craft practitioner. Unlike other authors who have written on the topic of craft in 20th century, his writing reflects his practice. Hence the semantic of craft is absent from his writing. Instead, he chooses to focus on understanding the making process and its relationship with design.

In his book *the nature and art of workmanship* (1978), Pye postulates the idea that craft is about workmanship and technique. Within workmanship (be it good, bad, rough or precise) lies an intimate relationship between the intent of the designer and the execution of the work. To make a precise judgment of workmanship is to understand how closely the design is aligned with the executed object. Here, he described a 'sliding scale' relationship; for example, good workmanship is where the physical object is aligned with the design and bad workmanship is where the executed object is far removed from the intent. This sliding scale model is of interest because it allows one to evaluate workmanship. What used to be a subjective reading of workmanship is moved towards a model that is almost quantifiable. However, this scale has no comparative model to calibrate it and it remains abstract within Pye's writing.

The second aspect is technique. This is closely related to workmanship and the level of risk the maker deploys in his/her work. The term *Workmanship of Risk* and *Workmanship of Certainty* although set up as dichotomy, it is intended as another 'sliding scale' model. Pye in his critique on mass production discussed the lack of risk in workmanship. Similarly, he also recognized that at various stages of work, there are different levels of risk. For example, in a mass production scenario and from product design point of view, there are high levels of risk at the early preparatory stage in term of tooling: preparation of tools, mould et cetera. However, once the procedure is refined through appropriate tooling process, establishing control over the material (using mold or jig) and dexterity, the level of risk is reduced. This of course coincides with the economic requirements of most manufacturing procedures; lower cost, repeatability and controllable production.

Most craft practice tends to lean towards the workmanship of risk end of the spectrum. However, there is always a certain level of control and dexterity in the process, which we observe in our case studies. It is important to clarify that there are certain craft practices that are outside the boundary of this reading, namely those based on free forming processes.

## 2.2. RISK IN MAKING

From the above analysis, we have devised a web diagram illustrated in Figure 1. The diagram attempts to spatialise the relationship between tools, material and techniques based on a reading of Pye's writing. The relationship of tools and technique raises the question of appropriateness, while the relationship between tools and material raises the question of the establishment of control. Lastly, the relationship between material and techniques is based on care, dexterity and judgment.

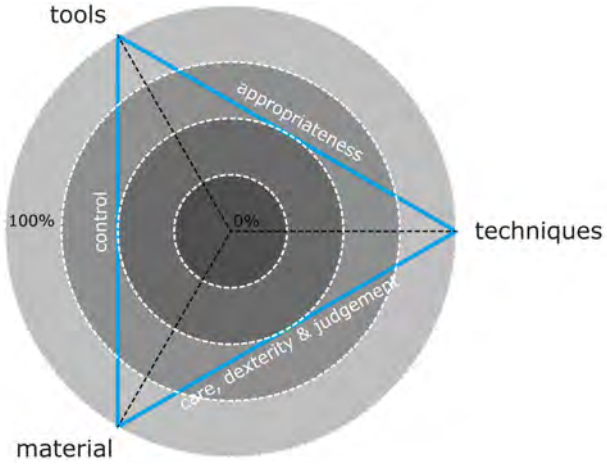



*Figure 1. Web diagram mapping relationship between tools, material and techniques.*

Producing a web diagram for various stages of a manufacturing or craft production process, we can start to compare the stages of making within one process and also compare the mappings for different processes. Through comparative study of the various stages of work, the diagrams can be calibrated relative to each other. This becomes a useful analytical tool to understand the type of making and its context. For example, we use this analytical tool to compare the making process between craft practices in order to understand the relationship between tools, material and techniques at the various stage of making. We will discuss this in greater detail.




*Figure 2. Web diagram mapping level of risk at different stages of making.*

## 2.3. SEMI-STRUCTURED INTERVIEWS

In parallel to textual analysis of Pye, we interviewed five craft practitioners; Brendan Dwyer (shoe maker), Kris Coad (ceramic artist), Marcos Davidson (jeweller), Damien Wright (furniture maker) and Steve Howden (leather jacket and inflatable structure maker). Four of the practitioners work within traditional media while Steve Howden works across both a digital medium and fabrication. On average, each craft practitioner interviewed has over 20 years of practice and is an established leader in their field. All the practices are small scale with focus on making custom and one off products or design. Each participant is asked the same set of questions with slight variations depending on trajectory of the conversation. The questions are centred around their practice with key emphasis on their techniques, tools and processes. Below is a small sample of the questions:

- How do you develop your technique?
- Do you think the tools you use define your practice?
- Do you invent your own tools?
- How do materials or material systems influence your design or design thinking?

Responses from the interview are analysed and synthesised in the following sections.

## 3. Structure coupling of practice

### 3.1. CONTINUOUS DESIGNING

While the outcome of each craft practice may vary, there are commonalities in practice:

- Completeness of the process from design to production. That is, the entire process of making from start to completion is overseen, managed and designed by a single practitioner. While there may be assistants involved, the work is developed within a set of 'controlled' environments. Marcos Davidson described this as having autonomy over techniques, tools and material.
- Design is seen as a continuous, evolving practice. The design process of each practitioner evolves with the workmanship underpinned by techniques and material understandings. Knowledge in the techniques, tools and materials is developed within the workflow itself; as in an autopoietic system where tools are modified, adapted and invented to become generative within a design process. It is important to note the original domain specific concept of autopoiesis (Varela et al 1974) has since been apply to non-biological systems and is outside the scope of discussion of this writing (Urrestarazu 2012).
- The type of material deployed conditions the toolsets, techniques and ultimately the boundary of the practice. The clarity of the boundary in fact defines the locus of the practice.

These initial findings start to describe the formation of repertoire in craft practice where the fluid relationship between tools, material and techniques can produce a variable set of material outcomes; tools, materials and techniques are identified as the three key aspects in the making process, referring back to Pye's model of workmanship. This study demonstrated that a defined bandwidth of tools and techniques applied to a specific material or material system leads to a repertoire within which a wide range of variation is possible.

This description is quite different from the traditional perception of craft practice as linear thought process; where abstraction of the object's form and function is preconceived before the application of certain techniques and material using a predefined set of tools (Risatti 2013). One of the reasons why it is difficult to pin down the relationships between material, tool and techniques are because the relationship is in fact opaque; precisely because the design process takes place within a closed loop. That is to say, the incremental innovation that occurs within each of the studied craft practices is self-referential and is only deeply understood by the individual makers them-

selves. Meanwhile its impact on design allows each of the practices to develop unique aesthetics and design strategy. For example, in the work of Marcos Davidson, he actively invents as well as modifies tools to allow him to punch and shape silver into specific geometries and decorative designs. Brendan Dwyer modifies his skiving knife so it can perform multiple tasks. Kris Coad develops techniques to fire feathers and paper as delicate porcelain objects. Damien Wright modifies and builds bespoke jigs for each of his custom furniture projects. Steve Howden develops custom scripts to unroll developable surfaces for his inflatable structures and leather bike wear.

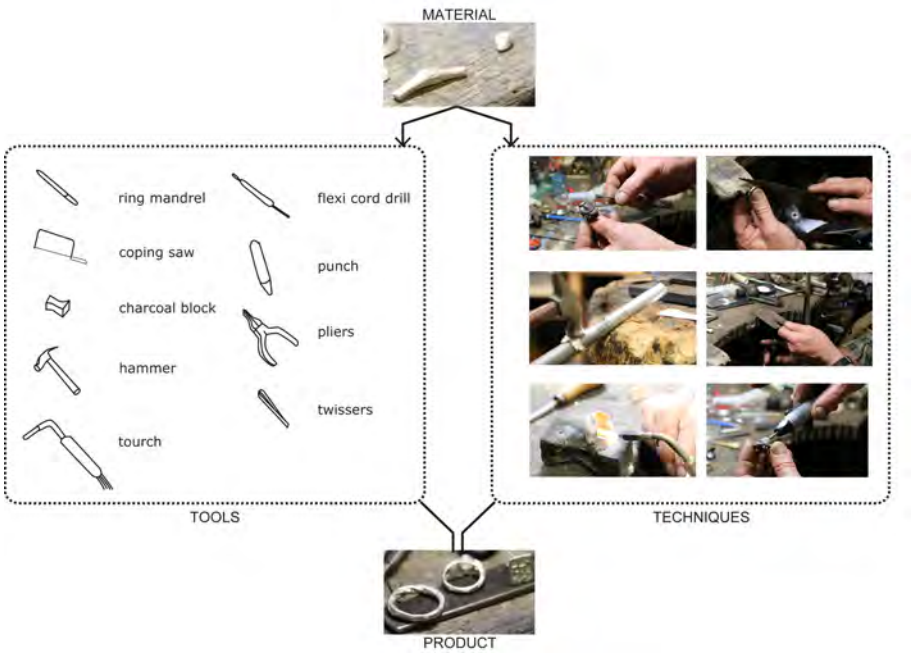



*Figure 3. Loose workflow of Marcos Davidson's practice forming a design repertoire.*

Fry (2009) called craft a proto form of design intelligence. The knowledge of techniques, tools and material are structurally coupled to produce a feedback system; as pictured in our earlier web diagram. This feedback however is not just recursive but also generative in so far as the practice evolves, the aesthetics and design co-evolve with this knowledge incrementally either over time or over projects. The practice takes on its own life; it is not just self-referential but also self-making (Reichel 2001). This evolving model has similarity to Reichel (2001) autopoietic theory of technology. He described technology as a self-referential system independent of the environment of society and the individual. It is a system that observes

itself and evolves not through artificial intelligence but through a perpetual coupling with society and its function system such as economic, science and design. Rachel argues that technology evolves and evaluates itself by the work of the engineer through coded language or through social acceptance (either work/fail technology). Returning to our craft practitioners, their works are already coupled with economy, technology, art and/or design. The survival of a 15 to 20 plus year – old practice is a testimony of social and cultural acceptance.

It is therefore interesting to re-read the web diagram not just as a mean to evaluate risk: high, medium or low or as quantifiable percentage, but to precisely reveal the structural coupling of craft practices; in other words, craft practices is the coupling of techniques, tools and material. In system theory, structural coupling (Wood 2007; Reichel 2011**)** brings two or more distinct systems together in order to exert influence over one another in a mutual manner. In creative writing, Wood (2007) called this the act of 'co-authorship' where creativity co-evolves to produce innovation.

### 3.2. FROM WORKFLOW TO NETWORK

This research aims to develop a deeper understanding of the coupling structure between tools and techniques. It is the obvious link to digital fabrication, as CNC tooling and digital workflow is firstly conditioned by the type of machinery as tool and scripts or coding as tool making process to aid the automation workflow (Fisher 2008; Davis 2013) as well as to produce novel effects (Kolarevic 2008). In this section, we will discuss the need to invent tools within an autopoietic system.

Heidegger (1967) already suggested that tool forms systems and the invention of tools is formed out of a larger system from which it obtains its meaning; he argued that the cultural context is implicit when anything is made. Therefore, the need to invent tools in craft practices (Pye includes form determining systems like molds and jigs as part of toolset) is part of the self-making process. Within the larger system, the tools form a chain of use; however this chain can be broken and reconfigured depending on the nature of making. The authors observed from the workflow of Steve Howden that the introduction of digital software and CNC machinery allows for a flexible 'plug and play' relationship between tools whether it is manual, analogue or digital; Howden called his practice Flexible Manufacturing.

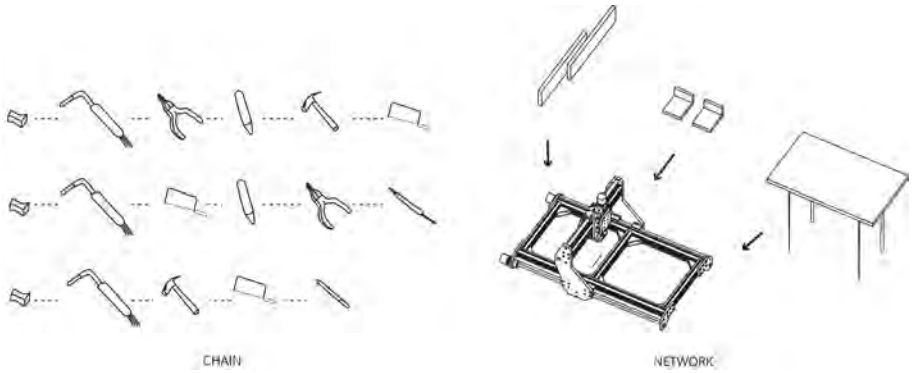



*Figure 4. Tools as network and chain.*

The workflow of information is not linear but is inherently networked. Through observing Marcos Davidson working on a wedding ring, one could see the well-rehearsed strategy of making in play. Here, the tacit knowledge of how to use a particular tool forms a link in the chain within the workflow of material production (Risatti 2013). The tool can be assembled and re-assembled to suit the design intent. In some cases, the toolset become part of the design process. The above suggests a process of continuous designing in practice (Fry 2009).

What is of interest is the information flow from the techniques to the tools to the material. The information although not written explicitly, is nevertheless coded. Reichel (2011) described 'information as a pattern that influences the formation and transformation of other patterns. That is to say, data in the first instance only becomes effective when placed next to or used to work or influence another set of data to become useful information. This working of transformation process is visible as pattern. Returning to the making of a ring, the pattern of assimilating tools to transform the metal into a specific geometry (identifiable as a ring) is the transforming of material as matter into visible effects (of decorative patterns and geometry) as the actualization of information; the crafted artefact is an embodiment of the practitioner's implicit knowledge exercised through complex coupling of tools, techniques and materials. Through further social coupling, the ring gains sentimental value.

## 4. Conclusion

While the current theoretical framework in digital fabrication around Pye's workmanship of risk (McCollough 1998; Kolarevic 2008; Marble 2010) constructed an analogy between craft and digital fabrication, they also implicitly structured a discourse coupling materials, tools and techniques. The-

se structure couplings allow researchers to develop a deeper understanding of the mechanism within craft practice. We suggested that the nature of these relationships can be instrumental in how we practice digital fabrication in architecture; from making and invention of tool through to re-conceptualizing tools and techniques as a part of design repertoire. The paper suggests that making is not just a set of workflows or means to an end but is a form of self-generating or generative practice. We argue that digital fabrication is itself a form of practice that co-evolves technology with material systems.

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# INTEGRATING CFD AND VR FOR INDOOR THERMAL ENVIRONMENT DESIGN FEEDBACK

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**Abstract.** In the context of environmental consideration and improvement of living standards, design of high performance buildings that are both comfortable and energy saving is important. Simulation tools (such as CFD) enables analysing and visualizing environmental factors (such as temperature and airflow) based on the design properties and can be used to improve the building design for better performance. However, these tools have limitations in providing interactivity with users for creating multiple CFD visualization results to be used for analysing design options. This research presents an integrated design tool which consists of CFD and VR technologies. The proposed system visualizes CFD results in a VR environment together with architectural design. Additionally, it enables configuring CFD parameters within the VR environment and allows repeatedly executing simulation and visualizing updated results. The proposed system enables visualizing information in relationship with the actual architectural design, space configuration and thermal environment, and provides efficient design feedbacks.

**Keywords.** Interdisciplinary computational design; design feedback; indoor thermal environment; Computational Fluid Dynamics (CFD); Virtual Reality (VR).

## 1. Introduction

To cope with global environmental issues, high-performance buildings that provide both comfort and less environmental impacts are increasingly demanded. Hence, building design requires careful considerations for energy efficiency as well as thermal comfort. In recent years, many of design pro-

jects for large facilities are using several designers with different specializations and from different subcontracting companies. Therefore, in order to realize high-performance buildings, a collaborative design process becomes an important issue to gather professional knowledge and skills. In the design process, stakeholders such as owners, designers and engineers are expected to consider both usability and thermal comfort for each space in the building.

Meanwhile, modelling and simulation tools for architectural design have been developing to cope with the inherent unpredictability of complex design process. For instance, visualizing and simulating physical phenomena at the design stage have been enabled by using environmental simulation methods (such as Computational Fluid Dynamics (CFD)) and visual simulation methods (such as Virtual Reality (VR)). Decision-making for design, which previously had to rely only on designers' experience and specifications from product manuals, can now be accurately and objectively ensured using simulation tools (Altabtabai and Yan, 2015). Furthermore, fast calculations allows timely feedback on new design alternatives for a project, rather than relying on simulation results acquired from other design projects. However, the effect of having timely feedbacks of design alternatives on the quality of design has not been discussed yet (Chung and Malone-Lee, 2010).

CFD simulation is used to predict and assess building’s thermal environment in the design phase. By using CFD tools, stakeholders can visually and numerically evaluate the thermal comfort in a target space at the design stage. However, there are some issues that prevents the efficient use of CFD simulations during building design. The first problem is the lengthy processing time. Therefore designers would not be able to perform various experimentations by changing CFD parameters. Second problem is related to CFD post-processing. Currently, numerical data generated by CFD simulation is visualized in a 3D model on a PC monitor. As this 3D data is projected to a 2D plane of a monitor, it would be difficult to grasp the visual data and its spatial relationships. Third problem is the difficulty to operate CFD tools, hence, many researchers or practitioners subcontract the CFD simulation tasks to consultants or specialists. This usually takes long time in the design process and does not allow for interactive responses. To solve these problems, combining CFD and VR which generates a 3D space in the virtual environment of a computer is expected (Shahnawaz et al, 1999; Onoue et al, 2010; Fukuda et al, 2015). However, existing methods required both extensive hardware and specialized software, and available systems still do not allow feedbacks on the new design alternatives because of low interoperability with design tools.

Therefore, this study proposed a new simulation tools for architectural design which accelerates CFD using GPGPU (General-Purpose computing

on Graphics Processing Units) and displays the simulation results in an immersive VR environment. The developed system supports different visualization techniques (such as streamline or arrows) and also supports user defined value range settings for visualizing simulation results formatting data. Additionally, this system allows users to see the results of the simulation instantly and compare results when parameters of the CFD simulation model are changed. Using this system, stakeholders can understand the results of the CFD simulation more intuitively, which leads to more accurate design feedbacks.

## 2. Previous studies

CFD enables analysing thermal distribution and air flow to be used for architectural thermal environment design (Nielsen, 2004; Den Hartog et al, 2010). Researchers and practitioners evaluate building performance with CFD from the design stage to solve problems and reach advanced designs (Chung and Malone-Lee, 2010; Kaijima et al, 2013). Additionally, the evaluation with CFD makes it possible to share design evaluation with stakeholders who are non-professionals and also to promote interactive responses in the process.

Due to the fact that CFD results are huge numerical data sets, it is necessary to transform numerical data into visual representations as post-processing. Present pervasive visualization software applications target engineers who are familiar with CFD, hence it would be very difficult for non-professional engineers to operate the software and evaluate CFD results. Therefore, displaying CFD results using models created in Building Information Modelling (BIM) or 3D-CAD, in a VR environment, which is a high interactivity method, have been presented (Bahar et al, 2013; Bille et al, 2014; Matthias and Veruna, 2015). Some projects visualized CFD results in the VR environment where architectural design is represented in order to understand the design better in a more sophisticated design environment. For example, Fukuda et al. (2015) proposed a system which integrates commercial CFD and VR software applications to display CFD result in a VR. However, there were problems in presenting thermal simulation results in the VR. For example, the vector data converted from CFD to the VR could not keep arrow information presenting wind-flow and colour information presenting temperature distribution.

Additionally, previous research projects did not provide direct feedback from VR to CFD. Consequently, users have to repeatedly operate CFD software to change parameters to create alternative design proposals after observing visualization data. For that, subcontracting work to external consultants or specialists may be required which imposes delay for making a next

design plan. Consequently, in order to promote more efficient interactive design process, it is necessarily to change CFD parameter directly and make alternative suggestion in the VR where CFD result is presented. Therefore, this research presents an interactive visualization method by making design parameter modifiable to promote design feedback in the VR.

## 3. Proposed method

The proposed system visualizes not only the CFD analysis results but also the detailed architectural environment taken from a 3D BIM tool which is integrated with the VR. Hence, the users can observe architectural and thermal environment designs while performing the walkthrough or the aerial viewing in the virtual environment (for example by using a Head Mounted Display (HMD)). Additionally, in the design study process, CFD parameters can be changed and different results can be visualized for stakeholders to compare design options. For that, values such as the physical properties of building components or settings for the air conditioning system can be changed in the User Interface (UI) of the proposed system. The result of the changes is fed back to calculation processes, and is visualized to enable design comparisons. Using this system, the designer and owner can better understand the effect of applying changes to the architectural design on the thermal environment. It is expected that using this system world eventually lead to better design selection.

The developed system consists of four main processes; mesh generation and boundary condition definition, calculation, visualization, and design study. For that, a 3D model of the target building is created using a BIM application (such as Autodesk Revit). Figure 1 shows an overview of the system. Users can change parameters of components if necessary, and the system calculates and visualizes accordingly. Through this process, users can visually compare several design plans.

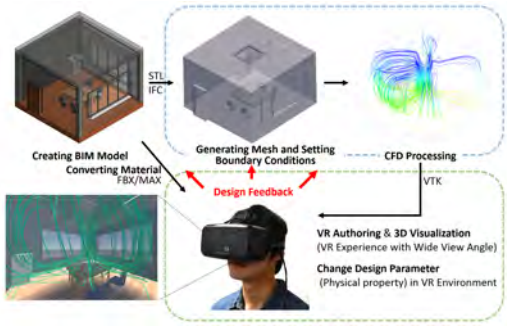



*Figure 1. Overview of the system process flow.*

### 3.1. MESH GENERATION AND BOUNDING CONDITION DEFINITION

In this step, given STL (Standard Triangulated Language) format files as the geometry and Industry Foundation Classes (IFC) format and Visualization Tool Kit (VTK) format files as the property, a mesh generation utility (i.e., snappyHexMesh ver.2.2) semi-automatically generate the unstructured grid mesh for the CFD. The heat transmission ratios of architectural elements and openings (which is one of boundary condition parameters) are extracted from the IFC file generated by the BIM software and are used as an input.

Next, the user settings for Heating, Ventilating and Air-conditioning (HVAC) are manually determined. The boundary conditions of inlet and outlet from air conditioner and ventilation are input in VTK format. Air-flow of air conditioner and ventilation is set based on Box method (Nielsen, 2004). The voxel meshes which cover HVAC machine geometry are generated with each mesh having thermal property recorded on VTK format.

### 3.2. CFD CALCULATION

CFD Calculation is executed using OpenFOAM (an open-source CFD toolbox. ver.2.2) to solve fluid flow (Goong et al., 2014). OpenFOAM is distributed under the General Public License (GPL), hence, it is possible to add original solvers and boundary conditions and output result data under any format. Additionally, GPGPU which uses high-performance multi-core graphics processing units to accelerate a wide range of applications together with improving CPU performance is proposed to be used in our system. GPGPU also enhances acceleration of CFD processing. This research also utilizes GPU solver which is accessed by Symscape in OpenFOAM and performs computations on a GPU. The CFD analysis was made as steady state and exports only convergence result. In order to accelerate data throughput, output data is generated in binary as VTK format file.

### 3.3. VISUALIZATION OF THE RESULT

In the visualization process, CFD numerical result' data are translated into visual representations in a VR environment. In this research, Unity 3D (ver.5.2), which is one of the game engine authored VR, is utilized. CFD results and the building model are inputs into Unity 3D and are visualized in the VR where architectural design are presented. Building model is created in a BIM application (i.e., Revit Architecture) and converted to 3ds format using a graphical solution software (3ds Max) and are exported into Unity 3D.

Based on the CFD results (which are imported using VTK file format) visualization process is carried out using a script in Unity 3D. The Unity script Activiz (ver.5.8) is employed which is C# library of VTK and enables visualization of CFD results. Filter function of pipeline flow in the VTK makes it possible to define data range for visualization and to implement algorithms. Finally, the modelled data is displayed by the renderer of the Unity engine.

In this research, to represent thermal distribution, planes with colour-mapping and isosurfaces, which are suitable for representing three-dimensional thermal distribution, are used. To express air characteristic, arrows are used where wind direction is represented by the direction of arrows and wind magnitude with their length. GUI which consists of a slid bar with mouse click operation enables users to operate visualization environment interactively by changing visualization method and the data range for the visualization. Mouse operation also enables users to freely perform walkthrough in the VR environment. VR image is displayed in 2D monitor and also in HMD which provides stereoscopic display. An immersive environment achieved by HMD makes users understand architectural design, spatial constitute, and thermal distribution more easily. Therefore, users can use results in an accelerated manner for comparison and selection between several design plans.

### 3.4. DESIGN FEEDBACK

This process enables comparing CFD results. The user analyses the CFD results that are visualized in a VR environment together with architectural features, and discusses changing the configuration of both architectural component and the HVAC. The user then changes parameters and the system performs new simulation and visualization, accordingly. The user can compare scenarios by switching between visualization outputs.

The user can change settings either by selecting from predefined setup values provided by the system (that can be accessed using drop-down menus), or can change CFD parameters. Predefined setup results are precalculated by the system and can be readily available to the user when selecting. In contrast, changing individual parameters requires processing time for visualization.

Consequently, by repeatedly changing settings, various visualizations can be achieved, analysed and compared by stakeholders in a meeting. This would result in identifying better design alternatives that leads to the improvement of building performance.

## 4. System verification

### 4.1. METHODOLOGY

To verify the applicability of the proposed system, a verification experiment was conducted for an existing room. The research room M3-403 of Osaka University Suita Campus was selected for the experiment. By using the proposed system, the thermal environment of the room M3-403 was visualized and analysed for the improvement. BIM model of this room, was created using Revit Architecture 2016. The authors used a PC with 3.5 GHz of CPU (Intel® Core™ i7-5930K Processor), 32GB of RAM, 4GB of VRAM (NVIDIA Quadro K4200), running Microsoft Windows 10 64 bit.

Table 1 shows a summary of CFD parameters. The internal mesh is an unstructured grid mesh. The mesh near HVAC is voxel mesh which is imported as VTK file format.

TABLE 1. Summary of CFD analysis condition.

| **CFD code** | OpenFOAM |
|---|---|
| **Turbulence model** | Standard k-ε model |
| **Finite deference scheme** | First Order Upwind |
| **Algorithm** | Steady State |
| **Meshes** | 25,360 |

In this case study, the radiation heat transfer was not considered. However, an overall heat transfer coefficient was used. The outdoor reference temperature of walls, ceiling, windows, and the door was set to 35 degree and indoor reference temperature was set to 25 degree, and heat transfer flux from outside was set to a fixed value. In order to simplify the heat transfer of windows, the average of heat transfer rates for constituent elements was selected. The internal heat generation was not considered.

HVAC is selected as a 4-directional packaged air conditioner and a ceiling embedded cassette ventilation. The air-flow rate of the air conditioner and the temperature of each four inlets were configured with identical values. Air flow rate of an outlet was set as the total value of inlets. Regarding turbulent statistic value, turbulence intensity was set at 10% and turbulence dissipation rate $\varepsilon$ is calculated using equation (1).

$$\varepsilon = \{(0.09)^{3/4} \times k^{3/2}\} / l \quad (1)$$

Where $k$ is the turbulence intensity and, $l$ is the representative length.

Air-flow rate of ventilation's outlet was configured with the same value as of the inlet. Turbulent statistics values were set equal to those of the air-

conditioner. Table 2 and 3 show bounding conditions for the current setup of the room.

TABLE 2. Bounding Condition (Architectural Component).

| | Interior wall | Exterior wall | Ceiling | Floor | Door | Window |
|---|---|---|---|---|---|---|
| **Heat transmission coefficient [W/(m$^2$·K)]** | 0.55 | 1.38 | 0.97 | 1.27 | 3.0 | 5.65 |

TABLE 3. Bounding Condition (HVAC).

| | Air-conditioner | | Ventilation | |
|---|---|---|---|---|
| | Supply | Return | Supply | Exhaust |
| **Flow rate [m$^3$/min]** | 14 | 14 | 5.8 | 5.8 |
| **Area [m$^2$]** | 0.03×4 | 0.15 | 0.05 | 0.05 |
| **Velocity [m/s]** | 1.9 | 1.5 | 1.3 | 1.3 |
| **Turbulence intensity [%]** | 10 | 10 | 10 | 10 |
| **Turbulent length [m]** | 0.01 | 0.01 | 0.01 | 0.01 |
| **Temperature [°C]** | 20 | - | - | - |
| **Supply angle [°]** | 25 | - | 45 | 45 |

After setting up the parameters for the current setup of the room (Case 1), the system visualized the temperature distribution and the airflow. In order to compare design options, the user was provided with options for new selectable settings. The system then simulated temperature distribution and airflow using new settings and visualized for design comparison. Table 4 shows predefined selectable configuration options for windows and HVAC. Different types of windows and different values for air-flow rate and supply angle of the air-conditioner were provided for selection. The values of heat transfer coefficient for windows were provided by IBEC (Institutes for Building Environment and Energy Conservation) and parameters of air-conditioner were defined using datasheets provided by the manufacture.

TABLE 4. Selectable Parameters.

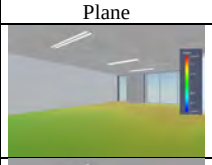
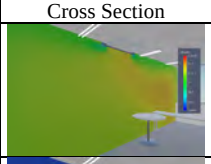
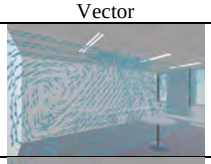
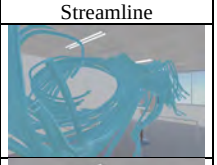
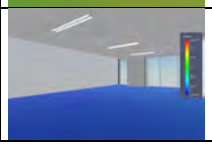
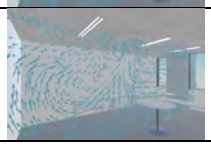
| | | Selectable options | Value |
|---|---|---|---|
| **Windows component [W/(m$^2$·K)]** | | Metal sash – Single glass | 6.5 |
| | | Metal sash – Double glass | 4.65 |
| | | Resinous sash – Double glass | 3.49 |
| **HVAC** | **Flow rate [m$^3$/min]** | Rapid | 27 |
| | | Strong | 23 |
| | | Weak | 18 |
| | | Silent | 14 |
| | **Supply angle [°]** | Highest | 25 |
| | | High | 37 |
| | | Low | 49 |
| | | Lowest | 60 |

The design goal was to achieve an even indoor temperature in the room. For that, an alternative setting to the current one (i.e., Case 1) was selected by the user and temperature distribution and airflow were visualized by the system, accordingly (Case 2). For Case 2, the supply angle of the air-conditioner was changed to the lowest value (i.e., 60°).

### 4.2 RESULTS AND DISCUSSION

The results are presented with colour-mapping planes, vector of arrows and streamlines in Table 5.

TABLE 5. Comparison between Case 1 and Case 2.

| | Plane | Cross Section | Vector | Streamline |
|---|---|---|---|---|
| Case1 |  |  |  |  |
| Case2 |  |  |  |  |

Comparing the visualization results enables us to confirm the changes in spatial heat distribution in the room. When the flow direction is horizontal, the air did not circulate entirely (Case 1) and caused the inconsistency of temperature. When it below in downward direction, the air circulated and eliminated the air stagnation (Case 2). Visualizing thermal properties in a VR environment enabled user to understand thermal specification more easily. However, this tool requires the use of mouse and keyboard operation while wearing an HMD (such as Oculus Rift DK2), hence, it lacks adequate user-friendly features for operation.

Considering the calculation time, in this case study, the calculation of a case took about 25 minutes. Hence, it is possible to discuss several design study in a meeting besides the cases which is calculated in advance. Additionally, when considering a thermal environment with many office equipment or machines that generate large amount of heat, this tool cannot be efficiently used.

## 5. Conclusions and future work

This study focused on developing a design feedback tool that facilitates interactive discussions between stakeholders to improve building performance.

The proposed system, which combines CFD and VR, enabled interactive visualization and design examination. Through the actual case study, the developed system proved to be able to visualize thermal environment and to compare several design plans efficiently. Additionally, the total calculation time was relatively short enough to allow recalculation for design feedback in a design meeting. Additionally, the proposed system enabled visualizing information in relationship with the actual architectural design, space configuration and thermal environment, and provided efficient design feedbacks.

However, this system cannot consider acquisition of solar radiation heat from the openings, hence, this system has limitations to simulate diverse environments. It is necessary to adapt various conditions. Additionally, to enhance design discussions, it also necessary to reduce the calculation time.

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# IMMERSIVE VISUALISATION OF BUILDING INFORMATION MODELS

*Usage and future possibilities during design and construction*

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**Abstract.** The design process of a building often involves many different actors and people with different experiences, level of knowledge and ability to interpret information. The most common information media in these processes are 2D-drawings, documents and 3D images of design. These media can be difficult to interpret and understand and could cause communication difficulties and design errors. However, in this context, Building Information Modelling (BIM) and Virtual Reality (VR) have been shown to offer an efficient communication platform. In this paper we present and evaluate a portable immersive visualisation system that uses the BIMs directly from the design tools. The system is validated in a real construction project, where the different disciplines in the design process used the system. The result was collected through interviews and observation during usage of the system. All the participants expressed that this type of visual interface helped them to get another level of understanding and perception of space, which lead to better decision-making process and resolving of design issues.

**Keywords.** Building information modelling; virtual reality; head mounted display; Oculus Rift.

## 1. Introduction

During the design process of a building the outcome depends on the involved people's interpretations, perceptions, and prejudices (Colin and Hughes, 2007). As each design team member will have individual perceptions of the design problem and ideas of how to solve it, it is important that

all the involved actors understand, participate, communicate, and collaborate with each other to obtain a high quality outcome of the design process. Communication difficulties mainly occur as a result of the different cultures, and because there is insufficient collaboration and information sharing during the process. The most common problem is that the information is not presented in such a way that people can understand it. In this context, real-time visualisions and Virtual Reality (VR) have been shown to offer an efficient communication platform (Bouchlaghem et al, 2005; Roupé, 2013). With the ability to navigate freely through 3D scenes from a first-person perspective, it is possible to present and communicate ideas regarding future buildings in a way that facilitates understanding among all involved parties, despite their background or professional expertise. While the use of this technology has been naturally limited in the past due to lack of available 3D data from the design process, the concept of Building Information Models (BIM) has opened up new possibilities. As the required 3D data can be extracted from the architect's own design-environment, the use of real-time visualisations has become more accessible in practice (Johansson and Roupé, 2012; Johansson et al, 2015).

To further enhance user experience it is commonly advocated to take advantage of immersive display technologies. Although real-time visualisations have been shown to be useful per se, stereoscopy, large screen and wide field of view all provide additional benefits (Shiratuddin et al, 2004; Castronovo et al, 2013). Nevertheless, when considering the integration and use of immersive VR within the actual design process, the current adaptation still suffers from a number of limitations such as high cost and limited accessibility (e.g. CAVEs or Panoramas are still expensive and are restrict to a specific room or location) as well as limited BIM support (e.g. BIMs are typical too large and complex to be visualised in real-time without further optimisation and preparation).

However, in a recent study, Johansson et al (2014) presented a system that allows immersive VR to become a natural and integrated part of the design process. It was realised through the use of the Oculus Rift Head Mounted Display (HMD) - a comparably low cost device that supports a large field of view, stereoscopic viewing and physically rotation - together with a rendering engine specifically designed to manage large and complex BIMs in real-time. With the system implemented as a plug-in in Autodesk Revit and connected to a high-end laptop, it serves as a portable system for immersive BIM visualisation.

In this paper we focus on how this system has been used and integrated into the design process in a real-life project. We will present results from observations during usages of the VR-system together with semi-structured in-

terviews with different clients and design team members that has used the VR-system in the case project. The interviews addressed the current usage and future possible usage of the VR-system in construction project and benefits or challenges connected to this type of tool in the design process.

## 2. Method

This paper is based on a qualitative study where semi-structured interviews and observation during usages of the VR-system has been done. Participants of the study were people involved in the case study project of a new office building. In total 9 interviews has been conducted. The participants had the following work titles in the case project; Property Developer (Construction company), Property Owner, Facility Manager, Architect, VDC-coordinator, Structural Engineer, Site manager, Assembling supervisor, Steel Workers.

### 2.1. CASE PROJECT – THE OFFICE BUILDING

The new office building will have an office area of 25 000 $m^2$ and will provide about 1000 workplaces. The office building is mainly constructed from pre-fabricated concrete with a steel structure. The project delivery method is design-build and the project time plan is scheduled to year 2013-2016. The interviews and usage of the VR-system were conducted during detail design and the construction and assembling of the pre-fabricated concrete and the steel structure. Selling price was 868 million SEK.

### 2.2. THE VR-SYSTEM

As described in (Johansson et. al, 2014), the VR-system is based on the Oculus Rift HMD DK2 and a real-time viewer application implemented as a plug-in in Autodesk Revit. For all the visualisation sessions within the scope of this paper, the VR-system was connected to a laptop equipped with an Intel Core i7-4860HQ CPU and an Nvidia GeForce GTX 980M GPU. To allow for a wide range of users, the system features a very simple navigation interface by means of a so-called PowerPoint remote control. As illustrated in Figure 1, a user can move forward or back by pressing the corresponding buttons on the remote control, with the direction of movement being decided by the user's orientation of the head, see Figure 1.

During the interviews, the BIMs from the real new office building were used. Two different visualisation sessions were considered according to the background of the interviewee – one featuring primarily the architectural model (Figure 2, top), and one featuring all the different disciplines (Figure 2, bottom). In the complete model, eleven BIMs from different disciplines were visualised together, and color-coded according to the different con-

struction worker trades. The VR-system supported filtering of these models, e.g. switching on and off the different models for the different disciplines.




*Figure 1. The navigation user interface.*

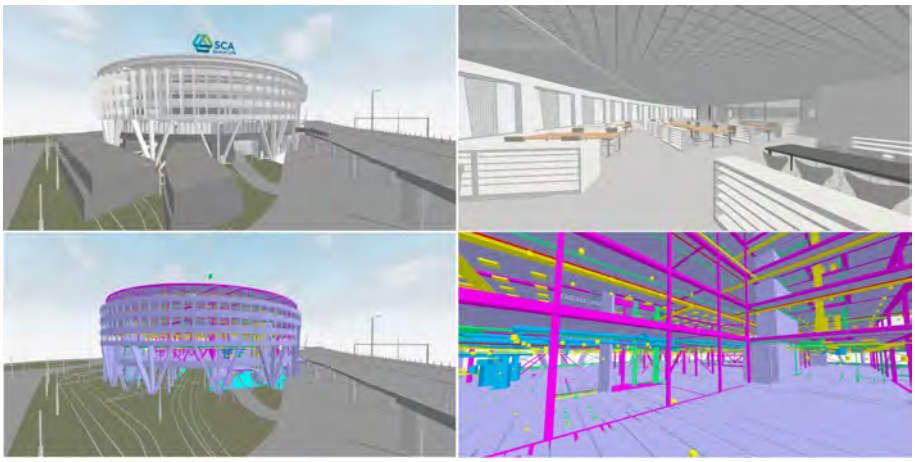


*Figure 2. The upper model; the office building from the architectural model. The lower model; the color-coded model with all the disciplines.*

Both visualisation sessions were extracted directly from Revit using the viewer plug-in. Except for assigning a specific colour to each sub-model (i.e. discipline), no other preparation or optimisation of the models were done. The architectural model contained 13,377 objects and 3,358,715 triangles. The complete model contained 83,032 objects and 23,470,848 triangles.

The participants used the VR-system to explore the BIM for approximately ten minutes before the questions were asked. This was done to provide the user with the immediate experience, allowing a better insight in answering the interview questions. Often the participants navigated to the place in the model where they currently worked e.g. in design or construction.

## 3. Results

Both the observations and the interviews showed that the participants could easily navigate in the model using the presented VR-system. Almost directly all participants explored and navigated freely in the model. However, the structural engineer mentioned that shortcuts or jump to specific viewpoints are necessary; otherwise navigation with the VR-system will take too much time. Most of the interviewees shared this opinion and mentioned that it would be good to navigate fast to different parts of the building, instead of walking through the "whole" building to come the specific viewpoint.

Furthermore, all the participants expressed that this type of visual interface helped them to get a better understanding, not only in terms of specific details, but also for the project as a whole. Site-manger, VDC-coordinator, architect, facility manager mentioned that it gave them a better understanding of space and mentioned that this type of visual interface makes you experience the virtual building in 1:1 scale. Furthermore, they mention that this type of visual interface gives them new possibilities to understand, share, experience and provides a better decision-making process.

### 3.1. SUPPORTING UNDERSTANDING AND PERCEPTION OF SPACE

In this context, the ***architect*** expressed that this type of visualisation can be a good way to communicate and share designs ideas to their co-workers and clients. *"It can be a new approach to design a space and communicate with colleagues, to get the feeling of a room, heights and other details that simulate the actual reality. It is a very good tool for us when we work, like just checking out how the rooms will look, and to try different ideas with our co-workers*". Furthermore, the architect mentioned that the visualisation could also support the decision-making when considering a certain solution. In the case project there had been major discussions regarding the stairs in the atrium e.g. entrance lobby, an issue that would have been easier to solve if the VR-system had been available. Additionally, the architect expressed that the HMD visualisation gives *"another level of perception considering the natural scale 1:1 combined with the level of realism. This can help to understand how big or small a room needs to be, how other objects in that room fits. This level of perception is hard to experience in other type of visualisations."* An annotation from his experience was that the architect bought a HMD-system after his interview, to make it possible to work in the above-described way.

From the perspective of a ***property developer*** and ***property owner***, the communication point is mainly orientated towards the client, which may be a tenant or an investor. Both the property developer and property owner men-

tioned that many times the client or tenant may have limited understanding of how a future acquisition or rental may look, judging only from 2D drawings and even 3D representations. The property developer argued that the VR-system can be very helpful in this context. Using the tool for client visualisations can be a complement to the pictures and drawings, and perhaps a more powerful experience. According to the property developer; "*I think this tool can help clients get in love with the project, and if they get to that step, it helps a lot*."

The property developer and the property owner further explained that the perception and the capability to understand space is one of the most important capabilities with the VR-system.

The ***facility managers*** work assignment in the project was to communicate both with the contractor, but also internally with own employees. As the facility manager started to navigate only for a short distance in the model, it was explained that the HMD visualisation contributes with a better understanding. Furthermore, experiencing the model at a scale 1:1 was explained as beneficial compared to 2D-drawings. More specifically she used the HMD visualisation for spatial function analyses of the building design. To be exact she mentions: "*the tool makes it easier to see how many doors are needed to be opened before reaching a specific area. Also, it can be helpful to be aware how to find different locations or objects inside the building. For instance, finding the right suitable elevator, where the HMD visualisation may help to simulate the reality to a higher extent*". Finally, the facility manager considered that the tool can be part of the decision-making process, where different interior set-ups with equipment, as part of the collaboration between the lab teams and the architects, could be judged. Using it early in this process, the amount of drawings showing many different solutions could be decreased and the BIM together with the VR-system could be the carrier of information.

The ***site manager*** sees the tool useful within the design phase in helping to understand details and to support the decision-making when considering a certain solution. The tool is further explained to give another level of understanding and perception of space and that this is hard to experience in other type of visualisations. According to the site manager, "*this is just the beginning, in a couple of years the HMD visualisation will be a useful accessory, where one may have them on site and just put them on to see something which is not clear*."

### 3.2. SUPPORTING DECISION-MAKING AND RESOLVING OF DESIGN ISSUES

In the case project, the VR-system was introduced during a design review meeting and was immediately used in an actual decision-making process concerning the design of the solar shading system. The first issue was regarding aesthetics, where the architect argued that the solar shading panels were too large and that they would block the view too much and be "perceived as a peaked cap when a personnel sitting inside the office", see figure 3. The second issue concerned whether or not the window cleaner could stand and walk on the solar shading panels while cleaning the windows, and what dimensions and design of the panels that would be required.

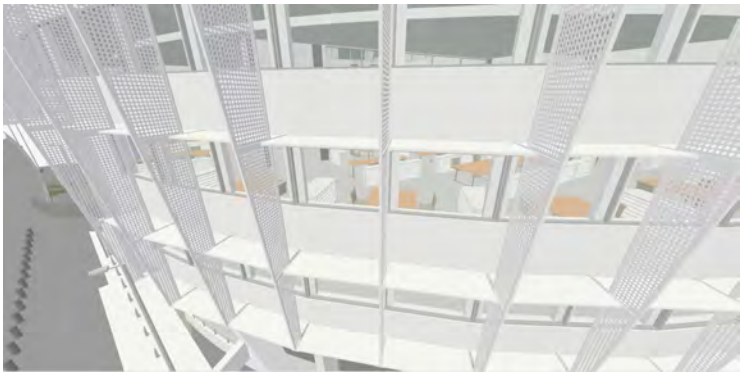


*Figure 3. By experiencing the solar shading system in VR-system, the design team could come to consensus and resolved the design issue.*

By using the VR-system the different participants from the design team explored the BIM and investigated how the solar shading panels would be experienced in its natural 1:1 scale. All in the design team were amazed how the HMD visualisation gives another level of understanding and perception of space and that this is hard to experience in other type of visualisations. When the site manager explored and tested the window cleaning possibility, e.g. of standing on the solar shading panels and walking between the vertical panels and the building façade, he actually pulled in his stomach when passing the vertical panel. This type of behaviour shows that he was fully immersed in his experience of the virtual environment.

The end result from the HMD visualisation session was that the design issues regarding the solar shading panels were solved e.g. they decided that the solar shading panels did not block the view, as the architect had earlier stressed and argued. Based on the virtual test, the design team also agreed that the window cleaning procedure would be functional in practise.

During the interview later, the site manager explained that the use of the BIM and HMD visualisation of the model at a scale 1:1 creates a better understanding regarding design issue, which could shorten time to decision. Decisions that involve large costs and where project participants need to have a wider understanding, was presented as problematic in the design decision-making process by the site manager. The site manager mentioned that *if we would have had the HMD visualisation earlier, we could have saved numerous hours and money*.

### 3.3. SUPPORTING CONSTRUCTION PLANNING AND ASSEMBLING

The site manager explained the VR-system as providing a more natural way of looking at things compared to on screen visualisations, and that it can complement the working environment; both in design phase as in construction, to easier understand how parts should be designed and then further understand how to actually assemble them. This was also mentioned by the ***structural engineer***, *stating that*: "*the site manager can see the structure in scale 1:1 and then notice problems or solutions regarding how to produce or assemble"*. Furthermore, when using the structural model in combination with only the interior ceiling (architect model) turned on, the ***supervisor for assembling*** came with *new insights* during his exploring in the HMD. By viewing these two disciplines in parallel, it was easier to understand where the joints in the concrete floor would end up being visible. He also mentioned that if the workers can see the model early in the project, their knowledge can affect the structural design in a good way, as to fit the assemble work better. Several ***steel workers*** in the case project, who tried and used the VR-system, highlighted this as well. Also, when trying the VR-system it was observed that they directly navigated to the specific places where they were currently doing work (i.e. at the real construction site) and started discussion about the structural model with steel parts. The VR-system was explained to create a deeper understanding on how the assembly work from different disciplines affect each other. In this context, the color coding and the ability to hide/show other disciplines was highlighted as an advantage in that each discipline could focus on their details and responsibilities, but also give them an overview of others responsibilities. Regarding integration, both steel workers and the supervisor for assembling stressed that the VR-system can be something natural to use daily before entering the construction site. The site manager, VDC-coordinator, structural engineer, also mentioned this type of daily use of the VR-system.

### 3.4. INTEGRATION ASPECTS OF A NEW TOOL IN PRACTICE

The structural engineer, site manager, as well as the VDC-coordinator all mentioned that the most benefit with the VR-system is for people with less knowledge in reading and understanding of construction drawings, and that for people with much experience in using 2D drawings and 3D models, the tool is not really that big of a help. The VDC-coordinator further explained that for clients in the collaboration with architects, or during assembly planning for workers on the construction site, the VR-system could support these processes. For example, before the assembly of some elements e.g. columns, beams, each worker could use the VR-system to enter the BIM and see how it is suppose to be assembled. "*Considering that category of people, the HMD visualizing is a powerful experience that helps to better understand the 3D model. To be in the model at a scale 1:1, it is a real world, a total new way to experience things, you can't misunderstand*."

Another issue that was mentioned by the architect and the facility manager was the willingness to share the design. The architect mentioned that in the discussion with the client it is better to have a higher level of realism, but with in-house design work, high realism is not that important. The architect pointed out that it is important to consider how much you show. It is depending on the design stage, because the end product may look different, leading to different expectations.

According to the facility manager, the employees have not been involved in all details with the reason that the facility steering group wants to be more ready. When reaching that stage, the VR-system was explained as a possibility to use. Considering this tool, "*I think it is good to use the VR-system in communications, but at the same time as you are changing things, people may be upset if it is not the correct version*." Not using the tool too early in the feasibility phase is due to the level of realism. "*The model is so real when using the VR-system. The tool gives you a real impression, e.g. how the desks are positioned. This is why we need to be a bit wise to not use the tool too early.*"

## 4. Conclusions and Discussion

As the result section shows, all the participants expressed that this type of visual interface helped them to get a better understanding of space and mentioned that this type of visual interface makes you experience the virtual building in "1:1 scale". Everyone in the design team was amazed how the HMD visualisation gave another level of understanding and perception of space and that this is hard to experience in other type of visualisations. Additionally, they mention that this will give new possibilities to better under-

standing and perception of the designed space, which will support a better decision-making and resolving of design issues. The result from the case project also showed that the VR-system could support construction and assembly planning and to give construction workers better understanding of how the structure and the elements are assembled together, something that was expressed as much aided by the ability to show/hide different disciplines.

An integration issue surrounding BIM visualisation using the presented VR-system was the willingness to share the design. Both the architect and the facility manager mentioned that they had fear and limited willingness to share the design with other actors/receivers in the process. Both were afraid that the end product may not look the same and will lead to miss-expectations by the end-user. The facility manager also mentioned that she was afraid of getting questions, why they will not get a certain type of furniture etc. The property owner and the property developer, on the other hand, pointed out this as one of the benefits with the VR-system, where the possibility to try different designs with furniture, colours etc. together with the end-user. This will support the decision-making when considering a certain solution for the client or tenant.

It could be concluded that the VR-system can facilitate better shared perceptions, interpretation and understanding of the design problem in the design team. Additionally, this will facilitate a better communication, which leads to better decision-making process and resolving of design issues.

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# UNMEDIATED CULTURAL HERITAGE VIA HYVE-3D

*Collecting individual and collective narratives with 3D sketching*

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**Abstract.** Cultural heritage is traditionally mediated through institutional bodies that are authorised to broadcast heritage information, whereas new media technologies such as social media platforms continue to enforce individual storytelling and information sharing. Therefore GLAMs (Galleries, Libraries, Archives and Museums) have to cope with a shift of public interest from their services to more accessible, entertaining and democratic engagements available as 'living' media. Unmediated cultural heritage is the paramount aim of this work and, in a theoretical sense, a utopia for generation of authenticity or meaning-making. Within the realm of digital heritage, this study explores the nature of engagement with cultural heritage using an innovative means. In this phase of the research, a photogrammetric model of Kashgar's narrow alleys is deployed in a system, called Hybrid Virtual Environment 3D (Hyve-3D). Via its 3D cursor technology, the concept of unmediated cultural heritage is unfolded through active participation, collaboration and interaction. Thus, in the context of heritage, this research explores a hitherto undocumented frontier of Hyve-3D designated to immersive collaborative 3D sketching.

**Keywords.** Digital heritage; Hyve-3D; photogrammetry; authenticity; 3D sketching.

## 1. Introduction

The proponents of unmediated cultural heritage in GLAMs (Galleries, Libraries, Archives and Museums) co-exist with the contemporary advocates

of social inclusion and multiculturalism in the heritage sector (Hall, 1999; Message, 2009a, 2009b; Waterton, 2010). This may be a consequence of decreasing focus on the materiality of heritage canonised since the Renaissance, where the aestheticisation of the past was integral to the appreciation of ruins (Watson and Waterton, 2010).

The idealist guise of heritage has long been attributed to privileged strata and legitimised by institutionalised selection and display processes. In Singer's (1998) words, "the repression of error [i.e. 'glitch', as we refer to in our research] has served as the fulcrum of aesthetic autonomy whenever autonomy has been the standard of aesthetic perfection, and for good reason."

The ambiguous definition of the term 'artefact' as a human-made object, exposes the scope of this paper in the heritage realm. An artefact is seen as an 'error' (i.e. 'glitch') when the object is de-contextualised. However the decentred object creates its own narrative to guide understanding of its value beyond its materiality. In the heritage discourse, this meaning-making process still sits between the representational and the performative-subjectivist approaches (Smith, 2006). The objective is "to explore the nature of the engagement itself; the ragged line between what is represented and what is understood or otherwise experienced as put forward by Watson and Waterton (2010).

Heritage making and heritage narratives have recently been taking different forms, inviting subaltern perspectives such as unmediated cultural heritage. In this context, we see a potential elucidation of its facets through (computer generated) glitches that would not only be a thought provoking item for human-human relations but also initiate a dialogue between the human and the machine that generates them both by malfunction or design. In this respect, this research is an extension of previous work (Norman, 2002; Schnabel et al, 2004; Tang and Gero, 2001) in the heritage context.

This paper alludes to the digital heritage project of 'Augmenting Kashgar' (Schnabel and Aydin, 2015), where the aesthetics of glitches and their contextualisation in cultural heritage making are discussed both theoretically (Aydin and Schnabel, 2016) and practically with comparison to other cases concerned with the 'unexpected-ness' of objects (Aydin et al, 2016).

Here we add a novel facet to the research, relating it to the representational ecosystem as discussed by Dorta and Kinayoglu (2014), by deploying a system called Hybrid Virtual Environment 3D (Hyve-3D) (Dorta et al, 2014; 2016). Hyve-3D was originally developed as a co-design tool and is presented in this research context for the first time as an unmediated cultural heritage environment to present aspects of Kashgar's old town.

In relation to unmediated cultural heritage, we argue that users (in a non-immersive version of the system running on a laptop) may reinstate their

interpretations of Kashgar's heritage with their own models of the ancient town. In this paper we focus on the progress of a spontaneous reconstruction of an unmediated heritage-making through co-reconstruction links as well as individual and collective heritage narratives potentiated and facilitated by the features and functionalities of Hyve-3D.

## 2. Project "Augmenting Kashgar"

This is a design research project in the field of digital heritage, which ties together architecture, history, virtual reality and game design. The project is built upon the concept of 'The Museum of Gamers' (Aydin and Schnabel, 2016) where three key pleasures of cyber-space are investigated; immersion, agency and transformation (Murray, 1998).

While the use of Hyve-3D for co-design aspects has been evaluated in another publication (Dorta et al, 2016), this paper investigates the direct link that sketching with its 3D cursors provides between users and meaningful experiences in the making of cultural heritage.

### 2.1. PHOTOGRAMETRIC MODELLING

The availability of open source/access applications dedicated to modelling encourages laypersons' engagement in an operation, which historically has been computationally expensive or complex. A free *Autodesk* App, called *Momento*, allows easy generation of 3D digital models by 'scanning' the operator's vicinity.

Kashgar's maze-like street network is first modelled in *Autodesk Recap* (Figure 1). Resulting geometries may create 'holes' or glitches where the algorithm confronts a hard task, e.g. discrepancy in overlapping photos uploaded. This kind of error can be alleviated by *Memento's* patching function that directly optimizes an average piece of mesh based on neighbouring polygons around the hole. Other functions of *Memento* include basic manipulation of the geometry, e.g. decimating the number of polygons or smoothing, pushing and pulling parts of the mesh.

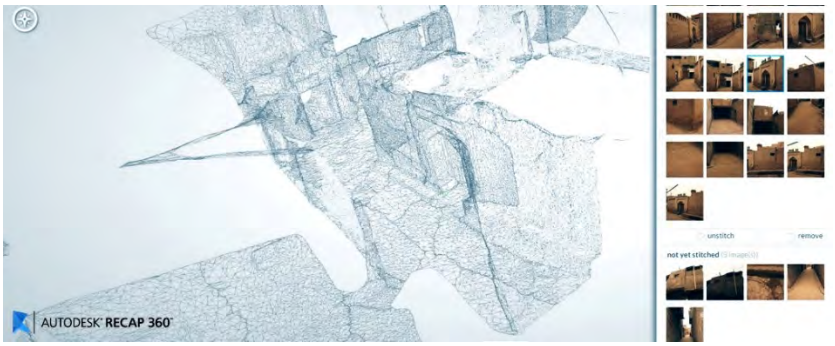



*Figure 1. Screenshot of a piece of raw Kashgar model in Autodesk Recap.*

During all geometrical operations in *Recap* and *Memento*, the texture is automatically mapped on the surface. However, unless exported as FBX, a proprietary format owned by *Autodesk*, other export options, e.g. OBJ may cause detachment of textures in other modelling software (Figure 2). Nevertheless OBJ files were successfully used importing Kashgar's photogrammetric models into Hyve-3D.

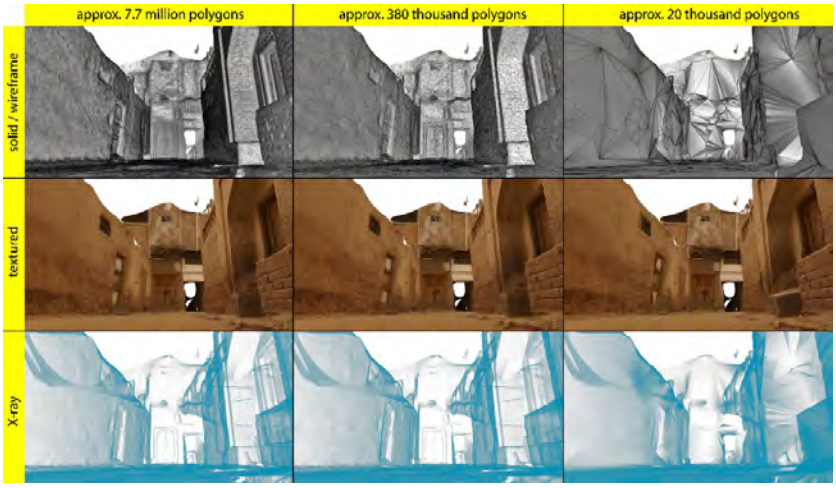



*Figure 2: Successive decimation of polygons in Memento by 95% from left column to right.*

Additionally it should be noted that the photographs of Kashgar were taken at different times and in different environmental conditions such as cloudy days with evenly distributed light or sunny days that brighten white surfaces excessively, causing parts of geometry to be unrecognised by the algorithm and thus creating random black holes. These are errors that are revealed in textures and other misalignments caused in the photogrammetric

process, which necessitate consideration of the glitch aesthetics mentioned in the introduction.

### 2.2. IMPORTING MODELS INTO HYVE-3D

After the photogrammetric process, the model can be directly imported into Hyve-3D as an OBJ file. However, optimizing the polygon mesh allows for smoother real-time interaction and remote collaboration within the system. This can be done during the photogrammetric modelling but it is advisable to test the decimation in order to achieve the level, which is optimal for the purpose of the exercise.

## 3. A representational ecosystem for cultural heritage making

Hyve-3D is an immersive design and visualization system that allows collaborative and real-time sketching in 3D without the need for headsets. The Hyve-3D setup allows shared interactions with 3D models inside an immersive environment without necessitating a complex graphical user interface. The visualization technique uses an anamorphic *trompe-l'oeil* projection onto a spherical concave screen.

This concave screen is sufficiently spacious to accept several inhabitants simultaneously, thus enabling user engagement in both real and virtual collaboration (Figure 3). Hyve-3D also works in a non-immersive mode using desktop computers or laptops. It allows export of the design interactions as 3D sketches to any 3D modelling software as 3D vectors (DXF format). The technical aspects and functions of Hyve-3D are explained in detail by Dorta et al (2014; 2016).

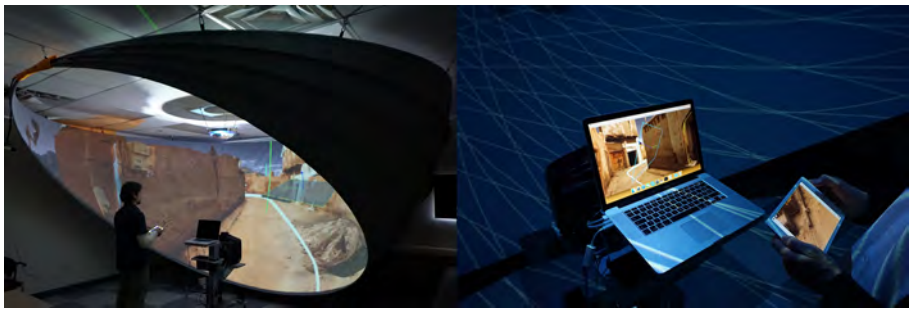


*Figure 3. Hyve-3D, immersive (left) and non-immersive (right) settings.*

Sections 3.1 to 3.3 below show how Hyve-3D can serve as a platform for an unmediated cultural heritage. Thus the following distinct properties and

functions of the system are noted as specifically relevant and add value to the realm of digital heritage.

### 3.1 THE 3D CURSOR

Hyve-3D permits active virtual engagement via its 3D cursors (Figure 4). A key feature is that every user has a handheld tablet with 3D cursor, which allows them to interact with the model displayed in the virtual environment. Navigation occurs through tablet movements and common multi-touch gestures; every user possesses a control plane that can be positioned anywhere within the virtual world in order to generate sketches or annotations and display orthogonal views of the 3D scene, in addition to the shared immersive view surrounding the users.



*Figure 4. User experiencing 3D navigation while sketching on orthogonal view on tablet.*

### 3.2 A COLLECTIVE IMMERSIVE EXPERIENCE

Hyve-3D encourages shared interaction, whereby users are aware of the presence of other co-located or remote users. This possibility allows a wide range of social interactions that are facilitated through the hybrid realm. The overall configuration and set up of Hyve-3D permits verbal and non-verbal communication to be picked up by participants with ease.

### 3.3 REMOTE DISCUSSIONS VIA REMOTE ANNOTATIONS

Hyve-3D's 3D cursor within the virtual environment is also a reference plane upon which users can sketch and make annotations. These graphical elements support communication and annotations can also be used as virtual landmarks, sign posts, or notice boards to leave interpretations or comments about specific locations or elements of the model. This element is crucial to the research presented here as it allows for generation of unmediated heritage as well as the collecting of individual and collective narratives (Figure 5).

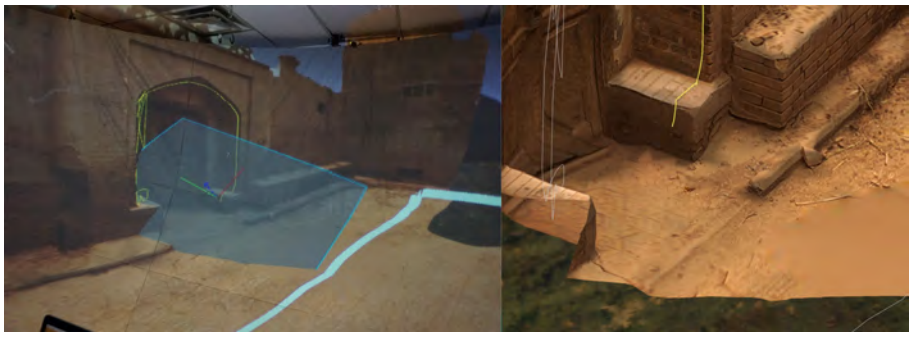


*Figure 5. '3D cursor' in Hyve-3D (left) showing a detail with an axonometric view (right).*

## 4. Aesthetics of glitches

In the modelling process there are several determinants of photogrammetric production including transparency, brightness and subtlety between repetitive elements that can be relevant to the object(s) or device-related e.g. camera lens and shutter speed. Frequently data transformation from 2D images to 3D objects may change the message (Manovich, 2001), so that photographs are converted into 3D sculptures with 'errors' that appear like holes on excessively dark or white surfaces. Such internal errors are potentially representative of a gap in knowledge where users must project their own conceptual understanding in order to complete it. This aspect of Hyve-3D's navigation and input technology, paves the way for exemplifying it through the project, which thus becomes a crucial ingredient of the process.

### 4.1. AN INCENTIVE TO NARRATE

An aestheticisation of the limitations of a technical process such as photogrammetric modelling can be characterized as 'glitch aesthetic', or the 'beauty of error'. Decimation of the original scanned meshes, which causes glitches to magnify, can be celebrated as reinterpretation by the digital realm of the interaction between users and the virtual model.

Another interesting and neoteric aspect of Hyve-3D is that users can interact and draw 3D intuitive sketches directly onto the immersive landscape of virtualised Kashgar, permitting participatory reconstitution of data (Figure 6). The user is no longer passive because the visualised ambiguity enables mutual engagement of the participant and the machine. This sets the context of digital heritage that we are advocating.

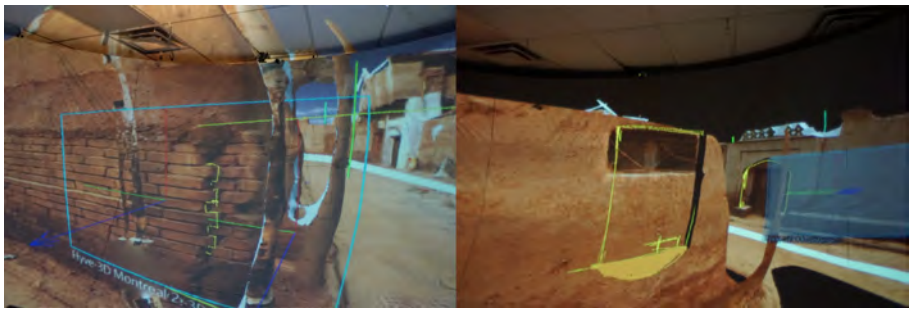


*Figure 6. User's 3D sketches over Kashgar model.*

## 4.2. TOUCHSTONES TO COMMUNICATE

Photogrammetry, Hyve-3D's representational ecosystem and Kashgar's heritage become a reflection on unmediated authenticity. Conventionally, authenticity consists of systems of values and knowledge. We refer to the concept of 'authenticators as authors of shared knowledge' in contrast to 'authenticators as guardians of knowledge' (Howell and Chilcott, 2013).

In Hyve-3D tagging is a self-referential example of authenticating shared knowledge, e.g. QR codes placed in the model, while editing textures or specific sketches or markers, provide an opportunity for users to leave their traces for others to follow. Tags may lead to photos, media or completely different kinds of representation such as a computer games.

We propose that the errant functionality of photogrammetry can offer a meaningful aesthetic experience to users. Unforeseen aesthetics of holes and glitches, which are both user driven and owned, become touchstones in the communication between all users thus generating authenticity in shared knowledge.

Like layers of history, a cyber-layer transmutes past into present or vice versa at different time-horizons. When the participant is in contact with the Kashgar model through a machine, the system draws upon voluntary memory, whereas interaction with other users activates the participant's memory involuntarily. When reflected as parts of Kashgar, such individual sketches become objects of a virtual museum, linking time and space in different horizons.

## 4.3. AFFORDANCES TO PARTICIPATE

The appropriated support of Hyve-3D representations provokes active collocated or remote collaboration between participants. Immersion and detailed orthogonal complementary views on tablets facilitate diverse scales and views of the heritage artefact. Furthermore, immersion dismantles the pic-

ture-frame of traditional representations. All these elements comprise essential aspects of the new representational ecosystem as presented by Dorta and Kinayoglu (2014). Subsequently, this affords users the opportunity to interact and participate authentically in an innovative way of reconstructing and accessing cultural heritage (Gero and Kannengiesser, 2012).

## 5. Conclusion

Unmediated cultural heritage is usually insurmountable within the politics, values and material circumstances of a digital reality. From the perspective of the Augmenting Kashgar Project, the primary focus of this paper is to contribute to the development of a concept of digital heritage theory by resolving the real problems of engagement in the broad context stimulated by the definitional ambiguity of an unmediated cultural heritage. By designing and testing interactive applications in this project, it becomes possible to read unmediated cultural heritage and then to deploy Hyve-3D for the first time in the context of cultural heritage.

Decentralisation of the artefact from its materiality, by tolerating glitches of the digital transcoding processes, leads us to evolution of means for stimulating the subjective performance of users whereby emotions and intertextual narratives can be represented. In this respect, Hyve-3D and its 3D cursor technology help the visitor map new narratives and emotions on the represented.

In the realms of virtual reality, it becomes possible to connect aspects of authenticity and interpretation of architectural and digital heritage. Within the hybrid environment, the virtual model of Kashgar becomes a medium to compile individual and collective narratives. The interactive experience and multi-locational participation via Hyve-3D turns into collaborative digital reconstitution of the virtual materiality in cultural heritage.

Digital heritage is thus instrumental in visualization of heritage but also provides a medium for its generation, communication and discussion. The methods presented can be developed into a robust and reliable methodology for modelling architectural heritage.

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# TANGIBLE USER INTERFACES FOR TEACHING BUILDING PHYSICS

*Towards continuous designing in education*

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**Abstract.** This paper follows our evaluation and research into designing tangible physical media for the purposes of teaching building physics to undergraduate architecture students. These media interfaces make use of a virtual environment to promote an understanding of the cycles, which govern architectural and urban projects (for example solar studies, the flow of heat, air and water). This project aims to create an ecology of devices which can be used by students to self-direct themselves and harbour critical making in their research methods (with the explicit intent of dissolving the barrier between design and research). The basic premise of this research, is that in light of growing student numbers, more students lacking confidence in numeracy skills as well as the desire to have self-directed or group-directed learning, tangible media has a promising role to play. There are several reasons for this optimism. The first is that a better sense of intuition is gained from an interactive model over reading notes from a lecture or textbook. The second is that tangible media engages in other modes of learning, being valuable to students who have an aptitude for kinesthetic and spatial learning over text-dominant learning.

**Keywords.** Pedagogy; tangible user interfaces; augmented reality; internet of things; designing for teaching.

## 1. Introduction

Tangible User Interfaces (TUIs) were popularised in research by Ishii and Ullmer (1997) who present them as a way of coupling digital information to physical objects. Several researchers have written about the benefits of

tangible user interfaces in pedagogy. Marshall (2007) describes their use as allowing for expressive and exploratory activities. Shaer et al (2010) present a general framework for the use of tangible interfaces in education. Fishkin (2004) presents a framework for analysing TUIs. It is believed that incorporating TUIs into teaching can benefit students who have an aptitude for kinaesthetic, visual or haptic learning over symbolic manipulation as well as those who have English as a second language (due to the reduction in reading and increase in interactive learning). Park (2001) presents studies showing that kinaesthetic and tangible learning is significantly preferred by children of seven different ethnic groups with a significant preference also shown by female students.

As a measure towards balancing our ever-increasing demands on students to learning, new fields (such as life-cycle assessments, energy analysis, deconstruction, BIM, simulation tools) we are looking towards supplementing the traditional class with new interactive media with a focus on intuitive as the goal. At the same time, however, it is important to keep in mind that this is a Tertiary course and therefore the content should be advanced enough to match. The interactive models used in places such as museums designed largely for children) are therefore not insufficient to achieve this goal. One way to open a path towards enriching the content of a TUI is to incorporate augmented reality. Augmented reality is proposed as a bridging tool to allow for an increase in the complexity and flexibility of what can be talk within a single module.

The surveys gathered indicate that students are enthusiastic for other modes of lesson delivery. We have sufficient cause to believe that interactive learning methods will be well received.

When embracing this mode of learning, educators are left with an interesting challenge – the designing of these tangible artefacts.

Design as a mode of academic research or pedagogical tool is still to receive recognition in the broader scope of academia. The status of design as an academic pursuit is examined by Downton (2003). In this research we look at following through with design as a mode of pedagogical delivery and strategies that can be used by educators to frame these as design projects.

## 2. A proposal for interactive media for education

> "Play is the answer to how anything new comes about." - Jean Piaget

Our key proposition in this research is that the use of mixed media – note that this is not limited to audio and video – can lead to an improvement in student engagement as well as experimentation. Our case study for this proposition, is a second year unit, part of the Bachelor of Architecture

degree which is dedicated to teaching building physics and principles of sustainable (energy efficient) design. The proposed course will keep many traditional elements (lectures, workshops, an online Blackboard and assessments) but will supplement them with a series of experimental environments, where students use tangible media to interactively learn about the key concepts of each weekly lecture as well as experiment with these media in order to gain an intuitive understanding before more formal methods of simulation are performed.

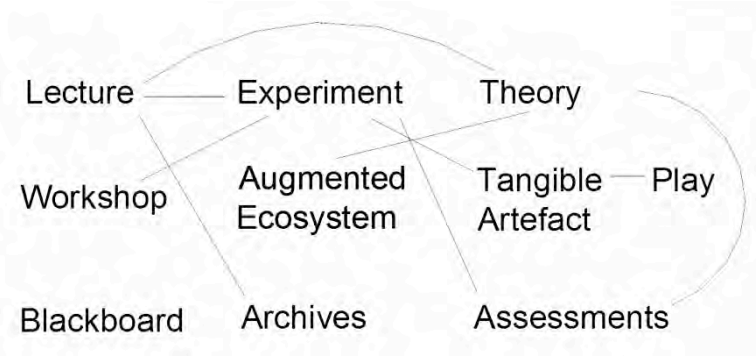



*Figure 1. Elements of Each Module*

## 2.1. GORDON PASK AND CONVERSATION THEORY

The great pioneer in the realm of using tangible media and interactive learning devices is the British cybernetician Gordon Pask. Pask is most famous for his development of Conversation Theory as well as interactive models such as ThoughtSticker and Saki (Haque, 2007). As with Piaget's constructivism, Pask shared the view that knowledge is constructed. Central to Learning Theory are models of analogy (relationships between elements) and entailment meshes which record the knowledge gained through interactions. Interactions play a big role in Pask's methods and are formally recorded elements of the system. Interactions between 'actors' (an actor can be a person or a machine) form the basis of a conversation. Therefore, knowledge (knowing) is never reduced in an abstract way to either facts or relationships between elements, but required kinetic action and energy. Pask is of particular interest in the teaching of design as rote learning is largely irrelevant to learning design concepts.

## 2.2. COMPLEXITY AND SCALABILITY

Tangible interfaces are now very popular in learning centres such as museums and exhibitions. The two areas which need development when

being adopted in tertiary education are their scalability and the level of complexity that they can be used to teach. With complexity, there has to be a layering of concepts over other concepts, gradually building a high level understanding of ideas to the standard of a tertiary education. For this reason, we look at tangible media as augmenting the class and being a stepping-stone towards more complex simulation. Regarding scalability, there has to be room for experimentation outside of the bounds of the class and one method that is being explored, is in encouraging students to design elements that can interact with tangible devices. The microcontroller platform Arduino has been incredibly successful in this regard, they created an ecosystem that fostered the Maker movement, people adapting and sharing designs.

## 3. Analysis of class and other local conditions

As part of this study, a census was taken with the class that is to participate in this course (in early 2016), in the year prior to the study. A later survey and focus groups will take place at the conclusion of the class in 2016.

### 3.1. SURVEY

The class was found to be typical (compared to previous years) in the age distribution, the level of prior experience and the number of students with English as a second language. The majority of students are under 21 years and most recorded no experience within the architectural industry. 57 % of students agreed with the statement that they were confident in their numeracy skills. 73% agree with the idea that lecturers should use physical and computer models in their teaching with 71% also saying that experimentation was an important aspect of learning. 65 % strongly agreed with wanting a hand-on approach over a theoretical approach.

### 3.2. USEFULNESS

It is encouraged within teaching culture of the participating university, to relate the content of lectures directly to the assignments of the course as well as criteria (and skills) that are considered necessary for employment in practice. This has met with mixed feelings from academic staff especially as architecture is both a discipline and a profession. There is an intentional aim in this class to find a balance between theory and practice.

### 3.3. OBJECTIVES OF THE COURSE

This course will be the students' first encounter with simulation and energy analysis, it is therefore particularly important in regard to their education of sustainability in architecture. Buildings consume approximately 40% of the world's energy and resources. This unit therefore has a special place in the overall strategy of increasing knowledge regarding energy efficiency and sustainable design strategies. As the majority of students are in the early stages of their studies, the importance of inclusiveness is also seen as a priority. Tangible models can be used collectively and can therefore assist in learning through collaboration and discussion. It is also important to recognize that there is a need for teaching methods that cater for those students who are better suited for kinaesthetic, tangible and interactive learning. Many researchers in education promote using inductive modes of teaching – to ask students to make predictions and form hypotheses before examining a case. Using tangible models support this form of learning and there is the potential to turn students to active participants. An increased use of models and other visual and interactive media would support students with English as a second language compared to modes of learning which text-heavy. The design and building of each tangible user interface also presents the opportunity to design and distil the key lessons into each model, which would structure each lecture and workshop.

### 3.4. TANGIBLE USER INTERFACES AND MIXED MEDIA

Ishii and Ullmer (1997) described TUIs as devices that connect the physical and virtual worlds. A distinction is generally drawn between multi-touch screen devices, which although have a physical input, are largely based in the virtual world. Tangible devices have a greater emphasis on kinetics and utilising these physical forces as part of their appeal. Augmented reality is the overlay of virtual data in the physical world (devices used by be projectors, headsets, sound or physical actuators). Schneider et al (2011) showed that tangible devices scored higher than multi-touch devices when students were later examined on concepts taught. Our interest in tangible interfaces and media stem from both the desire to increase engagement but also that each lesson has to be compressed to its core essence, which is encapsulated in the physical device. The TUI becomes the core around which the rest of the lesson and the lecture can be situated. Introducing an element where students can adapt and 'hack' is also seen as ways to improve engagement.

## 4. Case studies

### 4.1. AN INTERFACE FOR LEARNING SOLAR ANALYSIS

The first of our built interfaces is allows for the analysis of solar data. The critical piece of information for design students to understand, out of this module, is way in which light enters the structure and how this changes over the time period of a year. Additions to this include the design of light shelves, blinds, and solar tubes.

#### *4.1.1. Observations*

Comment from teacher (paraphrased): "We're tired of seeing sun paths drawn in plans, as if this concludes all that is needed to know about the." Solar studies have a tendency to be an area where student perform in an automated way, citing sun path diagrams or false colour solar images, presenting data with no obvious analysis to what impact or opportunities this presents.

#### *4.1.2. Key concepts*

Table 1. Elements of Solar Study Module.

| | |
|---|---|
| Key Theme | That optimizing the different shapes in a fenestration system can have an impact on solar gain as well as the lit environment. |
| Other Themes | The changing of the sun angle throughout the year and how it is desirable to cut off summer sun while allowing in winter sun (depending on location). |
| Summary | The tangible device takes the form of a generic building section where a slider can control the depth of the solar shade. This can be replaced with another fenestration component. |
| Challenges | While lighting can be understood as a moment in time, thermal analysis takes place over the course of (in most cases) a year. There is also the challenge of balancing qualitative and quantitative data – the qualities of light vs the metrics of solar gain. |
| Augmented data | The augmented reality can map the sun path in an animated form as well as graphs showing the yearly gain. This can be dynamically linked to the state of the physical mode. |
| Making Opportunities | Student can fabricate different shading mechanisms. |

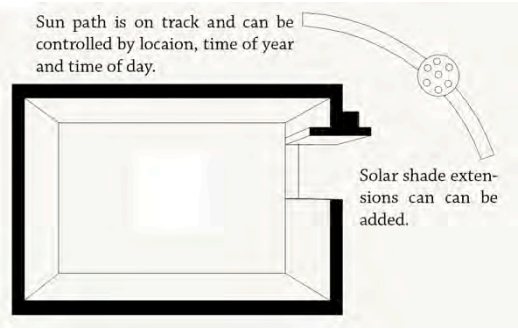



*Figure 2. TUI for teaching Solar Studies.*

## 4.2. AN INTERFACE FOR TEACHING THERMAL TRANSFER

One of the challenges of passive design comes in teaching concepts surrounding psychrometry – relating air, water and temperature together. One way this can be dealt with is in making visible the quality of temperature.

### *4.2.1. Observations*

There are a lot of units used in the study of psychrometry (Absolute Humidity, Relative Humidity, Dew Point, Dry Bulb Temperature, Web Bulb Temperature). What is not intuitive is that temperature (regarding our perception of it) cannot be measured simply on a linear scale from cold to hot – the quantity of water in the atmosphere changes our ability to lose heat through sweating.

### *4.2.2. Key concepts*

This particular module is meant to be used during a lecture, where an experiment with 4 glasses of water is set up and the amount of water that condensates around them are measured. Throughout the lecture, the device will take snapshots of data around it, so that at the end of the lecture, the process can be seen, in a sped up video.

Table 2. Elements of Psychrometry Module.

| | |
|---|---|
| Key Theme | That the hotter air is, the more water it can hold. |
| Other Themes | Conversely, air can be cooled by adding more water to it. Evaporative cooling is an example of a passive form of cooling. |
| Summary | The tangible environment takes the form of an array of thermal cameras that can give the temperature of objects through infrared measurements. These show false colour image with temperature distributions. |
| Challenges | The biggest challenge is the large number of terms introduced in this module. As with the previous module, what is being dealt with are physical and material quantities over time periods, which when formalized take the form of differential equations which present a challenge for many students. |
| Augmented data | The augmented map can show a fluid dynamics simulation overlaid on the objects that are placed. Particle dynamics can be used to visualize the amount of water in the air as a concentration of particles and their excitement as this temperature. |
| Making Opportunities | Student can fabricate (playful) mechanisms that make use of the evaporation and condensation of water. |

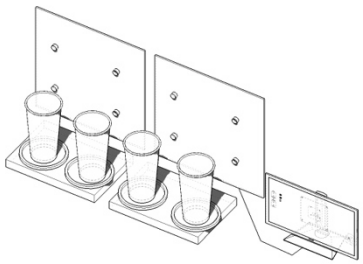


*Figure 3. Psychrometry Module.*

## 4.3. AN INTERFACE FOR TEACHING THERMAL TRANSFER

The last case study TUI that will be discussed is one dedicated to looking at thermal transfer. As with the other modules, the challenge here is to observe something takes place over a time period and in three spatial dimensions. As with the previous module there are a lot of terms involved (conductivity, specific heat, density, thermal mass).

### *4.3.1. Observations*

The relationship between surface area and volume is not always obvious in its relationship to heat transfer. Other areas which are important to learn are the effects of insulation and thermal mass – our intuition may give us

incorrect information – such as how cold water *feels* compared to measured (hence the need to understand specific heat as a material property).

### *4.3.2. Key concepts*

Table 2. Elements of Heat Transfer Module.

| | |
|---|---|
| Key Theme | Thermal lag can be used to great advantage in passive design |
| Other Themes | Water and Groundmasses can be used as sinks. The transfer of heat is dependent on surface area. Thermal breaks and their impact can also be examined in this particular experiment set. |
| Summary | This TUI is similar to the last in that it monitors heat, the key difference is that heat can be provided through a source such as a heat gun or radiator. Thermocouples on the other side monitor the heat travelled through the materials placed between two sliders. |
| Challenges | The challenge in learning mechanisms of heat transfer come in multiple forms – the changing of a buildings mode from gaining heat to needing heat, the relationship between geometry and heat transfer and the nature of composite materials. The effects of thermal mass take place over long periods of time (the duration of a day) so this required recording, if real data is to be used. |
| Augmented data | The augmented data shown in this module are the temperature distribution and record this over a period of data. It can also overlay false colour images onto the objects using projection. |
| Making Opportunities | Students can compose new material sets by sliding layers together. This includes altering composite materials to different shapes such as honeycombing cardboard or using reflective materials within the construction. |

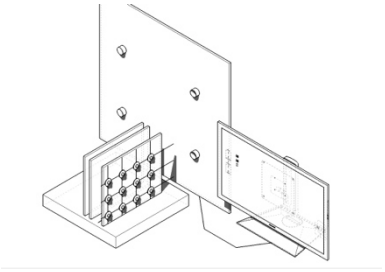


*Figure 4. Thermal transfer TUI*

## 5. Conclusion

The breadth of knowledge demanded on students of architecture has steadily increased over the last few decades. Educators do not always use all the

resources available when teaching and the idea of using design as a method of producing teaching resources has not received as much attention as other modes. Designing resources gives us the opportunity to revisit teaching from the point of view of learners and think about the experience holistically. One of the key difficulties is in finding a balance between lessons that are intuitive while still remaining complex enough to be at the level of tertiary education.

The solution proposed is that tangible devices can be used to create an interactive ecosystem that has data augmented. Augmentation can be used to allow for more complex ideas while the tangible model distils the essence of the lesson and has the greatest benefit to an intuitive understanding. Having students design components within this system forms a step towards interactive learning and experimenting.

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# AUTOMATIC MEASUREMENT SYSTEM OF VISIBLE GREENERY RATIO USING AUGMENTED REALITY

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**Abstract.** Greening has been promoted to improve the living conditions in urban environments. Quantification of greenery is an important issue to identify the criteria for stakeholders in the process of greening. This research focuses on the quantification of visible greenery ratio which is defined as the amount of greenery in the field of vision. Some measurement methods of visible greenery ratio have been already proposed. However, the quantification process is usually time consuming and prone to human errors due to manual operations by using an image processing software. Therefore, in this research, the authors developed an automated measurement system based on image processing technology for the efficient visible greenery ratio measurement. In the verification experiment, the proposed method achieved similar results for extracted pixels of green areas as the traditional manual method, with decreased calculation time. Furthermore, in addition to measuring the current ratio of greenery, this system can visualize possible future changes in visible greenery by adding planting (landscape) design models in an Augmented Reality (AR) environment. Using the proposed method, an ideal greening environment can be designed and evaluated by end-users, more intuitively. The developed design system is expected to eventually result in increasing the amount of greenery in the urban environment.

**Keywords.** Visible greenery ratio; image processing; automatic measurement tool; augmented reality.

## 1. Introduction

To reduce carbon footprint and urban heat island, and to improve the quality of urban landscape, greening has been promoted to improve architectural and urban environments. Quantification of greenery, such as green coverage ratio

and visible greenery ratio, is an important index for stakeholders to quantify the state of greening, to motivate increasing the greening, and to simulate amount of required greenery in the design process (Aoki, 1987). Specifically, due to technological developments and the diffusion of green walls, visible greenery ratio has been drawing more attention than before (Almazan et al, 2012). Aoki (1987) showed that the perceived impression of greenery largely changes when the ratio of visible greenery at a static viewpoint exceeds 25%. He also reported that when visible greenery ratio is almost 50%, most people feel that the amount of greenery is satisfactory.

Visible greenery ratio is as an index that provides end-users with a metric to intuitively grasp the situation of greening. Some measurement methods of visible greenery ratio have been proposed (such as, Osaka Prefecture, 2013; Li et al, 2015). One of the conventional measurement techniques is to measure the greenery percentage per each viewpoints using image processing software applications. In this technique, after taking photographs in representative viewpoints, the natural green areas in the images are manually selected and masked using a software application such as Adobe Photoshop. However, this process is time consuming and shows large variation in working time for different images. In addition, this measurement technique is suitable only for measurements at static viewpoints and is not practical for dynamic viewpoints, such as gathering continuous data of visible greenery while walking or running. This research proposes a method to automatically calculate the amount of visible greenery ratio with a higher precision comparing to the previous research due to its ability to exclude some unwanted objects (such as reflection of trees on the windows).

Additionally, this research provides visible greenery calculation method for Augmented Reality (AR) scenes. AR integrates 3-D virtual objects into a 3-D real environment in real time (Milgram and Kishino, 1994). There are several studies of AR applications in architectural and urban areas (Wang and Schnabel, 2010). Many current works have focused on adding virtual objects, such as new buildings, to the real environment scene (for example, Watanabe, 2011; Schubert et al, 2015). Although the application of image processing techniques, was presented in the tree identification field (Kumar, et al, 2012), visible greenery ratio which is calculated and displayed on AR have not been presented yet.

Ding et al (2015) developed an automated measurement system using Gaussian blur, Hue filtering (*Hf*) and Saturation filtering (*Sf*) functions based on image processing technology, as the basic step. Through the verification experiment using landscape photos, the range of hue and saturation values of general landscape images after applying Gaussian blur filter were identified. The values of $H$ = (40, 180) and $S$ = (0.2, 1.0) have been identified as opti-

mum ranges for general landscape images. However, in the previous research, some unwanted objects (especially the windows that are not target for visible greenery calculation) were also extracted. On the other hand, trunks, branches and soil of trees that are targets for visible greenery ratio could not be extracted.

Therefore, the objective of this research is to develop an advanced automated visible greenery ratio measurement system which can exclude some unwanted object types (i.e., windows) from the calculation and can work for dynamic viewpoints based on image processing technology. In addition to measuring the current ratio of greenery, this system can visualize possible future changes in visible greenery by adding planting (landscape) design models in an augmented environment.

## 2. Proposed method

Our proposed method aims to overcome the limitations of the previous methods (Ding et al, 2015) for automatic measurement of visible greenery ratio by extracting natural green pixels in the landscape images. In this study, an algorithm with four steps is developed: (1) input target images; (2) Gaussian blur, mean shift, hue and saturation filtering; (3) calculate the number of pixels extracted by filtering; and (4) calculate visible greenery ratio using OpenCV (ver. 2.3). Additionally, the same algorithm is utilized for the calculation of the visible greenery in an AR model. For that, possible future changes of greenery is visualized in an AR environment by adding planting design models which are imported to AR system using ARToolKit (ver. 2.72.1). The details of steps (2) to (4) are described in the following subsections.

The difference between this method and other similar research, such as the previous study (Ding et al, 2015), is to apply area segmentation technique using Mean shift method (Fukunaga et al, 1975) for identifying unwanted objects (such as windows), and to apply AR technology to study future changes in visible greenery by adding vegetation models. Figure 1 shows an overview of the proposed method. The process flow shown in the centre of the figure is the same for calculating the greenery ratio for both actual greenery assessment scenario (left hand side of Figure 1) and AR design study scenario (right hand side of Figure 1).

### 2.1. GAUSSIAN BLUR, MEAN SHIFT, HUE AND SATURATION FILTERING

In the captured images, variation in brightness values is generally found. However, after applying filters, many regions cannot be removed and remain

as noise. To reduce such noise, it is necessary to smooth the brightness values of the image. Therefore, processing by a smoothing filter is required. In the previous research (Ding et al, 2015), compared to simple averaging filter, Gaussian blur filter (*Gf*) was proved to be more effective.

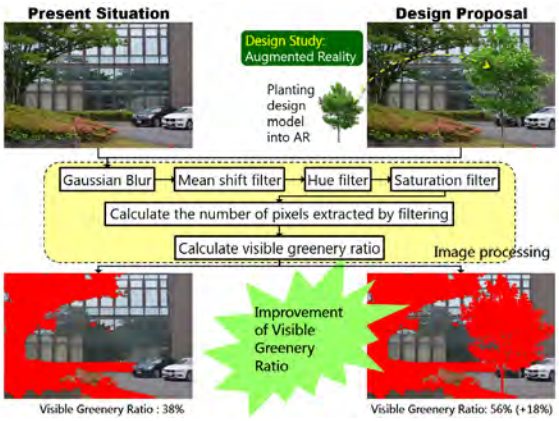



*Figure 1. Overview of the proposed system (AR scenario)*

Then, some unwanted objects (especially the windows that are not target for visible greenery calculation) should be excluded. Therefore, this research proposes using clustering techniques to identify and remove such objects for the calculation. Mean shift (*Mf*) algorithm (Fukunaga et al, 1975) is used to segment the image into some regions based on density of image data. This filter is a non-parametric feature-space analysis technique for locating the maxima of a density function, a so-called mode-seeking algorithm (Cheng, 1995), and is expected to divide the regions more naturally. To implement *Mf* by using the *cvPyrMeanShiftFiltering* function in OpenCV, three important parameters have to be studied: *sp* (spatial window radius), *sr* (colour window radius), and *termcrit* (termination criteria: when to stop mean shift iterations).

Next, filtering using *H* values (*Hf*) is performed. In the *Hf* process, first, the input image is converted from the RGB colour system to the HSV colour system by using *cvCvtColor* function in OpenCV. Then, the *H* value of each pixel in the image is extracted by *cvGet2D* function. Threshold for the green component by the *H* value in the extracted pixel is defined. *H* value ranges between 0 and 360 ($H = (0,360)$). In the previous research (Ding et al, 2015), the value of $H = (40, 180)$ has been identified as an optimum range for general landscape images.

Finally, in the pixels obtained by *Hf*, filtering using *S* values is performed. In the Saturation filtering (*Sf*), as well as the *Hf*, the *S* value of each

pixel in the image is extracted by *cvGet2D* function. The whole range of *S* values is *S* = (0, 1). In our previous research, the value of *S* = (0.2, 1.0) has been identified as an optimum range for general landscape images.

### 2.2. CALCULATION OF NUMBER OF PIXELS EXTRACTED BY FILTERING

For all the pixels extracted in Section 2.1, the contour of the green areas is extracted from the image by using the *cvFindContours* function. The pixels internal to the extracted contour are filled with red.

### 2.3. CALCULATION OF VISIBLE GREENERY RATIO

For all the extracted contours generated in Section 2.1, the area of the contours is calculated using the *cvContourArea* function. By dividing the extracted area by the whole area of the image, the visible greenery ratio is calculated.

### 2.4. IMPLEMENTATION IN AUGMENTED REALITY

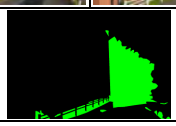
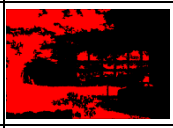
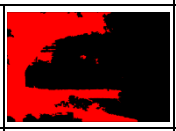
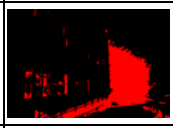
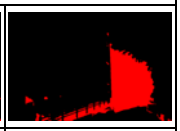
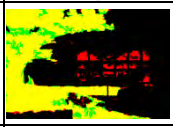
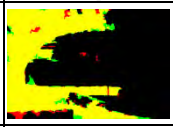
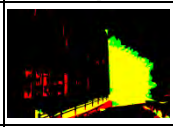
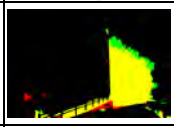
The developed algorithm from Section 2.1 to 2.3 is imported to the AR system by using ARToolKit. There are several methods for the registration of the live video images and 3D virtual objects. In this study, a vision based registration technique by using an artificial marker of ARToolKit was applied (Yabuki et al, 2011). In our proposed system, the user create 3D planting models together with architecture and urban design models by using BIM (Building Information Modelling) or 3DCG software, exports 3D model with texture by VRML (Virtual Reality Modelling Language) format, and imports the 3D model with texture to the AR system for display.

## 3. Verification case study 1: visible greenery ratio measurement algorithm

### 3.1. CASE STUDY DESCRIPTION

The developed automated measurement system has been verified for two landscape locations with natural greens, buildings and roads. The images were shot in November 16th, 2015 in the Suita campus of Osaka University in a sunny weather condition. The camera for the experiment was NIKON D5200 (focal distance: 24mm). A standard PC with 3.20 GHz of CPU (Intel® Core™ i5 Processor), 8.00GB of RAM, running Microsoft Windows 8.1 was used for the experiment.

TABLE 1. Comparison between the previous method (Ding et al, 2015) and proposal method

| | Case 1 | | Case 2 | |
|---|---|---|---|---|
| | Previous method | Proposal method | Previous method | Proposal method |
| Original image |  | |  | |
| *Gf* (previous); *Gf* and *Mf* (proposal) |  |  |  |  |
| IMG1: Ideal result made by Photoshop (Green: Natural green) |  | |  | |
| Pixel numbers of Green (G) | 361481 pixels | | 151290 pixels | |
| Total pixels of image (T) | 960000 pixels | | 960000 pixels | |
| Visible Greenery Ratio (G/T*100) | 37.7% | | 15.8% | |
| IMG2: Result by the automated measurement system (Red: detection of natural green) |  |  |  |  |
| Pixel numbers of Red (R) | 343492 pixels | 354438 pixels | 157355 pixels | 140216 pixels |
| Composite image (IMG3) between IMG1 and IMG2 (Yellow: Correct solution) |  |  |  |  |
| Pixel numbers of Yellow (Y) | 308767 pixels | 337133 pixels | 130058 pixels | 129566 pixels |
| Accuracy rate (Y/G*100) | 85.4 % | 93.3 % | 86.0 % | 85.6 % |
| Not extracted area (Green in IMG3) | 52714 pixels | 24348 pixels | 21232 pixels | 21724 pixels |
| Extracted area by mistake (Red in IMG3) | 34725 pixels | 17305 pixels | 27297 pixels | 10650 pixels |
| Pixel numbers of inaccuracy area (I = Green + Red in IMG3) | 87439 pixels | 41653 pixels | 48529 pixels | 32374 pixels |
| Inaccuracy rate (I/G*100) | 24.2 % | 11.5 % | 32.1 % | 21.4 % |

In the experiment, the visible greenery ratio was calculated both by the previous method (Ding et al, 2015) and the proposed method. In the pre-processing step, by using a conventional measurement technique, Adobe Photoshop was used to extract the natural green area manually (as reference pixels) to verify the developed system (Table 1: IMG1). Then, detected areas of natural green pixels using *Gf*, *H* and *S* filters (the previous method) were extracted, and natural green pixels by *Gf*, *Mf*, *H* and *S* (the proposed method)

were extracted (Table 1: IMG2). Next, a composite image which combined IMG1 and IMG2 of each method was created. The yellow areas of IMG3 in Table 1 shows correct extracted pixels. Finally, the accuracy rate was obtained by dividing the correct extracted pixels by the reference pixels. The *Not extracted area* in Table 1 was obtained by subtracting correctly extracted pixels from the reference pixels. The *Extracted area by mistake* in Table 1 was obtained by subtracting correctly extracted pixels from the detection of natural green pixels. Inaccuracy rate was obtained by adding *Not extracted area* pixels and *Extracted area by mistake* pixels, and dividing the pixels by the reference pixels.

### 3.2. RESULTS AND DISCUSSION

The results are shown in Table 1. The accuracy rates of two images in the proposed method were 93.3% and 85.6%. Both rates show higher score than the average 85% achieved by the previous method.

The accuracy rate in Case 1 was 7.9% higher than that of previous method. In the proposed method, less unwanted objects such as windows that are not a target for visible greenery calculation were extracted. The inaccuracy rate in Case 1 was 11.5%, and 12.7% lower than that of previous method.

The accuracy rate in Case 2 was 0.4% lower than that of previous method. However, the pixels located at the edge of some trees were not extracted well. One reason was that the trees were bamboo, which has thin branches and leaves. The other reason was that the colours of natural green edge pixels were changed from green after blending with sky. The inaccuracy rate in Case 2 was 21.4%, and 10.7% lower than that of the previous method.

Considering the overall performance, the proposed automated measurement system using Gaussian blur, mean shift, hue and saturation filtering function system was proved as a better system than the previous one.

## 4. Verification case study 2: studying future changes in visible greenery by adding planting models in an augmented environment

### 4.1. CASE STUDY DESCRIPTION

To verify the applicability of the proposed AR system with visible greenery ratio measurement algorithm, a verification experiment was conducted near an existing building. Both the Science and Engineering Library building and TechnoAlliance Complex building of Osaka University Suita Campus were selected for the experiment. The experiment was carried out at the end of November 2015 in a sunny weather condition (see Figure 2).

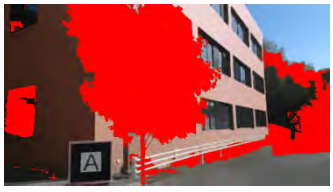
The procedure for the verification is presented in the following steps:

1) Data preparation: 3D shapes of the building and a tree were modelled by Trimble SketchUP. The position of the AR marker was defined in the model based on its real position (see Figure 2). Then, 3D geometries and textures were converted to the AR system via VRML format. Then, the horizontally flat and open space in front of the building was selected as a viewpoint field. The marker was installed at the open space.
2) Implementation: Initializing the AR system including the library and tree contents was confirmed. Then, the display of AR was carried out. Visible greenery ratios of both the present landscape and the proposed landscape by adding the tree were calculated.




*Figure 2. Left: 3D modelling for AR (In case of the Science and Engineering Library building), Right: Experimental photo (In case of TechnoAlliance Complex building)*

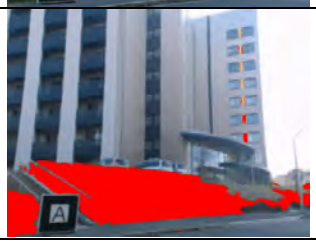
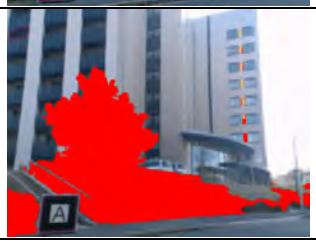
TABLE 2. Comparison between present landscape and proposed landscape using AR

| | The Science and Engineering Library building | |
|---|---|---|
| | Present Landscape | Proposed Landscape using AR |
| Original image |  |  |
| Result by the automated measurement system (Red: detection of natural green) |  |  |
| Extracted pixels (G) | 80205.5 pixels | 288329 pixels |
| Total pixels of image (T) | 806400 pixels | |
| Visible Greenery Ratio (G/T*100) | 9.9% | 35.8% |

### 4.2. RESULTS AND DISCUSSION

This experiment confirmed that studying future changes in the visible greenery ratio by adding planting models in an augmented environment was possible. As shown in Table 2, after adding the tree model, the visible greenery ratio is increased from 9.9% to 35.8%. Also, as shown in Table 3, the visible greenery ratio is increased from 15.1% to 25.4%. Using the proposed method, an ideal greening environment can be de-signed and evaluated by end-users, more intuitively.

TABLE 3. Comparison between present landscape and proposed landscape using AR

| | TechnoAlliance Complex building | |
|---|---|---|
| | Present Landscape | Proposed Landscape using AR |
| Original image |  |  |
| Result by the automated measurement system (Red: detection of natural green) |  |  |
| Extracted pixels (G) | 76520 pixels | 128123 pixels |
| Total pixels of image (T) | 505120 pixels | |
| Visible Greenery Ratio (G/T*100) | 15.1% | 25.4% |

## 5. Conclusions

In this research an automated measurement system based on image processing technology for efficient visible greenery ratio measurement to be used for real environments and also for an AR environment was presented. The research contribution was to propose a new approach by utilizing Gaussian blur, mean shift, hue and saturation filtering functions as opposed to using only Gaussian blur, hue and saturation filtering functions in the previous studies. As a result, comparing to the previous method, higher accuracy rates and lower inaccuracy rates were achieved. Although using clustering techniques excludes many unwanted objects from the calculation, some window

types such as car windows still cannot be excluded. Investigating about new algorithms to remove such objects is considered a future work of this research.

Furthermore, this system can visualize possible future changes in visible greenery by adding planting design models (e.g., trees) in an AR environment. As a result, after adding the trees to the AR scene, the visible greenery ratio was increased. Using the proposed method, an ideal greening environment can be designed and evaluated by professionals and end-users, more intuitively. The developed design system will eventually lead to increasing the amount of greenery in the urban environment.

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# A MARKER-LESS AUGMENTED REALITY SYSTEM USING IMAGE PROCESSING TECHNIQUES FOR ARCHITECTURE AND URBAN ENVIRONMENT

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**Abstract.** In this study, Augmented Reality (AR) system is proposed to be used for outdoor renovation and maintenance projects of buildings. The research proposes an outdoor marker-less AR system that considers the mobility of users and their long relative distance to target buildings where 3D virtual objects should be augmented on. The proposed system uses local feature-based image registration technology and Structure from Motion (SfM) which reconstructs 3DCG models using photographs from multiple viewpoints. A case study has been performed for a research building renovation scenario at Osaka University. The case study verified the performance of image registration and tracking, and confirmed the applicability of the method.

**Keywords.** Architecture and urban environment; Augmented Reality (AR); image registration; Speeded-up Robust Features (SURF); Structure from Motion (SfM).

## 1. Introduction

In recent years, in order to reduce carbon footprint, renovating existing buildings (for improving safety and strength or, adding new functions) has become more desirable than reconstruction. In comparison to reconstruction after demolition, renovation is expected to preserve resources and to reduce generating environmentally hazardous substances (Egbu, 1997; Juan, 2009). Using new materials, which are more environmental friendly, makes buildings more sustainable and reduces environmental burdens. For that, it is ben-

eficial to enable design stakeholders asses final visualizations of their design as they sometimes show hesitation towards new design challenges.

The use of Augmented Reality (AR), which can integrate augmentations with real world scenes, has become common in architectural and urban design fields (e.g., Wither et al, 2009; Schubert et al, 2015). AR can help visualizing full scale building projects at the design stage before the construction, and can be used to visualize some properties of the building at the maintenance and operation stage. For that, AR super-imposes 3DCG (3-Dimensional Computer Graphics) model objects on a live video feed of the surrounding landscape acquired by a camera. AR is similar to Virtual Reality (VR) technology. However, it does not require 3D virtual models of the environment. With the use of the AR system, the time and the cost required to perform a 3DCG modelling of present surroundings are drastically reduced. However, considering possible lack of familiarity of architectural designers with the Information Technology (IT) tools, it is necessary to build simple, easy-to-use, and low-cost system which its usability does not rely on designer's IT skills.

In this study, AR system is proposed to be used for outdoor environment specifically for renovation projects at the design stage. In order to realize an accurate outdoor AR, precise tracking of geometric registration between a live video and 3DCG models still remains as an important challenge. In the case of an outdoor AR, the relative distance between AR users and visualized 3D models tends to be large. The reference point for geometric registration is the sensor's position in sensor-based methods (such as GPS or 3D sensor) (Watanabe, 2011), or the position of an artificial marker in marker-based methods (which is an example of vision-based methods) (Yabuki et al, 2011). In sensor-based methods, the reference point of geometric registration is positioned near an AR user, hence, the sensing error highly influences the error of a 3DCG model registration. Meanwhile, in artificial marker-based methods, it is possible to place large markers near target objects. However, the marker needs to be properly captured by the AR camera, which imposes limitations on the user's movability range and requires installation of large markers.

Therefore, development of marker-less AR systems, which do not require artificial markers, continues to advance (for example, Klein and Murray, 2007; Ventura and Hollerer, 2012). Yabuki et al (2012) developed a geometric registration method which corresponds point cloud data to natural feature of the real world. However, in this method, natural features which are used for geometric registration need to be continuously captured by the AR camera, and special equipment is required for the acquisition of point cloud data as the system needs to use a large number of point cloud data acquired by a

3D laser scanner. In contrast, Structure from Motion (SfM) technique, which reconstructs 3D shapes from photographs taken from multiple viewpoints, is another method to create point cloud data (Hartley and Zisserman, 1994). It is an emerging, easy, and low-cost alternative method for creating models (Nagakura et al, 2015).

Therefore, in this study, a novel marker-less AR system that uses local feature-based image registration and SfM technology is developed. The proposed system supports free movement, has less limitations, requires less efforts, and is less expensive for outdoor AR applications. The developed system has been applied to a renovation design project for verification.

One of the features of the proposed system is that it does not require special equipment (such as sensors for geometric registration between augmentations and the real world) as it uses sensor-based registration. Additionally, the system does not require artificial markers which decreases user's flexibility. Finally, the point cloud data which is used in this system is reconstructed by SfM and does not require special hardware such as laser scanners.

## 2. System overview

The proposed method has two main steps; *preprocessing*, and the *real-time processing*. In the *preprocessing* step; first, a 3D model of the environment is reconstructed by the SfM method using photographs taken from multiple viewpoints. The position and orientation data of all viewpoints are stored in a database. Second, coordinates of 3D virtual objects that should be augmented are defined relative to coordinates of 3DCG models of the environment reconstructed by SfM and are stored in a database. Finally, key points and features of each photograph used for the SfM are extracted and saved in a text file. Additionally, file paths of all photographs are saved in a separate text file. In this research, an advanced local feature detector and descriptor namely Speeded-Up Robust Features (SURF) is used (Bay et al, 2008). SURF is an improved and speeded up version of Scale-Invariant Feature Transform (SIFT) that is used for interest point detection.

In the *real-time processing* step; first, the files created in the preprocessing step are imported. Second, features of the live video images are extracted using SURF in real time, and extracted features of the live video images are compared with features of stored images in the database. Finally, 3D virtual objects are precisely rendered in an AR display using position and orientation data of the camera and by finding the most similar image in the database. For tracking, motion vectors are calculated using optical flow. Then, external parameters are calculated using internal parameters, position

of points on the screen and the world coordinates of their corresponding points.

To realize this processing in real-time, three speed enhancement techniques are employed. In the SURF processing, for comparing key features between live video images and all stored images in the database, approximate nearest neighbor search by Locality Sensitive Hashing (LSH) algorithm (Indyk and Motwani, 1998) is applied instead of full search by linear search algorithms. And, a multithreading technique is applied when the features are extracted in the SURF processing. The live video images are also trimmed to process only their central area for the image registration processing step.

The overall view of the proposed system is shown in Figure 1, and the system flow is shown in Figure 2.

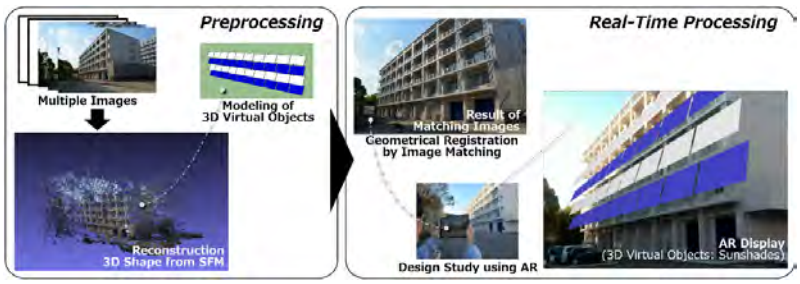



*Figure 1. Overview of the system.*

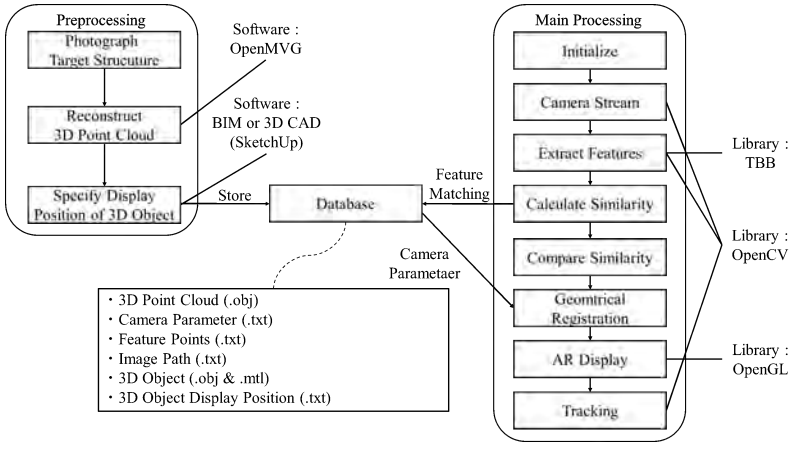



*Figure 2. Marker-less AR system process.*

## 2.1. MARKER-LESS AR SYSTEM DESIGN

3D model is shown on the screen using Equation (1) (Zhang, 2000). In the equation, *s* denotes expansion or reduction factor, *u* and *v* are the position of

object drawing on the screen coordinates. The value $f$ denotes the focal length, and $c_x$ and $c_y$ define coordinates of the centre of the image. These values are called internal parameters of a camera. $R$ is rotation matrix and $T$ is translation matrix of a camera. These values are called external parameters of a camera. The values $X$, $Y$ and $Z$ denotes the position of object in the world's coordinates.

$$s\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f & 0 & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} R_{3\times3} & T_{3\times1} \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \tag{1}$$

Internal parameters are possible to be calculated through camera calibration, and remain unchanged unless the camera lens is changed. In contrast, external parameters represent the position and posture data of a camera, and are specific to each photograph's viewpoint. Therefore, external parameters need to be calculated while using the AR system. In case of maker-based AR systems, these parameters are calculated based on the position of a marker, however, in case of marker-less AR system, another calculation method is required. Accordingly, in this study, external parameters of each photographs viewpoints are calculated by the SfM.

### 2.2. SYSTEM IMPLEMENTATION

In this study, the proposed system was implemented using C++ and by combining multiple open source software applications and libraries. In the preprocessing, OpenMVG (Open Multiple View Geometry. Ver. 0.7) which is an open source software was used for carrying out SfM. Additionally, Trimble SketchUp (Ver.15.3.331), which is a 3D modelling software, was used for defining coordinates of 3D virtual objects. In the main processing, OpenCV (Open Source Computer Vision Library. Ver. 2.4.9), which is another open source image processing library, was used for capturing real-time camera stream and image matching. Additionally, TBB (Threading Building Blocks. Ver. 4.4), which is an open source parallel processing library, was used for parallel processing. FreeGLUT (Ver. 2.8.1), which is toolkit for OpenGL (Open Graphics Library), was used for drawing 3DCG model on AR display.

## 3. System verification

To verify the applicability of the proposed system for renovation projects, a verification experiment was conducted for an existing building. The research

building M3 of Osaka University Suita Campus was selected as the target. The experiment was carried out on November 26th and 27th, 2015.

### 3.1. PROTOTYPE EXPERIMENTATION

For the renovation case study, the design of awning (sunshades) for a part of M3 building is chosen. In the AR scene, the prototype system allows users to change the material of to-be-installed awnings (sunshades). As for design alternatives, blue and white colour materials and different angles (10, 20 and 30 degrees) for shades were prepared.

A sample photo of the experiment environment is presented in Figure 3. The procedure for the verification study is presented in the following steps:

- 3D shape of M3 building was reconstructed by SfM. In this study, SfM processing was carried out using images captured by a digital camera. One hundred images (resolution 900×600) of M3 building were used for SfM. Moreover, drawing position of the awning was assigned to the reconstructed 3D shape. The photography route for SfM is presented in Figure 3. Examples of images used for SfM is presented in Figure 4 and 3D shape of M3 building reconstructed from SfM are presented in Figure 5. Drawing position of awnings is presented in Figure 6.
- Initializing marker-less AR system including M3 building contents was confirmed.
- The display of AR models on the same route where the images are captured for SFM was confirmed.
- Changing colour of awning material, and changing the angle of awnings were confirmed.
- Tracking 3DCG model on the same route where the images are captured was confirmed.
- The application of the developed marker-less AR system for building renovation was verified.




*Figure 3. Experimental photo (left), Photography route of SfM and Tracking route of experimentation (right).*



*Figure 4. Examples of images used for SfM.*

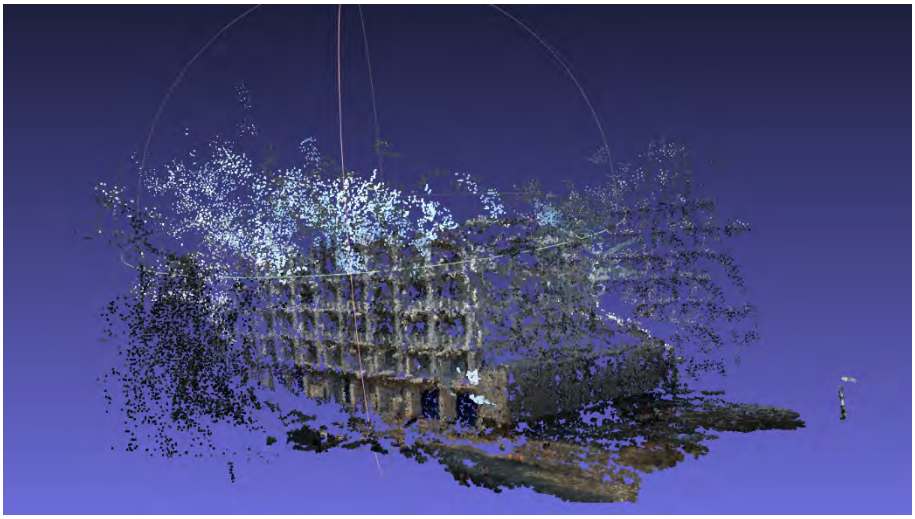


*Figure 5. 3D Model reconstructed from SfM.*



*Figure 6. Drawing area of 3D virtual models (left), Photomontage: Ideal image of drawing 3D virtual models (Sunshades: 3D virtual models; Others: Photo) (right).*

### 3.2. RESULT AND EVALUATION

The experiment verified that the developed system performs registration, tracking at the photography route, and changing colour and installation angle of sunshades. The result of feature-based matching with SURF between live video image and stored images in the database is presented in Figure 7. The results of registration and changing colour and installation angle by typical two patterns are presented in Figure 8. The continuous AR screen shot of tracking while moving on the route is presented in Figure 9.

Although developed marker-less AR system was able to register and track, visualizing error occurred in the registration process. The average error of AR drawing position were 14.5 pixels in the horizontal direction and 27.8 pixels in the vertical direction. In addition, the ratio of error for the AR display were 1.6 % in the horizontal direction and 4.6 % in the vertical direction.

In comparison with marker-based AR systems, the proposed marker-less AR system has two main advantages: (1) installation of artificial markers which affect the landscape view is not required; (2), the user does not require to constantly capture an artificial marker while tracking. Hence, it provides users with more freedom of movement.

### 3.3. LIMITATIONS

The proposed system is currently only capable of performing geometrical registration in the photography route. To solve this issue, new photography routes can be added to expand the coverage area for the system. Additionally, 3D virtual objects are sometimes shaking on the screen because of movement of the user's hand while tracking. In order to compensate user's hand shaking while tracking, the average of motion vectors in plural frames when calculating external parameter can be used. It is necessary to develop and implement new algorithms for such enhancement.

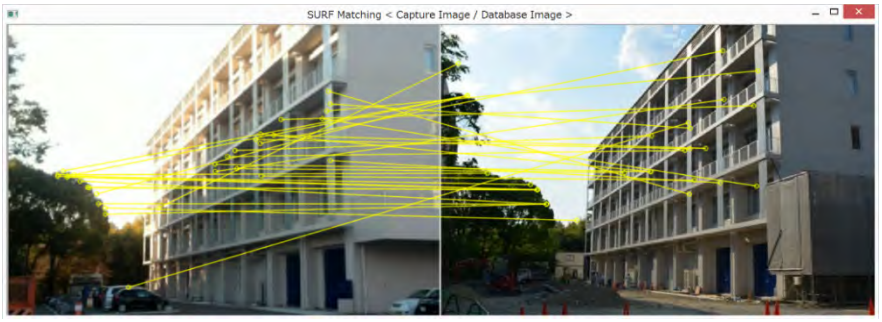



*Figure 7. Example of feature-based matching with SURF: live video image (left) and stored image (right).*

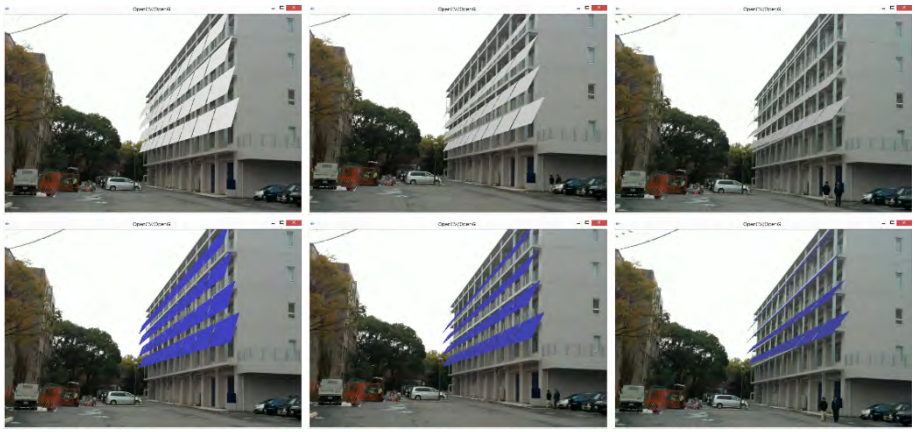


*Figure 8. AR screen shots of changing colour and installation angle patterns.*

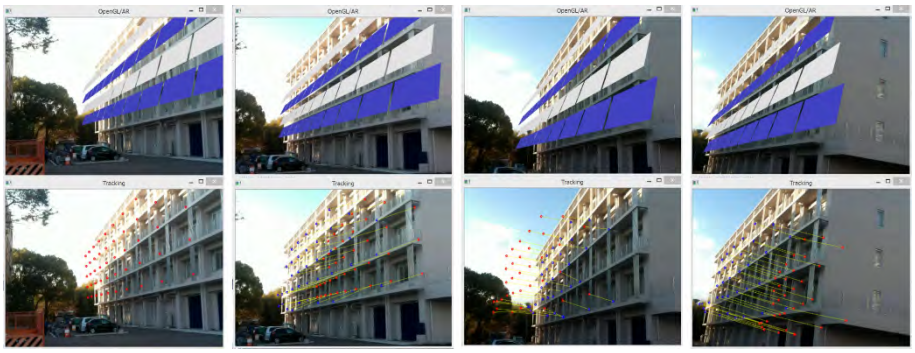


*Figure 9. AR screen shots of tracking while user's walking: AR display for users (above) and motion vectors (below).*

## 4. Conclusions and Future Work

In this research a marker-less AR system with local feature-based image registration technology and SfM, which reconstruct 3DCG model by using photographs from several viewpoints, was developed. The developed AR system has been verified in a case study. In the case study of visualizing sunshades on M3 building located in Osaka University Suita Campus, registration, tracking, changing colour and installation angle of sunshades were tested.

The study showed that it is necessary to precisely identify positional relationship between 3D virtual objects and real world scenes, and to improve the precision of registration and tracking as future work. In addition, it is possible to use this AR system at only the route in which photographs for SfM are taken. Hence, when using the AR system in other routes, camera pa-

rameters are required to be adjusted. Further studies are needed in order to solve these challenges.

## Acknowledgement

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# DESIGN AND FABRICATION OF 3D RECIPROCAL FRAME STRUCTURE

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**Abstract.** Reciprocal frame structure is a special type of spatial structure, which consist of elongated elements. The elements support each other along their span, compose a stable geometrical configuration without any clear structural hierarchy. Based on the morphology, the reciprocal frame could be categorized to 1D, 2D, and 3D. Compared to 1D and 2D, 3D reciprocal frame presents some novel features. It shows a growing pattern with some simple rules. Even with the same rule, 3D reciprocal frame could grow up to different form. It's a typical process of bottom-up which implies a considerable wealth of possibilities. Study on the 3D reciprocal frame gives the potential for achieving novel and complex forms. With the restriction of the category of 3D reciprocal frame, the paper summarized the characteristics of the frame as growth, regularity, and spatiality. And the structure should be repeated, simulated, and constructed. The paper also extracted three basic factors - growth rule, initial form, and bar size. Through the simulation experiments with different factors, the relationships between the frame shape and the factors were established. At the end, a full-scale model validates the feasibility of the growth result of 3D reciprocal frame.

**Keywords.** Reciprocal frame structure; spatial structure; 3-dimension; fabrication; rule-based.

## 1. Introduction

Reciprocal frame structure is a special type of spatial structure, which consist of elongated elements. The elements support each other along their span, compose a stable geometrical configuration without any clear structural hierarchy (Baverel and Larsen, 2011; Larsen, 2014). The structure is most commonly used for roof structures because the span distance could be much longer than the length of the element. Reciprocal frame structure can be

found in ancient China and Japan, also in sketch script of Leonardo (Parigi and Pugnale, 2014).

Based on the topological form, the reciprocal frame could be categorized to 1D (Leonardo da Vinci's bridge), 2D (Leonardo da Vinci's grid), and 3D. Most researches were focused on the form of 2D (Parigi and Pugnale, 2014). The 2D reciprocal frame usually is a topological planar surface, composed with some regular or irregular units. It shows a sprawling tiled pattern. And the design process is top-down. The reciprocal frame is applied to fit the predefined form. The key problem of such application is how to optimize the model to ensure collinear contacts while preserving the geometric from (Douthe and Baverel, 2009; Song et al, 2014; Thonnissen, 2014). Compared to 2D, 3D reciprocal frame presents some novel features. It shows a growing pattern with some simple basic rules. Even with the same rules, 3D reciprocal frame could grow up to very different result. It's a typical process of bottom-up which implies a considerable wealth of possibilities. Therefore, study on the 3D reciprocal frame gives the potential for achieving novel and complex forms (Parigi and Pugnale, 2014).

The complexity is the characteristic of 3D reciprocal frame, it's also the obstacle to study it directly. In this paper, we defined the researchable category of 3D reciprocal frame, summarized the characteristics of the frame, and extracted basic factors to generate the structure. With the simulation and fabrication of the parametric 3D reciprocal frame, we explore the potential morphology and design opportunity.

## 2. Definition of 3D reciprocal frame

Compared to 1D or 2D reciprocal frame, 3D one presents more abundant possibilities and complexity. In general, the structure composed by interlaced elements could be regarded as 3D reciprocal frame. However, there are huge differences among such structures. Interlaced elements could be composed as an ordered bird nest, or as an unordered haystack (Figure 1). Although the latter is also complex, it is very difficult to study since its absence of regularity. So we have to define the 3D reciprocal frame at the viewpoint of research.



*Figure 1. Different organized forms of interlaced elements.*

A researchable 3D reciprocal frame should possess the characteristics of growth, regularity, and spatiality. Moreover, the structure should be repeated, simulated, and constructed.

## 2.1. THE GROWTH OF 3D RECIPROCAL FRAME

The typical 3D reciprocal frame could be grown gradually. Just like a bird nest, it is generated piece by piece. We can restore a 3D reciprocal frame to its original state and observe the growth process to understand dynamic morphology. Also, we can rebuild it.

On the other hand, the growth of 3D reciprocal frame means that the final form is indeterminate. The form will be affected by many factors during its growing process.

The 3D reciprocal frame is grown from a simple unit. The unit is also the basis of the final frame. The bars of the unit compose a pool of components which provide structural support for the subsequent bars. Based on the existing pool of components, any two bars could be selected to add the third bar which ensures the three bars construct a new basic reciprocal frame unit. Meanwhile, the new bar is added to the pool to generate the next bar. With the continued growth, the pool becomes larger, and thus the possibility of the next growth becomes larger, the potential of the final form becomes more. Such growth characteristics, making 3D reciprocal frame difficult to predict the final form, while also showing the richer possibility and complexity.

## 2.2. THE REGULARITY OF 3D RECIPROCAL FRAME

Without limitation, the growth of the 3D reciprocal frame could be out of control, and the result is not only difficult to predict, but also difficult to cognized. Therefore, the application of the rules has a profound significance for the study of 3D reciprocal frame.

In the description of the growth, any two bars of the pool could be used to generate the third one. However, in practice, limited by the length and diameter of the bar and the distance between the bars, only a few bars could be used. The new added bar also causes different results. Some are beneficial to the next growth of the frame, some are not. Therefore, the regularity of 3D reciprocal frame includes two parts, one is the rule of selection from the existing bars pool, and another is the rule of growth of the new bar. The combination of these tow rules makes the 3D reciprocal frame with distinct growth logic, and makes the final form recognizable.

### 2.3. THE SPATIALITY OF 3D RECIPROCAL FRAME

Finally, the research of 3D reciprocal frame is used for exploring the novel enclosed structure. Therefore, the spatiality of the form is an important criterion to evaluate the research. The different initial form, bar size, and growth rules may result in a completely different spatial form. From a practical sense, the study of the spatiality of these elements is valuable.

In summary, the growth and regularity characteristics make the 3D reciprocal frame be repeated, simulated, and constructed. The spatiality could be used to evaluate the form of 3D reciprocal frame. In the study, we also focused on the bar as the element of the reciprocal frame to simplify the research object.

## 3. Simulation and fabrication of 3D reciprocal frame

Many researches demonstrated the shape of reciprocal frame is influenced by the basic unit and bar size (Baverel and Larsen, 2011). For the 3D reciprocal frame, the growth rule is also a very important factor (Parigi and Pugnale, 2014). So we extracted three primary factors – growth rule, initial form, and bar size. Based on the Rhino and Grasshopper, we wrote the program to simulate the growing process with the parameters of initial form and bar size. Afterwards, we constructed a physical model to validate the characteristics of 3D reciprocal frame.

In the process of computer simulation, we set single variable to testify the effect of different factor. To avoid the interference, we also set the most basic condition of three factors.

The basic initial form of 3D reciprocal frame is a fan mode of three bars. It is also the smallest unit of a reciprocal frame. The basic size of a bar is 40mm in diameter, 600mm in length.

The basic growth rule is “recursive” rule which is much like the “flame” model developed by Parigi and Pugnale (2014). Figure 2 shows the growth rule step by step. Starting form a three bars fan, every turn three new bars were added. And from the third round, the added bar was supported by one bar of the former round and one bar of the round before former one. Following the same logic, the frame grew recursively.

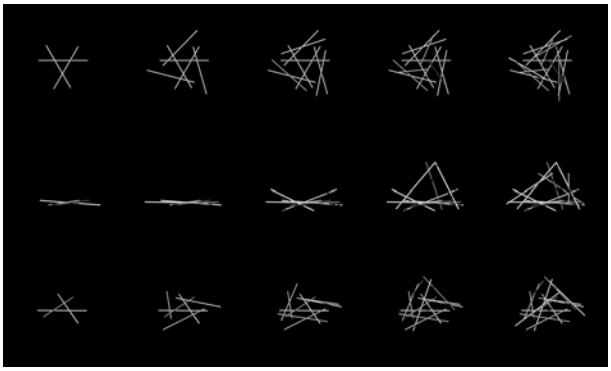
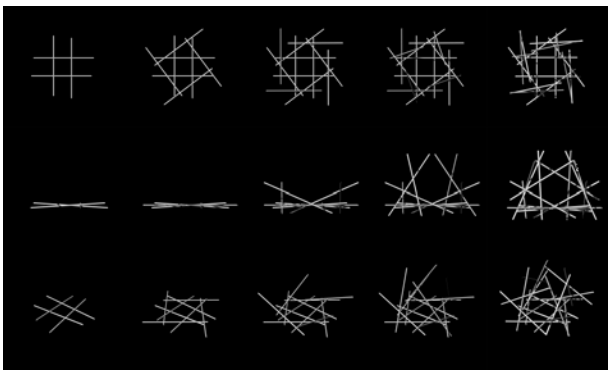


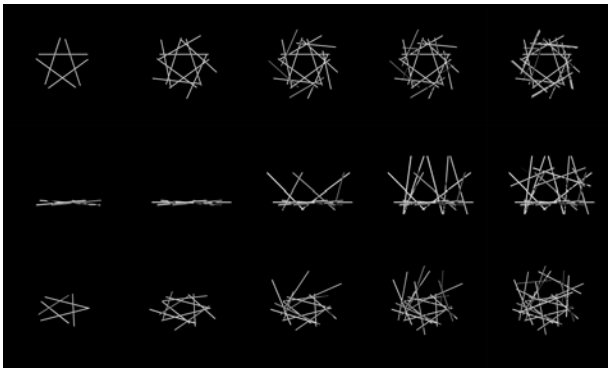
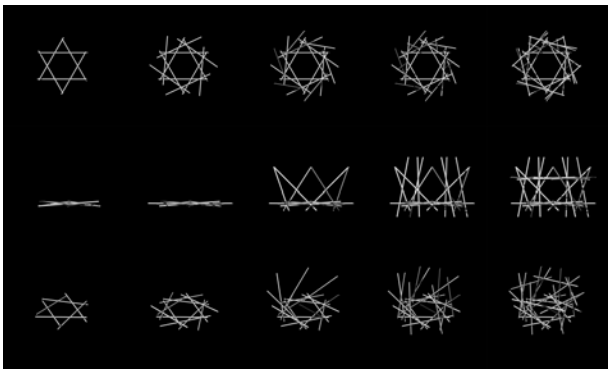
*Figure 2. Diagram of the recursive growth rule.*

### 3.1. THE INITIAL FORM

With the same growth rule and bar size, we tried different initial forms. All initial forms are single unit of fan mode with different bars. Table 1 presents the growing processes of these different initial forms – from three bars to six bars. Every example grew five rounds.

TABLE 1. Growth processes of 3D reciprocal frame with different initial form. (In each image, top row is plan view, middle row is front view, and the bottom row is perspective view.)

| Initial form | Growth processes |
|---|---|
| 3 bars |  |
| 4 bars |  |

| Initial form | Growth processes |
|---|---|
| 5 bars |  |
| 6 bars |  |

As shown in Table 1, with the increase of the bars of initial form, the final form gradually tends to be upward and inward. Especially for the six bars fan, the bars grew at the fifth round tend to be horizontal again, which is similar to the initial form.

## 3.2. THE BAR SIZE

With the same growth rule and initial form, we tried different bar size including diameter and length of the bar.

Figure 3 is the results of reciprocal frame grown after five rounds with different diameter of the bar. The length is fixed at 600mm, the diameter ranges from 10mm to 60mm. With the increasing diameter, the overall shape from flat gradually become stereo, and more open.

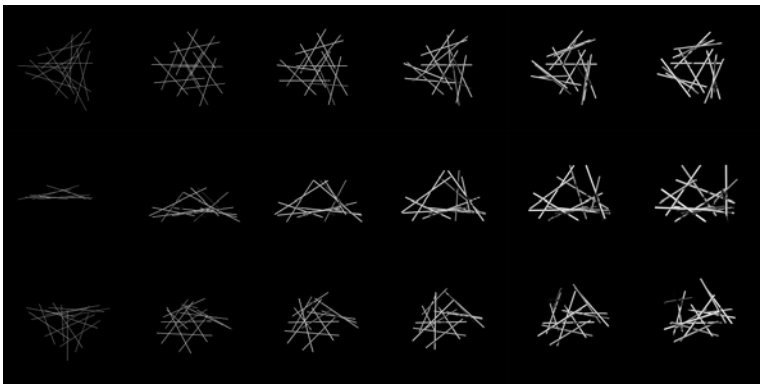


*Figure 3. Reciprocal frame with different diameter of the bar.*

Figure 4 is the results of reciprocal frame grown after five rounds with different length of the bar. The diameter is fixed at 40mm, the length ranges from 300mm to 900mm. With the increasing length, the overall shape from stereo gradually become flat, and more closed.

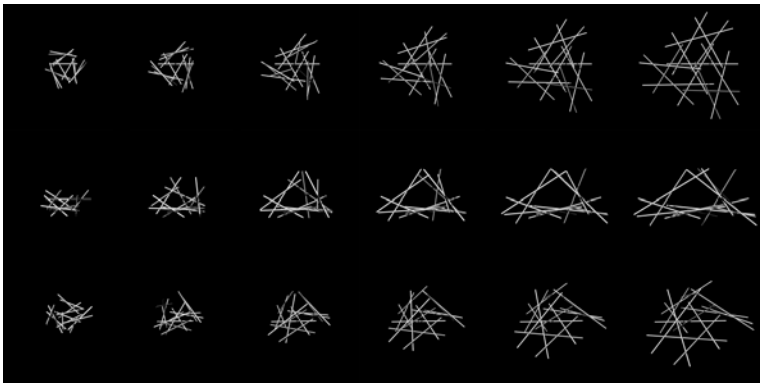


*Figure 4. 3D reciprocal frame with different lengths of the bar.*

Comparing both two groups of the reciprocal frames, we found the close relationship between the form and the bar size. The bar is more slender, the form is more flat and closed. The bar is thicker, the form is more stereo and open.

### 3.3. THE GROWTH RULE

Besides the basic recursive rule, we developed another growth rules to generate the 3D reciprocal frame.

Other than the basic rule, every round we attempted to generate two bars through one existing bar. All of three bars composed a basic reciprocal

frame. Furthermore, we discarded the symmetrical balance for every round. Each round only one bar was selected to generate two new bars. The rule is named “branch”. Figure 5 demonstrates the one possible growth process with branch rule. The green bar is the one selected to generate new bars which are red. It had grown for 8 rounds. With the branch rule, the reciprocal frame is represented as a spiral. It presents a strong regularity, since the selection rule is regular.

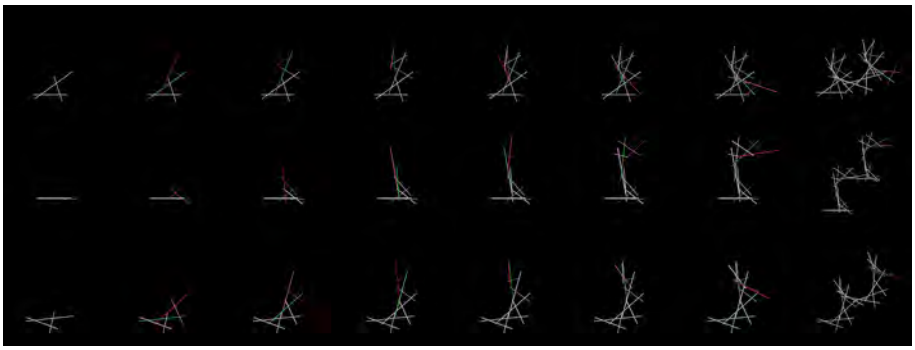


*Figure 5. Growth process with branch rule.*

Although only two rules applied in the study, the result showed that the rule has the different effect compared with other factors. The growth rule is a crucial factor for the shape of the frame.

### 3.4. THE FABRICATION OF THE 3D RECIPROCAL FRAME

The regularity of the 3D reciprocal frame makes the structure easy to construct. And the growth process is also the construction process. To validate the characteristics of 3D reciprocal frame, we constructed a full-scale physical model. We chose a fan mode of three bars as initial form. The diameter of the bar is 60mm, the length is 1800mm. And the final result is the frame grown after 8 rounds with recursive rule.

Because of the complexity of 3D reciprocal frame, the friction of the joint is insufficient to keep the structure stable. During the three families of joint type, we chose the bilateral joint with aligned elements axes which can supply the strongest joint (Parigi and Kirkegaard, 2014). Here we used swivel coupler as the joint which usually used to connect two tubes together at any angle (Figure 6). With the consideration of the thickness of the coupler, we set the diameter of the bar 45mm. In addition, to save the materials, some bars were shortened. The materials used for the final construction included 9 1800mm bars, 15 1455mm bars, and 45 swivel couplers.



*Figure 6. Components used for fabrication of the 3D reciprocal frame – wooden bars and swivel coupler.*

Figure 7 shows the process of the fabrication of the 3D reciprocal frame, and figure 8 is the final result. It is much similar with the simulated result. It validated the ability of the fabrication of the 3D reciprocal frame. And it implies more potentials of application.

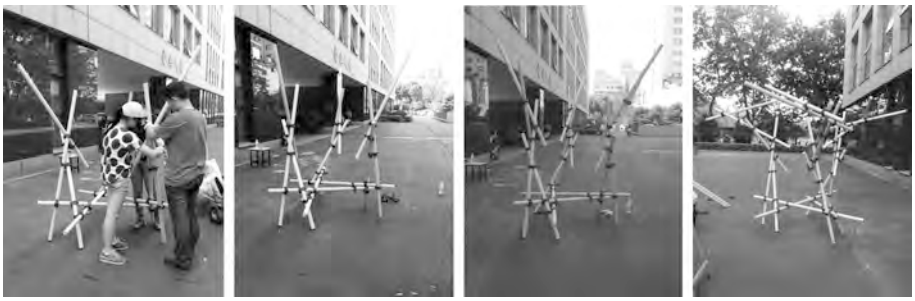


*Figure 7. Process of the fabrication of the 3D reciprocal frame.*



*Figure 8. Result of the fabrication of the 3D reciprocal frame.*

## 4. Conclusion and discussion

In our experiments, including computer simulations and full-scale model, we found the 3D reciprocal frame is more complex than 1D and 2D ones. And the complexity of the 3D reciprocal frame is well organised. It has a close relationship with the growth rule, initial form, and the bar size. The 3D reciprocal frame possesses the characteristics of growth, regularity, and spatiality. Moreover, it can be repeated, simulated, and constructed. Therefore, it is valuable to study and practice.

Within three factors, the growth rule is most crucial to the final shape of the 3D reciprocal frame. As long as the rules are clear, the 3D reciprocal frame can be regarded as a typical parametric structure. By adjusting the input parameters, we can get rich and interesting shapes.

Our experiment still applied some simple growth rules. The complicated rules haven't been applied. If allowing different rules applied in the growing process, the result may become more complex and interesting. All these are subject to our future experiments to verify and explore.

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# THE CORKCRETE ARCH PROJECT

*The digital design and robotic fabrication of a novel building system made out of cork and glass-fibre reinforced concrete*

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**Abstract.** The CorkCrete arch is a 1:1 scale construction aiming at testing the use of robotic fabrication technologies in the production of a novel building system made out of two different materials – cork and concrete (GRC). The combination of these materials is promising since it merges the sustainable and performative properties of first with the structural efficiency of the second one. The result is a material system suited for customized prefabrication and easy on-site installation. The current paper describes the design and fabrication process of the arch, which employed a single parametric design environment to bridge design and fabrication, and an innovative sequence of different robotic processes. The success of this experience invites the team to continue this research into the future construction of larger scale applications.

**Keywords.** Cork; concrete; computational design; digital fabrication; robotics.

## 1. Introduction

The research on robotic fabrication technologies has been a recent but vibrant field in architecture. The automation possibilities, flexibility of movements and diversity of fabrication operations of industrial robots have attracted those interested in exploring innovative strategies in building construction. Introduced in architecture by Gramazio and Kohler in 2005 at the ETHZ, the research on robotics has been widely focused in the production of prototypes and installations, usually made out of a single material. However, some architects have started to tackle the scale and complexity of

architectural buildings with such means. The brick parts of the Gantenbein Winery facade designed by Gramazio and Kohler in Flasch (Gramazio and Kohler, 2015), or the Landesgartenschau Exhibition Hall designed by Achim Menges (ICD) and the ITKE at the University of Stuttgart (Schwinn and Menges, 2015) are some examples of such efforts.

In this context, the Digital Fabrication Laboratory (DFL), a research group of the Faculty of Architecture at the University of Porto (FAUP), developed a 2-year funded research project dedicated to investigate how robotic technologies can assist non-standard modes of design and construction in architecture. After the production of several material experiments, this research was concluded with the CorkCrete arch project, to test the use of robotics to embrace the scale and complexity of construction in architecture.

## 2. The design of the CorkCrete arch

The CorkCrete arch is a 1:1 scale construction aiming at testing the use of robotic fabrication technologies in the production of a novel building system made out of two different, but complementary, construction materials: expanded cork agglomerate (i.e., internationally known as ICB – Insulation Cork Board, but simply referred in this paper as cork), and glass-fiber reinforced concrete (GRC). On the one hand, cork is a 100% natural, recyclable and lightweight material, which can perform many functions at the same time, like thermal, acoustic and vibration insulation (Pereira, 2009; Sousa, 2010). Taking advantage of such performative qualities, an increasing number of architects have used it as an exterior facade material since Álvaro Siza did it on his Portuguese Pavilion in the EXPO 2010. On the other hand, GRC is a composite material where the glass fibers are introduced in the cement matrix to increase the resistance to tensile forces, which is one of the main limitations of concrete (Brookes and Meijs, 2008; Peck, 2006). With this composition it is possible to achieve large-size building components, which are much lighter than traditional concrete ones. For this reason, the application of GRC in architecture is vast and is a growing tendency. Although there are some applications of using cork granules as aggregate in concrete mixtures, the proposed combination of cork and GRC constitute a novel building solution. They define a material system with structural and performative properties, which is suited for customized prefabrication and easy on-site installation in architecture. Envisioning the future construction of larger structures, this work chose to design and materialize an arch to add structural concerns to the formal and material challenges of the design project. To set an original and natural look and a bright interior condition in the

arch, it was decided to employ cork on its outer surface and GRC in the inner one.

## 2.1. PRODUCTION METHODOLOGY

Robotic fabrication experiments usually explore the use of a single material. By employing wood and concrete, the Utzon/40 research pavilion by Supermanoeuvre is one of the still very few examples attempting to robotically fabricate more than one type of material for an architectural construction (Pederson et.al., 2014). The CorkCrete arch project is inscribed in this last tendency. It addresses the critical challenges related with matching the physical tolerances resulting from using different fabrication processes (i.e., robotic and manual) and materials (i.e. cork and concrete). To do so, the geometry of the arch and its material deployment was thought from the beginning in an algorithmic fashion; this rule-based design condition allowed the full development of the project in a parametric design environment. It thus became possible the introduction of adjustments along the process without compromising the digital flow of information between the design and fabrication specifications.

## 2.2. THE DESIGN DEFINITION

The algorithmic foundation of the CorkCrete arch design prompted the use of Grasshopper to generate all the geometric data. A specific mathematical curve - the catenary - was the generator of the whole form. Inspired by some architects from the past (e.g., C. Wren, A. Gaudi or E. Saarinen), this option helped in assuring a certain degree of structural integrity of the design exploration. To confirm such intuition, a solid version of a normal extruded catenary was evaluated in Finite Element Analysis (FEM) software. The tradeoff between design and analysis helped in refining the curvature of the arch. The catenary curve was described in the programming environment as a polyline (i.e. also called a polygonal chain) and then transformed into a quadratic NURBS approximated curve. This element became the thrust curve (Moseley, 1833) and, together with two offset offspring curves defined the general projection of the inner and outer surface of the vaulted arch. This top-down approach turned Rhinoceros into a simple medium for visualization, therefore, no explicit modeling was employed at any moment of the project.

For both aesthetic and fabrication wise reasons, it was decided to use a polyline instead of a more obvious curve to negotiate the encounter between the cork and the GRC panels. Drawn around the thrust curve, each polyline segment had to correspond to the length of a cork panel, to avoid milling their bottom side too. The split of the GRC panels was also aligned with

some of the polyline's vertices. Concerning the sides of the arches, they were slightly tilted towards the interior to increase the structural stability of the arch.

The outer (cork) and inner (GRC) surfaces of the arch were conveniently defined to challenge the subsequent use of robotic fabrication processes. Given that cork was going to be milled, a great level of geometric freedom could be explored with this material. A network surface using three curved profiles and the two edges created a double curved surface, which would serve then as the base for engraving an undulating texture effect. The combination of these two features set a major challenge to test robotic milling. The bottom surface of the GRC panels took into consideration the further exploration of hotwire cutting process to produce their moulds. Thus, two straight lines in the bottom of the arch were connected to a "v" curve in the top to define a curved ruled-surface geometry with a very subtle spine-like effect. Despite all this customized and variable features of its geometry, the arch features a double bilateral symmetry to assume a provoking classic presence. The whole material geometry and structure of the arch is described on Figure 1.

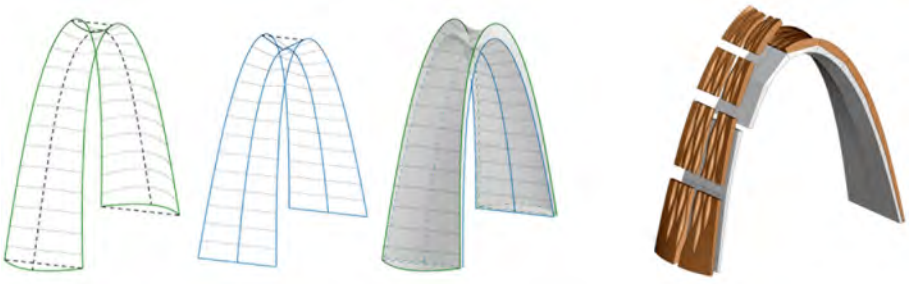


*Figure 1. The geometric generation of the CorkCrete arch, and the materials' structure composed by 18 cork panels and 3 GRC panels.*

## 3. The fabrication of the CorkCrete arch

The production of the CorkCrete arch was organized in two parts:

- the GRC panels - through robotically fabricated EPS molds and subsequent manual GRC spraying;
- the cork panels - entirely robotically fabricated.

All robotic processes were conducted at the DFL's lab using a Kuka KR120 R2700 HA industrial robot. In all situations, the exploration of a continuous parametric design process allowed to automatically generate all the necessary data for the various operations. Figure 2 describes the digital flow

from the programming of the arch geometry and material definitions to the fabrication of its various components. The manual spraying of the GRC took place in the precast concrete factory of the industrial partner Mota Engil.

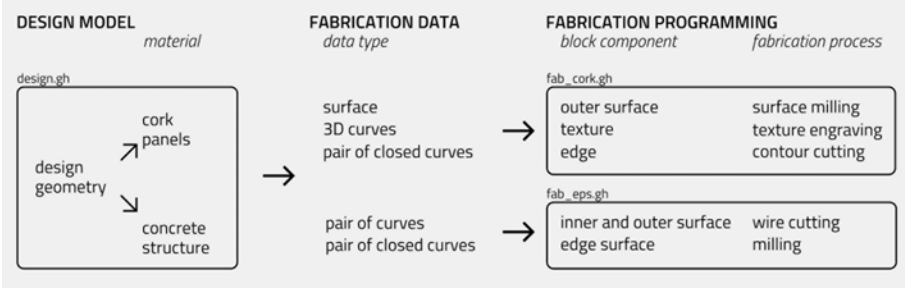



*Figure 2. The single parametric workflow that integrated the design and fabrication process.*

## 3.1. THE GRC PANELS

Taking advantage of the GRC properties, the concrete panels of the Cork-Crete arch were designed as thin elements with 15mm thickness with lateral folds in all with a minimum of 40mm height to assure its structural integrity. The geometry of such elements dictated the need of custom molds, which were fabricated using high-density EPS blocks (Figure 3).



*Figure 3. The fabrication of the EPS molds for the GRC panels.*

Although it would have been possible to mill the EPS molds, a previous experiment revealed that this process was inefficient regarding fabrication time surface quality and material waste generation. As shown in previous works by Feringa and Søndergaard (2014), robotic hot wire cutting (RHWC) of EPS molds is the ideal fabrication technology to address the situations dealing with ruled geometries, which was the case in the CorkCrete arch. Thus, the robotic production of each EPS mold was organized as a sequence of 3 hotwire cutting and 1 contour milling operations in order to produce the surface curvature and the boundary contour for the GRC panels. Due to the size limitations of the hotwire tool but also the nature of the ruled geometry

(i.e., concave in the too component), the molds had to be split in two symmetrical longitudinal halves. In total, the 3 GRC panels implied the robotic production of 6 EPS (half) mold parts. It should be noticed that the curved geometry of the top part of the arch required the organization of the raw EPS blocks in a “L” shape. Excluding tool changing and setup time, the fabrication sequence for each half took an average of 10 minutes to be completed. The resulting pieces were then glued together to define the final 3 molds, which were then shipped to the precast concrete facility of Mota Engil.

At the factory, the molds were initially treated with a demolding oil, while a set of metal connection rings were inserted into to EPS to become embedded in the final GRC panels. The GRC was then carefully sprayed and manually compacted against the mold, assuring a thickness of 15mm. in the end of this process, a positive EPS piece resulting from the mold carving was placed inside the cavity to provide support for fixing the cork panels (Figure 4). In this way, the building system absorbed the wasted material produced during the robotic fabrication process. After a 24 hour curing time, the panels were demolded and manually sanded to smooth some surface texture resulted from the EPS porosity.



*Figure 4. The fabrication of the GRC panels.*

## 3.2. THE CORK PANELS

As mentioned before, the design of the CorkCrete arch just considered the milling of one side of the cork panels. This greatly simplified the milling process while introduced an interesting design feature in the structure – the polyline joint separating the cork panels from the GRC ones. The stock material used for the cork panels was composed of expanded cork agglomerate blocks with 1000x500mm supplied by industrial partner Amorim Isolamentos. Their thickness ranged from 8cm to 14cm, in order to minimize waste material.

The fabrication routine for each of the 18 cork panels was structured in a sequence of 3 milling operations: (i) milling of the curved surface of the panel; (ii) engraving the texture, and (iii) cutting the contour of the panel (Figure 5). Both the first and third operations used a 150mm long flat end

tool with a 20mm diameter. The second operation used a wide tool with an end shaped as a paraboloid of revolution. By following a few undulating tool paths, this tool carved an impressive texture in the panels. To optimize fabrication time, the panels were produced in batches of 4.



*Figure 5. The robotic fabrication of the cork panels.*

## 4. The installation of the CorkCrete arch

To detect possible errors, check the best way to erect it, and survey its structural stability, the CorkCrete arch was pre-installed in the lab. This experience tested the bolt and notch connection system and allowed to detect some minor alignment deviations between three panels, which were easily corrected by hand.

The next day, the CorkCrete arch was assembled in the old garden of the FAUP, in order to record some video scenes to complete a short movie documenting the whole production process of this project. Being the second time, its assembly was faster. It took around 40 minutes with 5 people working without the need for any mechanical mean. The compressive behavior of the structure allowed the arch to simply rest over the floor and, after 3 hours, it was disassembled.

Three days later, the arch was assembled for a third time (Figures 6). This time it happened in a garden platform of the school to be officially presented to the public, as part of the final presentation event of the broader research project to which it belonged. Given that the earth was very soft and not leveled, a couple of small rods on each leg were inserted in the ground to provide some extra stability. The arch has stayed in place for 5 consecutive days and was experienced by students, faculty and other visitors (Figure 7).



*Figure 6. Installations of the CorkCrete arch at the DFL and at FAUP.*



*Figure 7. The CorkCrete Arch on its last installation at FAUP.*

## 5. Conclusion

This paper presented an original building system made out of cork and GRC components fabricated through robotic processes. To test this system, the

DFL team designed and materialized the project of an arch, which addressed a wide set of design, material and technological challenges in architecture and building construction.

Regarding the design, the catenary based geometry of the arch proved to be structural efficient in reality. Despite the solid condition of the built form, its assembly could be done manually and for three almost consecutive times, due to the lightness of the combined cork and GRC material system. This is an important feature because is aligned with current trends in the building industry towards lighter and more sustainable modes of construction. At the same time, the combination of both materials defined a singular aesthetic and perceptive effect. The external dark, textured and soft look of the cork covering, contrasted with the bright, smooth and rigid appearance of the interior GRC panels. These qualities triggered the curiosity of the people who felt compelled to visit and touch it. (Figure 8) Nonetheless, the thermal and acoustic insulation properties brought into the system by the use of cork could not yet be observed in this construction. A more enclosed space would be required to begin to understand them.



*Figure 8. Material details and effects of the CorkCrete arch*

From the technologically point of view, the use of robotic fabrication was confirmed as a precise and flexible process to fabricate building components. Besides the success achieved in matching different materials obtained by different fabrication processes, the use of robotic technologies opened some real innovative opportunities for the GRC and cork industries. The use of hot-wire cutting assured a fast and reliable way to obtain EPS molds for the production of single curved GRC panels. Regarding the cork panels, their intricate and variable geometry and texture simply could not be done by any other method. The 6-axis movements of the robot were decisive for this application.

After the construction of this arch, the DFL is now pursuing the construction of a larger structure – a pavilion - where other aspects of the CorkCrete building system (e.g., thermal and acoustic insulation and lateral assembly) could be further tested.

## Acknowledgments

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# EXTRUDED ARCHITECTURES

*Grading weight-to-strength ratio of cement based materials through extrusion techniques*

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**Abstract.** In recent years, a growing research agenda on the subject of additive manufacturing for architectural design has been established on the basis of jetting and extrusion technology. While jetting provides enough flexibility to print multiple digital materials in a single run, extrusion has proven to be the most viable technique for large-scale and on-site manufacturing. Because major contributions of both research lines cannot be combined due to technological differences, special attention has been devoted towards the development of printing strategies that could approximate similar material flexibility of jetting by means of extrusion techniques. In this context, this paper presents a computational design methodology for architectural components that enables grading weight-strength ratio of cement based materials through extrusion. Built upon the integration of modelling, analysis and fabrication, such methodology allows to optimize material distribution and geometric definition on the basis of physical and fabrication constraints. A case study is presented for describing the design processes of a circular column and the fabrication of a section it.

**Keywords.** Additive manufacturing; cement based materials; computational design.

## 1. Introduction

Traditional manufacturing technologies dominated by economies of scale are progressively losing ground against more democratized and digitalized technologies. Nowadays, designers have the capacity to produce in a way that, until now, was considered impossible or non-viable. Because of that, manu-

facturing is shifting from global to local, which is a promising condition for more integral and ecological processes.

Additive Manufacturing (AM) is the key element enabling this move from mass production to mass customization where the main problematic does not relay anymore on materialization, but on what worth to be materialize.

Aiming to face this dilemma, this research interrogates about the feasibility of designing building elements where material and geometry could be optimized by embedding constrains taken from physical and fabrication logics. A computational methodology is presented that facilitate the sequential transformation of voxel based models in order to drive the gradation of material´s weight through extrusion.

In doing so, a composite material has been formulated by mixing a cement-based matrix with granular lightweight materials. Such composite results on a porous yet structural network with various degrees of performances. Gradations range from an extremely lightweight, to less porous mixture with a high strength-to-weight ratio.

## 2. Background

AM has the potential to revolutionize current fabrication and design processes where main efforts for printing architectural pieces are established around jetting and extrusion techniques. Differences relies on the fact that jetting deposit droplets of material, either a binder or a photo-curable resin, while extrusion deposited a continuous filament of material. Most important studies based on jetting (Dillenburg and Hansmeyer, 2014; Oxman, 2010; Palz, 2012) are oriented towards the development of computational methods enabling the gradation of local properties and resolutions through state-of-the-art jetting machinery, where an exception is the D-Shape technology (Dini, 2015; Kestelier et al, 2014). On the other hand, studies built upon extrusion (Buswell et al, 2007; Khoshnevis, 2004; Khoshnevis et al, 2006; Kwon, 2002; Le et al, 2012a; 2012b; Lim et al, 2012) are focused on the development of tools and machinic setups for large-scale operations. Due to technical differences concerning the mode of depositing material, computational methods based on jetting cannot be directly used for driving material extrusion operations.

The main advantage of extrusion is the capability to operate in non-hermetic working volumes facilitating ideal scenarios for on-site construction through collaborative robotic setups. Additionally, it allows the usage of common building materials (e.g. cement, clays, and plasters), the relative reduction of secondary structures (e.g. scaffolds, formworks) and the simplifi-

cation of operations and mechanical devices. Because of this, the mainstream of studies for reliable large-scale fabrication are based on extruding high performance cement based materials through low-controllable curing techniques (i.e. wet processes). Because processes are extremely constrained by the low tensile and flexural strength of such mineral materials, additional studies have investigated design strategies for post-tensioning reinforcement of 3D printed pieces (Lim et al, 2011).

However, since objects are printed layer by layer, operations are equally restricted by the weight of each layer which is directly affecting the stability of the entire structure. Although this condition is not so relevant when printing with polymer composites, it is accentuating when printing with cement based materials. This is because each layer need to be strong enough to support the next upper layer without collapsing, and soft enough to allow old and new material layers to be blend. Considering the relative lack of studies on this subject, an interesting approach has been developed with the aim of enabling the capability of grading material's nominal through extrusion. As a result, a composite material with cementitious matrix has been formulated allowing to manage different values of strength-to-weight ratio.

## 3. Material experiments

Ordinary Portland cement was used in combination with varied amounts of silica fume to formulate the matrix of the composite material, Different controlled mixtures combining such cementitious matrices with small lightweight aggregates of expanded polystyrene foam (EPS) have been tested. Additional doses of super plastifier are required in order to reduce the amount of water in the mix. Such characteristic is of vital importance since it directly affects extrusion operations and blending quality with EPS. Because curing processes only depends on mortar's drying, machinic sophistication are reduced. This means that simpler production methods can be achieved by accurately controlling timing and ratio of components by setting specific numerical values.

Large number of samples were manually fabricated by gradually varying the quantity of EPS in the mix (Figure 1). From this, it has been stated that:

- **Excess of water** reduces the cohesion of components which is mainly manifested by the EPS floating on the surface of the mixture.
- **Excess of cement** leads to unwanted heavyweight mixtures despite having high strength characteristics.
- **Excess of EPS** drastically reduces component's cohesion and mixture's weights while its reduction will equally generate high-strength mixtures with undesirable heavyweight properties.

- **Small doses of super plastifier** reduces the requirement of water while guarantying mixture plasticity and cohesion with EPS.

Abstracted information of physical experiments serve to conduct design of experiment studies where hundreds of digital mixtures were analysed. Even though unlimited mixes can be calculated through digital packages, physical mixes needs to be finite. Therefore, five individual mixtures are defined with the greatest desirable properties for building purpose and extrusion operations.

A material coding terminology was constructed similar to #C#EPS, where C refers to the amount of cementitious matrix and EPS to the amount of lightweight aggregate. Large margin of errors are not allowed for the preparation of each mixture due to the advent of undesirable characteristics.

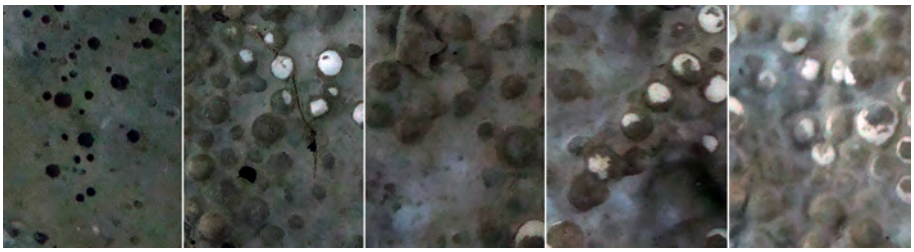


*Figure 1. Gradation of EPS in a cementitious matrix.*

## 4. Methodology

### 4.1. MATERIAL LOGICS

Digital and analogue material's experiments aided us to formulate principles for the development of generative techniques driving the gradation of material's weight. A customized process of voxelization and voxel's classification is then established. Through diverse structural analysis plugins, Beso2D (Zuo, 2016) and Millipede (Panagiotis and Sawako, 2015) for Rhinoceros-Grasshopper, building elements are analysed with the intention of extracting material densities when elements are subject to different forces. By horizontally and vertically slicing structural models, a collection of raster images is generated from analysis which, in turns, is used as input for the construction of a voxel based model.

Voxelization can be described as the three-dimensional extension of raster graphics where pixels are converted into voxels by adding the Z component to two-dimensional vectors defining locations. A voxelization algorithm implemented through Python in Grasshopper was used to match raster information extracted from analysis, into three dimensional geometrical mod-

els composed of voxels. Each voxel is geometrically represented by a box with a side length equals to material's thickness when extruded. Such condition allow to have horizontal layers of voxels equivalent on size to material layers of 3D printed pieces. Furthermore, data regarding colour's composition in each pixel is associated with specific materials properties in voxels. Because these models contain information of a high number of materials, an additional step for simplification based on sorting voxels is required.

In raster graphics, the colour of each pixel is typically symbolized by components representing red, blue and green (RGB), or cyan, yellow, magenta and black (CMYK). In order to display different colours into an image, a progressive linear transition from one colour to another is required. Depending on image resolution, this area could contain unlimited combinations of pixel colours. However, pixels being part of this transition are quasi unnecessary for drafting the general idea of the image. Thus, they can be condensed into more predominant colour values in order to reduce image's resolution.

Such approach can be equally applied for limiting the number of data in voxel based models by regrouping similar materials into major clusters corresponding to the five previously defined optimum mixtures. Nevertheless, these models continues to have a high degree of material resolution which is only supported by jetting technology. Since extrusion cannot deposit droplets of material, printing paths need to be extracted from boundary curves or regions.

## 4.2. PRINTING LOGICS

In the context of a two-dimensional orthogonal Cartesian system, each horizontal layer of our model generate a two dimensional irregular pattern with different regions corresponding to clusters of voxels. For each region, the centroid was calculated, and then converted into a seed for building a two-dimensional Voronoi diagram intended for smoothing purposes.

Printing path is then defined through sets of contour curves extracted from walls of Voronoi cells which means that layers are printed cell by cell in a non-continuous run. If a cell is too small for printing then it can be merged with the closest neighbour containing the same, or close to the same, mixture data. Two-dimensional cells are then lofted with its corresponding upper layer, creating an internal three-dimensional cell distribution.

As soon as one cell is manufactured, the nozzle stop extruding material and goes to a stationary position before restarting the fabrication of the next cell. For each cell, such position correspond to the centroid of the next cell to be printed with a safety value for the Z axis. By inserting these constraints,

timing of operations can be optimized, mixture's volumes accurately calculated and machinic operations paused for reloading the nozzle. While timing is correct, mixtures drying together shape a unique material system that supports various degrees of weight-strength ratio according to local positions.

## 5. Case study: single load case column

With the purpose of testing the methodology, we delineate an initial problem for designing a column with circular base that is subject to a unique load and a support region. The load expressing exclusively the self-weight of the material, is defined by a negative vector perpendicular to the horizontal plane (Figure 2).

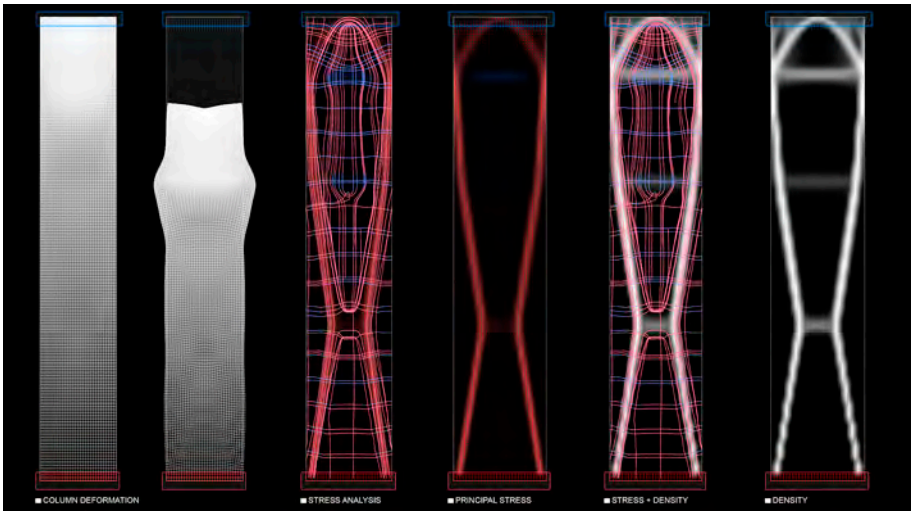



*Figure 2. Problem definition of single (vertical) load column.*

The design process starts with the structural analysis describing the deformation of the column and internal material densities. Voxelization is then carried out with the subsequent voxel's clusters classification (Figure 3). From this, centroids are extracted layer by layer in order to provide a populations of seeds for generating Voronoi diagrams (Figure 4).

The resulting model shows a symbiotic relation between complex inner structures and graded material's properties. A principle already adopted by bone's systems where material's properties are closely connected to geometry and topology in order to assure structural integrity. The column has revealed the emergence of patterns where complex cellular lightweight materials analogous to trabeculae bone, are strengthened by compact heavyweight

materials similar to cortical bone. The methodology has also been tested with different scenarios having multiple load regions (Figure 5).

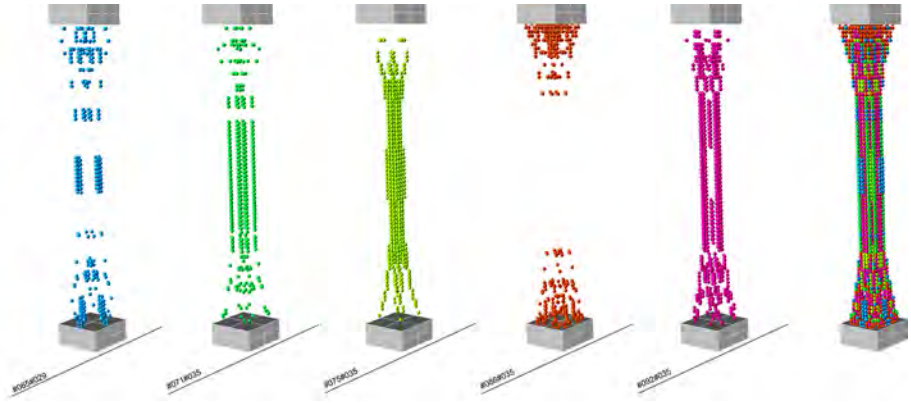


*Figure 3. Voxel's clusters distributions according to physical mixtures.*

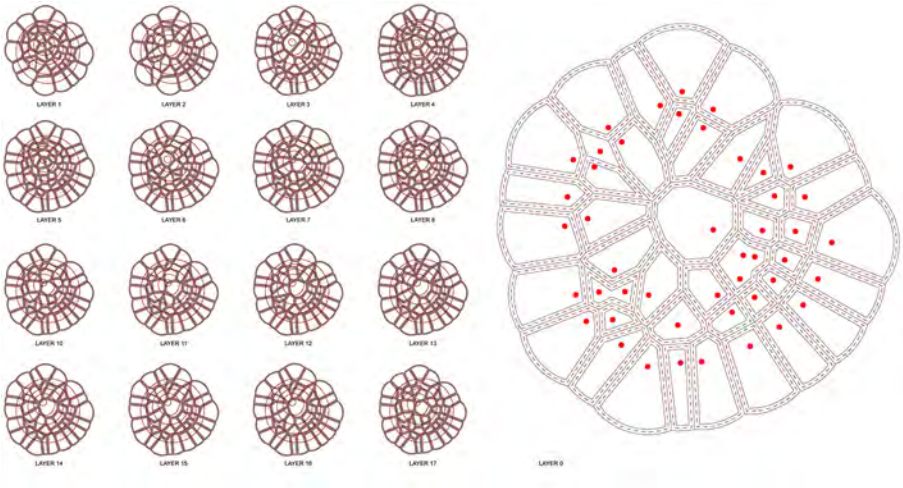


*Figure 4. Cell generation.*

A section of the column (Figure 6) was manufactured through a custom-built nozzle attached to a standard three axis CNC machine. An Arduino Uno board connected to an electrovalve is used to control the air compressor for extruding materials. Such nozzle has provided adequate control and precision for this step of the research even if it has displayed the impossibility to automatize preparation of mixtures.

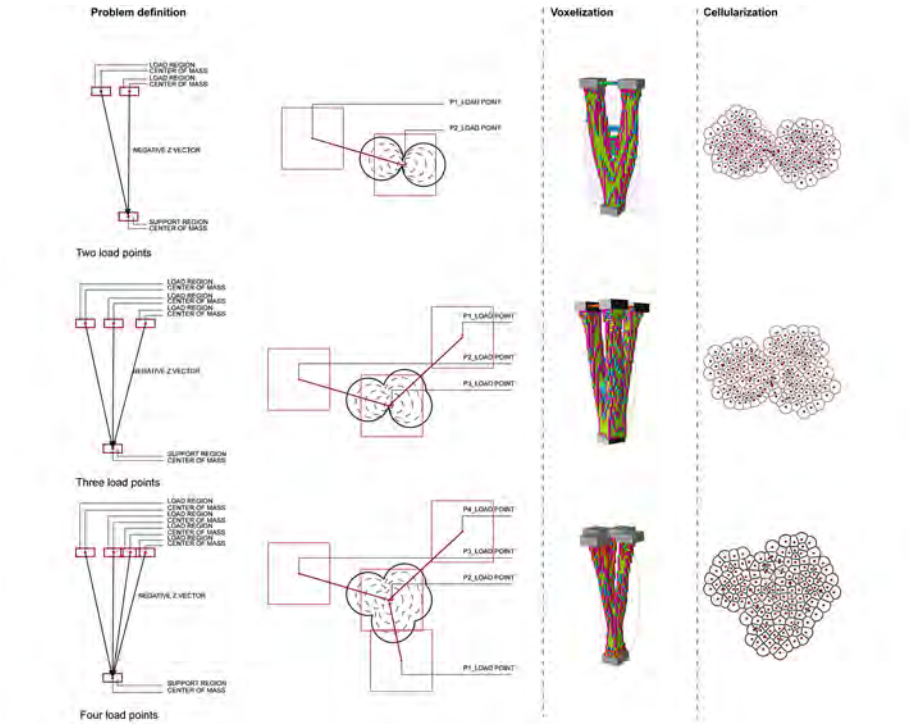



*Figure 5. Column with different load case scenarios.*

Mixtures have then been prepared by hand and loaded into the nozzle in order to initiate the extrusion process. Because printing process can be paused for recharging the nozzle, mixtures can be arranged into layers inside the nozzle. The amount of required material as well as the timing of operations is directly specified by the computational model.



*Figure 6. Column section.*

## 6. Conclusion

This research began with the aim of investigating how material's properties of cement based materials can be graded on the basis of extrusion operations. On this basis, a new methodology has been presented where voxel based models are transformed into cellular based models facilitating the extrusion of five types of cement based materials. This methodology has solely been tested on compression-only structure giving the low tensile capacity of cement based materials. Special attention for upcoming studies demands the incorporation of strategies for secondary support material enabling the fabrication of more complicated geometries.

In addition, efforts need to be equally directed towards the development of highly specialized effectors (e.g. nozzles, mixers). Automatizing mixing operations has proven to be an extremely complicated labour. Such process is of vital importance for the research since a major number of physical mixtures could be produced without affecting timing of operations. A condition that is essential for guarantying the integrity of the structure during the entire manufacturing process.

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# SMART ASSEMBLY IN DIGITAL FABRICATION: DESIGNING WORKFLOW

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**Abstract.** Digital fabrication project in academia has produced many grounds for experimentation. In recent years, techniques have also been tested extensively in practice within commercial project setting. This gives rise to an emerging breed of architectural practices whose work is increasingly centred on resolution of complex geometry to realizable projects. The resolution of parametrically driven design to production projects requires a different workflow, as often the compressed timeframe and budget requires the parametric model to cope with multiple streams of construction output as well as utilize the model in concurrent design processes. This paper examines a commercial project as case study to explore the abstraction, reduction and dissemination of information within a digital fabrication workflow. In this project, digital fabrication is deployed to reduce risk; mainly in manufacturing and its lead time. The research reveals how metadesign process at an early stage of the project can contribute to increase efficiency of the parametric model as well as delivering multiple streams of information for all the collaborators: architects, fabricators and builders. The team designed the assembly procedure into the parametric workflow to facilitate off-site and on-site assembly. This is possible through imbedding 'smart' detailing and structuring information with the workflow. The paper concludes by reflecting on the workflow and asks if a metadesign driven fabrication workflow can create a more holistic approach to digital fabrication. The outcome of the case study is just one instance of the parametric machine that is developed from an understanding of assembly process. This paper responds to the theme of continuous designing, through looking at digital fabrication as co-emergence of design procedure and practice.

**Keywords.** Digital fabrication; construction; design workflow.

## 1. Introduction

Novel technique aside, the primary concern in digital fabrication is the information translation of descriptive geometry to Computer Numerical Control (CNC) fabrication. Scheurer (2010) identified this process as the abstraction of the problem and the reduction of information through removing redundancies. While digital tool making facilitated the procedure (Burry 2011) it is not without its set of difficulties in practice; front loading, deterministic, anticipating flexibility to name a few (Scheurer 2011; Davies 2013).

This paper looks at the digital fabrication of a commercial project as case study, an undulated ceiling for a showroom, to further explore the problem of abstraction, reduction and dissemination of information in practice. The resolution of parametrically driven design to production projects requires a different workflow (Shadkhou and Bignon 2010; Scheurer 2011; Pen de Leon et al 2013), as often the compressed timeframe and budget requires the parametric model to cope with multiple streams of construction output as well as utilize the model in concurrent design processes. In a commercial project, the manufacturing framework is often well defined; that is to say the type of machinery (tools) and material system are implied to reduce the commercial risk of the project, both financially and in manufacturing lead-time. With a prevalence of advanced parametric modelling, this tends to create a situation where the construction method or techniques of a particular project is least developed especially in a commercial project environment. There is neither time nor financial incentive to prototype and develop the material system. Traditionally, architects tend to rely on the builder to resolve the construction and assembly problems. In practice, this poses two issues. Firstly, the design resolution is greater than the construction resolution. The contractor becomes overwhelmed by the complexity and starts pricing in risk to the project (Tower and Bacarini 2012). Secondly, the parametric model becomes representational; an image to build from. The information built into the workflow is descriptive geometry especially in the absence of a physical prototype (Loh 2015).

The team designed a ‘smart’ assembly procedure which allowed the construction sequence to align with the information structure of the parametric model. The ‘smart’ assembly suggested an approach to develop digital fabrication workflow from construction and assembly logic which allowed a more cohesive process from design to fabrication to on site assembly.

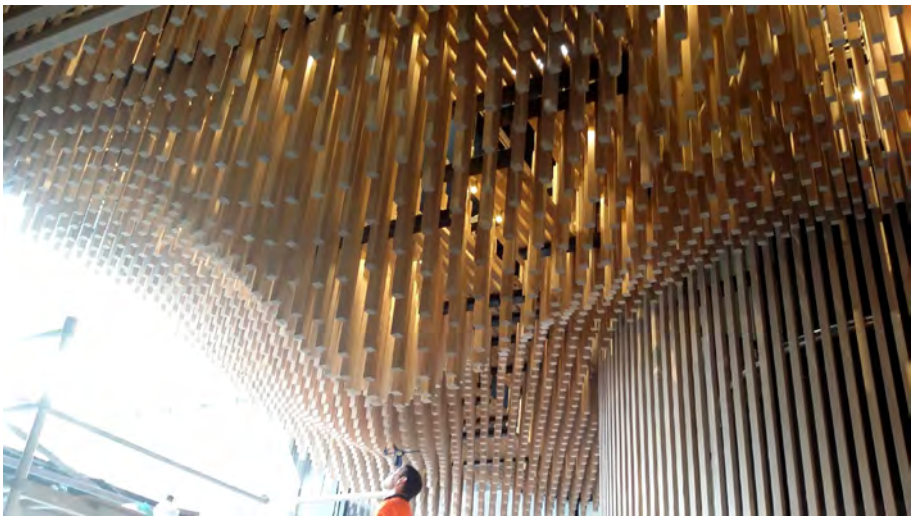


*Figure 1. Completed ceiling project.*

## 2. Background

The project was an undulated timber ceiling for a show suite in Australia, Figure 1. The ceiling consisted of 2,100 battens of Tasmanian Oak each with a 42 x 42mm square profile. The area of the project is about 7m x 7m. The initial design of the ceiling was by Woods Bagot. Power to Make was employed directly by the main contractor, Westbank Constructions, to complete the design and produce fabrication information. At the time of appointment, the design to fabrication team was given a parametric model from the architects sketching the overall form and rough boundary of the ceiling; no further technical resolution was given. The fit-out of the show suite was already half way through the build and the team was given 5 weeks to complete the design (3 weeks for design and 2 weeks for fabrication and installation on site by the contractor) in time for the opening.

This paper will mainly focus on the workflow carried out by Power to Make. Their responsibility included:

- Design and develop the ceiling hanging structure. The hanging structure needed to be flexible enough to avoid the large array of services in the ceiling zone as well as enable a simple and speedy installation procedure.
- A parametric model to allow the architect's team to fully interact and adjust the design. The survey of the ceiling boundary was not defined at the start of the design process.
- Identify the material quantity so the contractor can confirm final pricing.

- Produce fabrication information for the contractor. Although the contractor used his preferred CNC fabricators, the design team owns and operates a 3-axis CNC router and the tooling knowledge is imbedded in the design.

While the above fits into the context of post-design process (Shadkhou and Bignon 2010) where construction, assembling and fabrication information are assimilated into an integrated digital workflow, the authors argue that there is opportunity for designing through developing construction and assembly strategy as metadesign.

## 2.1. BUILDING IN SMART ASSEMBLY

The ceiling design consisted of two systems; a standard steel c-channel sub-frame supported by hanging rods forming bays and timber components consisting of vertical timber battens notched at variable heights onto a horizontal batten, typically 4 vertical battens per horizontal batten, refer to Figure 2 below. The steel sub-frame between bays is shared where possible between the timber components of adjacent rows. The timber components are fabricated off-site.




*Figure 2. Assembly sequence of ceiling.*

The system is designed to enable the steel sub-frame to be erected on site while the timber components are fabricated off site. When the timber components were completed and delivered to site, the steel hanging structure is ready to receive them. Each piece was indexed so the fabricator and contractor could arrange the components in the correct sequence. The challenge for the design team was to build this assembly sequence into the fabrication process. During the process, the team designed and developed smart assembly detail in response to the various construction and design issues:

- As mentioned, all the fabrication is to be completed by other fabricators. The design team had no control over the fabrication and its assembly procedure.

The contractor was based off site and there was no opportunity to check the parts before delivery to site. Effectively, all the instructions needed to be self-explanatory and indexed on each piece.

- Time constraints on site required components to be quickly erected with a fool-proof assembly sequence to minimize the contractor's risk. This came down to the detailing of the timber components; to be as simple as possible with minimal amount of steps to reduce labour. The team designed a simple notch within the timber components to facilitate the 3d positioning of the parts. Adding notches to the steel frame was not feasible as it would increase the cost of the package.
- The optimum setting out of the steel sub-frame hanging planes effectively reduced the amount of steel and weight to the entire ceiling. The sub-frame sets out the positioning of all the timber components. As an assembly strategy, it meant that once the first row of timber components is positioned, the spacing of the remaining rows are defined; leaving little room for misalignment as long as each set of timber components are pack tightly, refer to Figure 2, step 3.

From the above, the 'smartness' of the design was not in the fabrication process but rather in the assembly sequencing. That is to say, the information of the 3d position of each piece was governed by the assembly sequence or action. The challenge was to develop a workflow that allowed for a concurrent processing of information that mimics the planned sequence. It is worth noting that the geometric complexity of the project was not in the undulated surface but in managing the information flow, from design to fabrication to assembly information.

## 2.2. BUILDING IN SMART WORKFLOW

The workflow for both design and fabrication visual script was set out in McNeel Rhinoceros with Grasshopper v0.9.0076. The workflow merged the construction logic with the design logic. Construction setting out is declared at stage B of the workflow; tabulated as bays and grids. At stage D, its structure was reorganized to align with the assembly data output. Pen de Leon et al (2013) described the above workflow as Flexible Automated Digital Design to Fabrication Workflow. However there is a key difference; their model excluded or perhaps didn't prioritise the assembly logic in the workflow.

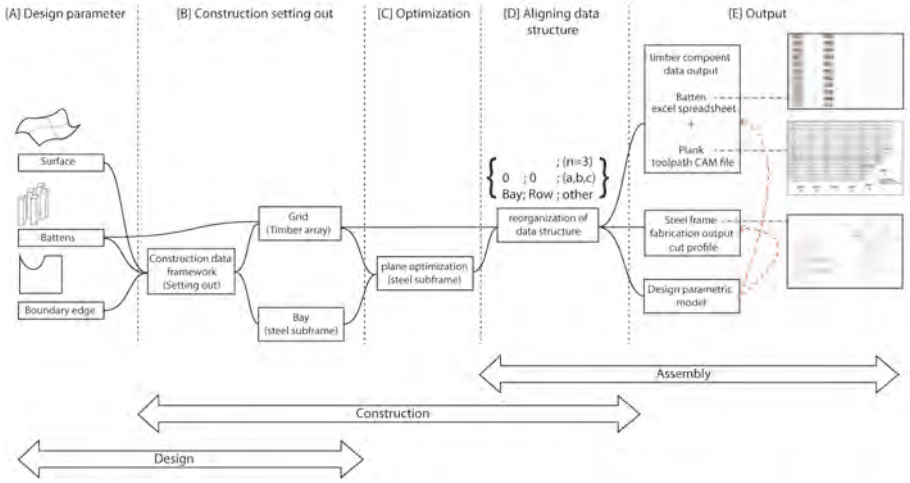



*Figure 3. workflow diagram.*

The above workflow in Figure 3 sketched out the metadesign of the process; designing the design (Giaccardi 2005). The unique positioning of the team within the design and fabrication processes allowed the team to redesign the project from first principle; through construction and/or assembly information (Shadkhou and Bignon 2010). While the construction information described the topology and 3d positioning of the parts, the assembly information described the type of joints or assembly connection; in this case study, the type of notch which enabled precise positioning of the timber components onto the steel sub-frame. What is unique here is the 'and/or' possibility of the visual script to process both sets of information in parallel. The team in designing the assembly sequence into the design of the ceiling effectively re-worked the operating system through metadesign process (Giaccardi 2005) in which the visual script plays a larger engagement role in connecting design feedbacks, site survey and site assembly. As a result, the script acted as a coordinated model for the various collaborators; architects, fabricators and builders. This coordinated model allowed the collaborators to close the gap between design, fabrication and assembly. The latter is perhaps the least discussed in research on digital fabrication (Griffith et al 2006; Shadkhou and Bignon 2010) and yet (from the author's experience) construction is one of the least controlled and messy aspects of any fabrication project (Loh 2015).

## 3. Integrating construction and assembly information

### 3.1. ALIGNING DATA STRUCTURE WITH CONSTRUCTION SEQUENCE

The visual script is designed to have multiple predetermined output requirements. Firstly, to produce a geometric model with low resolution construction detail for the architects to review, make adjustments and feed back into the workflow. Second, it simultaneously produced a construction model with high resolution construction detail that outputted relevant information to multiple parties: the builder and CNC fabricators. Built into the ceiling components of the construction model was an additional layer of information; instructions for on-site assembly sequence. This layer of assembly sequence required particular information to be included from the outset that allowed for a construction data framework to be setup. The script relied on the flow of information downstream which increased in number of layers as construction information was progressively added to the model. When analyzing workflow of the script, what can be seen as contributing factor to its success was the transfer of the data structure; more precisely, the inheritance of information by each script block whether it was written for design parameter, construction setting out or assembly sequencing. It is the inheritance of the data structure that allowed the continuous work flow and merging of design with construction within the same parametric model.

The team needed to deliver multiple streams of information within a single parametric model. A construction data framework was developed at an early part of the script (stage B). This framework provided two important functions, firstly it provided an opportunity for the script to allow for tolerance in the site conditions to be built in (for example the alignment of existing walls), and secondly initiated the first level of data structure that would be inherited by subsequent scripts. While a seemingly innocuous observation of the data structure, or transfer of data structure, it provided the function for developing the construction and assembly information in parallel. For example in stage B, it showed the ‘Grid’ and ‘Bay’ blocks of the script both inheriting the data structure initiated in the ‘construction data framework’ block. The ‘Grid’ and ‘Bay’ blocks are scripted for both design and construction purpose. While inheriting the same data structure, it demonstrated the development of parallel streams of outputs that exist within the metadesign.

### 3.2. TRACING THE DATA STRUCTURE

The construction and assembly logic can be observed when tracing the data structure throughout the script. It set out the site constraints and sub-frame

system which led to the conception of the construction data framework; that allowed the design information to be scripted over the top. This was reflected in the construction sequence of the ceiling, for example the first stage of construction involved the installation of steel channels and rods that provided structural support for the timber components.

The 'Grid' block (stage B) of the script generated an offset grid that is used to inform the position of vertical battens. The z coordinate of the battens visually represented the geometric resolution of the form as defined by the input surface; the design process. The x and y coordinates which define the grid can be considered as a section of the script owned by the construction process. It is the organizational system for the geometric forms. The regularity of the grid must not be visually interrupted by the structural rationalization of the channels; otherwise the resolution of the surface would be lost. The parallel development of models within the one script allowed for easy negotiation between the design and construction processes. That is to say the structure sub-frame adapted to the geometry of the input surface and vice versa.

Branching out from the 'grid' script block (stage B), curves were discretized to represent the input surface and generate the steel channel construction information (stage C). The steel channel information itself had no requirement for the inherited data structure because we only required the length of the members and their datum above the ground. However, it is important that the data structure is inherited by the horizontal battens which rely on the datum of the steel channels and their position to the vertical batten.

The data structure for the horizontal batten saw the convergence of the structural steel channels; the grid and the vertical battens (stage D and E). The horizontal members had to extract pieces of data from each component for a successful outcome; the datum from the structural steel, the location on the grid and the intersection value from the vertical battens for accurate geometric and construction output. It was required to inherit multiple data structures for the information to be passed further downstream and embed into the components in the form of an instructional labelling system.

Stage D, aligning the Data Structure, was a critical and administrative process that collates, aligns, filters and distributes packages of information to the appropriate outputs. Even within the output packages, it was necessary to withhold and release layers of relevant information. Taking the horizontal batten and vertical batten information as an example, both require assembly and construction information to be embedded and have similar information on the first two layers,{Bay; Row….}, however beyond this the required information for each differed. Further positioning information for the timber battens within a row and the addition of notch geometry (this was for posi-

tioning the timber component onto the steel channels) was incorporated while the data structure was converted to labelling text for fabrication. The vertical battens required further positioning information in the form of a letter that indexes the order within the row, refer to Figure 4. Additionally the vertical battens required the output of another piece of information to position the varying locations of notch geometry. This selective distribution of information relied on the correct information layers within the parametric model and the distribution of structured data for appropriate outputs.

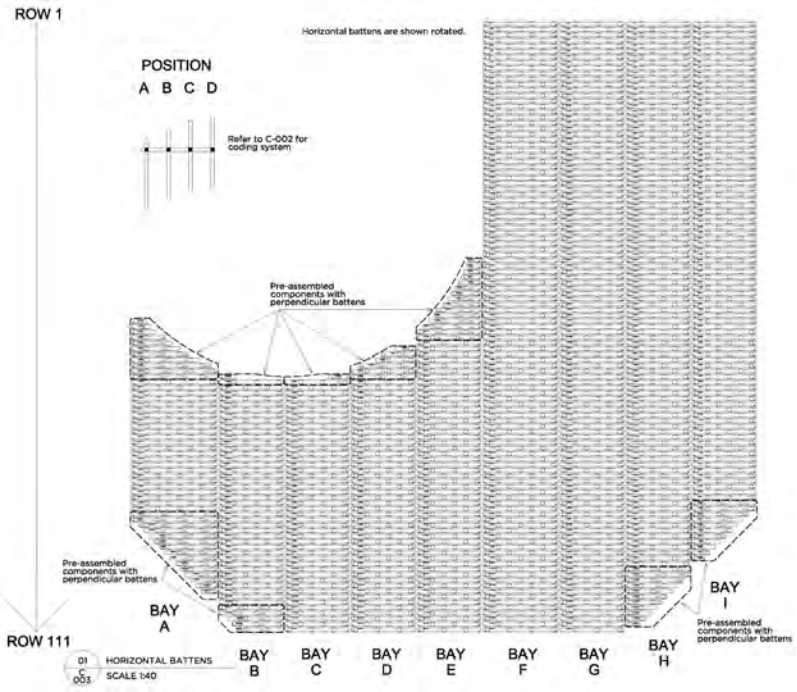



*Figure 4. Plan showing indexing of components and steel sub-frame.*

The above demonstrated that it was useful to introduce a framework based around construction strategy that fitted within the design parameters. It demonstrated flexibility in the parametric workflow which allowed for the production of both geometric and construction models in parallel, each influencing the development of the other. What was less obvious was the continuous input of knowledge and expertise throughout the process between the design team, the fabrication team and the contractor. The layers of information and organization of data are evident of a collaborative and coordinated design and make approach to the project.

## 4. Conclusion

The above analysis suggests that digital fabrication can be approached from the making perspective; that is, thinking through a set of problems through digital fabrication techniques, CNC tooling and construction strategy. The paper highlighted the potential to narrow the gap between design, fabrication and construction through embedding assembly logic within the design workflow; that is to say, designing from making and not making from a design.

The metadesign process allowed the design team to restructure the 'operating system' of the visual script. This was critical in delivering the multiple streams of data within a tight commercial timeframe and budget. It demonstrated the ability of the script to bring together information from different collaborators as well as disseminating the information from an integrated parametric model; a holistic approach to digital fabrication from design to fabrication to construction.

## Acknowledgement

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## DIGITAL FABRICATION AND CONSTRUCTION 2

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# CORKVAULT AARHUS

*Exploring stereotomic design space of cork and 5-axis CNC waterjet cutting*

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**Abstract.** This paper presents the design, fabrication, and construction of CorkVault Aarhus, which was designed using parametric and physics simulation software and realized from ECA cork sheets cut using a CNC waterjet cutter. We recount the lessons learned through the intensive two-week workshop that explored the limits of the materials and tools through prototypes and culminated with the assembly of the final free-form vault structure. Various vaults and arch prototypes provided pedagogical and research value, building up knowledge essential to the final structure built, a human scale pavilion designed and built in three days and made of a thin shell of cork panels working only in compression. Three driving concepts were crucial to the experience: stereotomy as a supporting theory, expanded cork agglomerate (ECA) as the main material and water jet cutting as the principal means of fabrication. The complex vault shape called for precise 5-axis cuts supporting a new paradigm in building stereotomic components for architecture.

**Keywords.** Stereotomy; generative algorithm; digital fabrication; waterjet; cork.

## 1. Motivation

The Hard Co(u)r(s)e Digital at Aarhus School of Architecture is a series of workshops focused on bringing students into close contact with digital technologies, software and hardware for the purposes of architectural design research and fabrication. Connecting technology and architecture is the driving

factor of this course, and stereotomy is an architecture discipline, which has bonded these two realities from its earliest times. The need for covering larges spans with blocks of stone is a construction method that calls for technical know how and physical feasibility. On the other hand, technical power is but a part of architecture, *firmitas*. Technical constraints have always modelled in some way architectural expression. The ongoing relation in development of technology and free expression of form is gaining increased exposure and interest especially in regards to stereotomy principles.

Stereotomy (from greek *stereos*, solid + *tomia*, cut), is a construction technology that relies on stones which are cut to a specific shape so that, when leaned against each other, lock due to gravity and remain suspended in the air creating a vault. As a discipline, it is intrinsically connected with geometry, and with the cutting abilities of stonemasons. Algorithmic modelling allows exploration of geometries with an added level of non-standard complexity, and CNC machines make these geometries physically possible; a 5-axis water jet cutter is particularly interesting for its accuracy, speed and geometric possibilities. The experimental crossing between stereotomy as a discipline and the water jet cutter has been explored before (Kaczynski et al, 2011), but not to the extent of a finalized vault.

## 2. Vault Design

### 2.1. MACROFORM

Arches and vaults have a long tradition in architecture, dating back to Mesopotamia. The usage of ideal shapes such as the circle in vault design is an idea funded by Romans, which was only completely discarded in the 17th century with the discovery of the correlation between a hanging chain and a stress free arch design by Robert Hooke, giving way to the thinnest shell structures ever made since. With expressive shapes in his design, Antoní Gaudi set new standards in vault design with stereo-funicular models of ropes and weights.

This design method introduced by Gaudi is the basis concept used for the generation of the macro form of the vaults in the workshop we report in the present paper. The main difference from Gaudi's method is the virtuality of all the process, contrary to the Barcelona architect's physical models. This virtual model is built in a parametric definition, and the physics simulation is carried out by Kangaroo. The strings model adopted is a topological 4-sided grid (Fig. 1-a), which connects two opposite curves (Fig. 1-b); in each of the knots in this grid an equal force is applied. These strings act as springs, able to vary their length to a certain extent. When the simulation runs and reaches

an equilibrium (Fig. 1-c), it is presented a three dimensional representation of a mesh of ropes holding a series of weights (Fig. 1-d) or, as Hooke put it, “so but inverted will stand the rigid arch” (Block et al, 2006) - or vault, in this case. If the two opposite curves[1] are two parallel lines, as in the opposite sides of a rectangle, we are given a catenary-shaped barrel vault. If these generator curves involve deviations from a straight line, a more complex emergent shape arises. The architect can experiment and explore various input curve forms and the algorithms enable a circular flow in which a given input develops into a form of increased complexity as is the case with genes and resulting phenotypes in living organisms. It is an automatic system, a working algorithm for designing the thrust surface (Rippmann and Block, 2012) for an ideal structure under compression (Fig. 1-e).

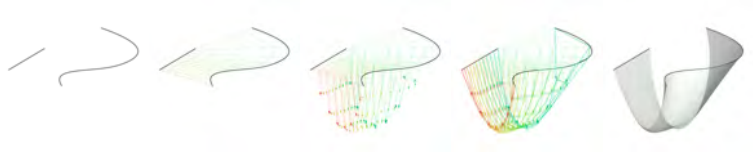


*Figure 1. Left to right: (a) Generator curves, which are to be the base of the vault and anchors for the simulation. (b) Funicular network where nodes are be subject to gravity and segments act as tensioned springs. (c) Vectors illustrating the new location of each node under the force of gravity and springs. (d) Reconstruction of stereo funicular structure, maintaining its original topology. (e) Inverted vault surface, draping like a membrane under gravity. This is the thrust surface.*

## 2.2. SURFACE TESSELLATION

A mathematically described surface does not suffice in real construction. Even if this surface is given a thickness somehow, the larger and more geometrically variable this surface, the more difficult and improbable is to build it in one single monolith. This simple fact leads to one of the key features of stereotomy: *apparecchiatura* (Fallacara, 2003), or the division of an architectonic continuum in significant parts. Dividing a vault surface in smaller parts must meet specific requirements, other than abstractly tessellating a surface in a regular or irregular pattern. A vault, being a compression-only resistant construction, must obey to specific principles regarding the orientation of joints. On the other hand, the material and fabrication constraints, as well as intrinsic architecture geometry, govern laws of UV tessellation (Rippmann and Block, 2010).

For pedagogical purposes, it was decided to leave the tessellation grid as simple as possible and, as such, a topological grid was built on the surface. UV coordinates were informally translated as U rows and V columns, in which U were to be force knowledgeable (normal to thrust vectors) and V

would be a mere subdivision of these task bearing U rows: as Vandelvira put it, we can use joints in the most convenient fashion[2]; in this case we make a continuous grid with an arbitrary number of continuous divisions. The U joints are topologically parallel[3] to each other, but with a variable interstitial distance inversely proportional to the U curvature of the surface (Fig. 2-a). The intrinsic curvature of the U joints was controlled in such a way that their angle with the vault opening edge would tend to a normal. This control method is a crude approximation to thrust informed joint orientation, but it does it in an efficient way in the most critical location of the vault (Fig. 2-b,c). Although this approach allows for simpler calculations, which was a key factor in the student experimentation flow within the course, some shortcomings were observed. In a non-planarised tessellation such as this, the curvature weighted U subdivision would have proved much more useful in a surface wide consideration, allowing for much more localized weighting. This would allow, for larger blocks in the planar side of the vault, creating an expressive linguistics of correlation between curvature and cell dimensioning.

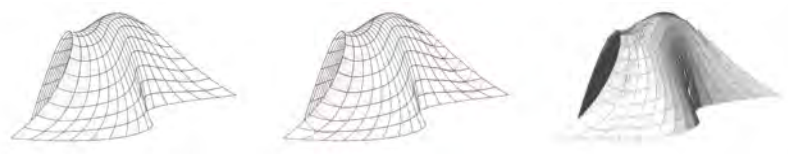


*Figure 2. Left to right: (a) Curvature weighted subdivision of U lines (near horizontal ones). (b) In red, the new directions for naked edge adjacent divisions normal to thrust vectors. (c) Planar extrados resulting from subdivided cells.*

## 2.3. VOUSSOIR GENERATION

A surface subdivided in smaller cells is by no means enough to characterize a stereotomic vault. Stereotomy needs weight, and weight relates to volume. This volume, defined by the thickness of each constructive module - called a *voussoir* - has in its side faces the interface joints that allow this system to work. If the tessellation should comply with the thrust vector along the surface, it is also true that three-dimension joint surfaces should also be normal to the thrust surface at every point.

The modelling strategy for creating thickness from the gene surface relied on creating a copy of the control points that define the voussoir surface cell (Fig. 3-a), along the thrust surface normals (Fig. 3-b,c), allowing enough information for rebuilding the cell bounding curve[4]. Since the control points are shared by consecutive cells, a good contact surface between voussoirs is guaranteed, and a composition of voussoirs is thus achieved (Fig. 3-d, 2-c).

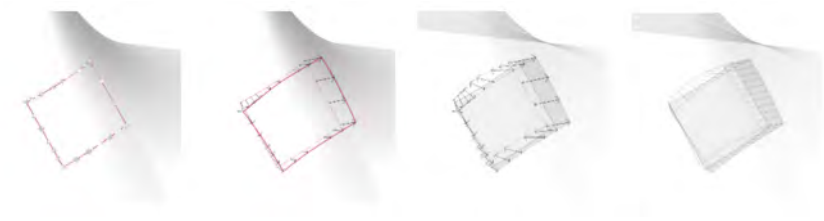


*Figure 3. Left to right: (a) Voussoir cell in thrust surface with curve control points. (b) Translation along thrust surface normals for extrado curve. (c) Generation of intrados curve defines the voussoir. (d) Final voussoir with planar intrado and extrado and side ruled surface.*

## 3. Materiality and fabrication

We now discuss cork as the main material for the vault construction and the waterjet cutting facilities.

The construction material for the vault is cork, in its expanded agglomerate form.[5] Cork has traditionally played a part in architecture for its insulation properties, as is observable in the Convent of Capuchos in Sintra, or the Convent of Santa Cruz do Buçaco, both set in cold mountains and having a layer of cork outside doors and windows. Besides these properties, cork is also highly resistant to compression and is a strong acoustic barrier. These remarkable properties are due to the cellular structure of this material, composed of tiny pockets of air enclosed in polyhedral air-tight membranes, packed in a prismatic fashion (Pereira, 2011).

Apart from the outer layer function of cork panels, Nuno Graça Moura has used ECA blocks to build load-bearing walls. Following these experiments, and those of José Pedro Sousa (Sousa and Duarte, 2012) in which cork is machined with digital processes, Pedro de Azambuja Varela has experimented on the usage of this material for building load bearing stereotomic vaults, given the compressive resistance of cork (Varela et al, 2014). Another key characteristic of cork is its softness to abrasion, making the 100mm thick ECA boards a very interesting material for water jet cutting. The same tool was used to cut the springer foundation from 100mm thick LECA concrete blocks as well as 19mm plywood boards for vault models.

For a broader understanding of the maximum extent of cork possibilities - due to its compressibility and lightness - regarding maximum span, the students performed a span proof-testing exercise in which an arch is extended in steps—this is visible in the upper left of Figure 7.

The usage of multi-axis digital tools for machining mass materials (Kaczynski et al, 2011; Fallacara, 2003) for stereotomy purposes is the contemporary manifestation of a mason's expertise. Water jet cutting depends on a very high-pressure stream of water with an optional abrasive powder

mixed within the stream to remove material in the cutting process. The accuracy of this method is widely sufficient for architecture purposes, as the cutting trails are 1mm thick and the edges have controlled angles thanks to an algorithm, which inclines the nozzle tip to control kerf known as IKC. This inclination is possible due to the 5-axis nature of the machine, which allows for <45º angles, allowing the fabrication of slanted wall blocks in one single pass.

The nature of the process, relying on a stream of water, makes it a machine suitable only for cutting ruled surfaces. The maximum angle of the jet stream on the Idroline 1720 machine that was used in the project is 60º with the vertical and the maximum depth of raw material is 130mm, cutting all the way through. The machine is optimized to cut material wide, rigid and heavy enough that is does not move while the operation is in progress; cutting a small block is not possible as there is no practical way of fixing it. All of these characteristics hint to a very specific usage of the jet stream, which is to cut curtain-like surfaces, leaving the top and bottom side untouched. Although this clearly constrains geometric freedom, the speed and fine finishing provided are more than enough to spark the intellect in finding the best way to use these kinds of surfaces to the benefit of architecture, following a deep tradition in stereotomy. The strategy used was to make intrados and extrados planar, parallel to each other and finding the best fit to the thrust surface.

The water jet software is mainly targeted to the cutting of 2D shapes, that is, vertical cuts following an XY path. Creating a 3D cutting routine relies in specifying pairs of points, which together define a straight edge in space. Given a bottom polyline and a top polyline, the software tries to match the point pairs but fails to do so if the polyline are not topologically equivalent. Another finding is that the start and end points should match, as well as the direction of the polyline; comparable to a simple “Loft” operation.

## 4. Vaults construction – centring, de-centring, & springer

During one of the class sessions, students were challenged to assemble a vault having only the fabricated voussoirs made of plywood on a 1/5 scale, (Fig. 4). After giving up, this naïve exercise was clear enough to explain the importance of the centering when building a vault.

Students were given the freedom to design various centrings, relying mainly in an abstract grid composed of interlocking vertical planes made of cardboard. These were designed using the intersect operation between vertical planes and the intrados for the contact contour of a continuous running vertical plane which would define one of the minimum two lines for each

voussoir intrado. The total profile of these vertical planes was obtained by subtracting the interlocking thickness of the cardboard, which was then fabricated by laser cutting.



*Figure 4. Left to right: (a) Students trying to assemble a vault without centring. (b) Generation of intrado curve, finishing the necessary steps to define the voussoir. (c) Final voussoir with planar intrado and extrado and side ruled surface (d) Experiment with puzzle fitting voussoirs made of plywood.*

De-centring involved the removal of the centering and is a crucial part of the construction project; various strategies were experimented, mainly driven by the scale of the model. A first try on the plywood model consisted on having the vault built on top of a base with a hole for the centering. This allows for the centering to be lowered or the whole structure including the base to be raised. A second method relied on having a sub-base under the proper centering that could be slid out below the proper centering, which was a test for the third strategy which involved a pallet jack. The jack was used for lowering the centering in the "mini-vault" construction, a small vault made of cork voussoirs. While this method proved efficient, it was clear that the area controlled by the pallet jack was too small for the final six-meter structure. Taking cues from the Free-form Catalan Thin-tile vault by the Block Research Group, the "mini-vault" was rebuilt so that the decentering would be done with the aid of cardboard softening by water hosing as shown in Figure 5.



*Figure 5. (left) Cardboard centring is dampened by spraying water from a hose. (centre) Dampened centring removed carefully. (right) Small cork vault with centring removed supporting weight of a person.*

In order to stabilize the base of the vault, a simple solution was developed using to handle the lateral forces. Force vectors within an ideal vault, alt-

hough two-dimensional intrinsically, are three-dimensional extrinsically. These vectors, given that the vault covers an actual span, always have a horizontal component pushing it outwards. Just as Earth's gravity is compulsory for a vault to function, Earth's soil is also the traditional clamping which prevents a vault from collapsing.

Given that the cobbled stone pavement should not be affected, a temporary springer was constructed from light concrete blocks held to the ground with 150mm metal poles stuck in the earth between the stones. These poles prevented the concrete from sliding horizontally, while the cork vault weight pushed them vertically to the ground. This base was built on top of 1:1 scale planes plotted in large format, providing a very accurate planning for the vault construction.

After the base was built and the centering put in place, the construction of the vault, which consisted mainly in laying cork voussoirs on top of each other (as a consistent UV grid hinted the location of the next block), took less than four hours (Fig. 6-7). Adding the time of the vault design (with a pre-built algorithm), the centering design, vault and base fabrication, centering cutting and total assembly, the whole process took three days.



*Figure 6. (left) Time lapse of the construction process, from centring to decentring. (right) Exploded view showing the springer, centring and base blocks, and voussoirs*

## 5. Analysis and conclusion

The successful construction of a vault is historically one of the key challenges for a stonemason to achieve professional maturity. The knowledge to build stone vaults was regarded as a secret of almost mystical proportions until Philibert de L'Orme transformed it into a science, which should be accessible to all architects. On his treaty, the traits explained clearly how to successfully plan a vault structure and, following this tradition, an algorithm guided the students in this course to build vaults.

By using a lightweight material such as cork, the relation between learning hands on through handled material was kept tight, and the degree of freedom and experimentation was leveraged to a degree, which would be impossible with real stone. Besides the ease of handling due to its lightness, cork is also easy to cut within its total depth, unsurpassed only by environmentally problematic polymers. Besides these clear advantages of cork, its lightness and softness play against the very nature of vaults, which need a heavy and stable material to achieve balance. In the end, it was verified that the thickness used was enough to counter-act these negative aspects while the clear structural design kept the construction upright.

Digital technologies were one of the cornerstones of this course. The combination of digital design and digital fabrication showed its full potential. The design algorithm was tuned for the machine that produced the voussoirs, and the final construction only took three days, from initial sketch to the end of assembly. The role of digital processes was critical, and although some parts of the flow could be hand made, the time to accomplish the tasks would be unbearable within the scope of a two-week course. Speed is one of the positive aspects of digital processes as is accuracy. Stereotomy is highly dependent on accuracy, as it depends on dry joints with no mortar, and the water jet cut is brilliant in achieving that degree of perfection.

All these components were fit together in a course in which the students got direct contact with vaulting and stereotomy, building various arches and vaults with a fabrication method providing speed and accuracy at the cost of a geometry constraint, which proved an architectural expression theme.



*Figure 7. (left) All the voussoirs fabricated for the final vault. (right) The final vault.*

## Endnotes

1. In Rhinoceros3D terminology, a curve also encompasses straight lines.
2. “Vandelvira se desinteresa por la longitud de las dovelas, diciendo que las cerchas cerra-rás por do quisieres.” (Calvo López and Alonso Rodríguez, 2005)

3. In this design, U and V curves are cartesian grid equivalent to an open 4-sided NURBS sur-face; in that regard we can easily establish informal analogies with parallelism, perpendicular-ity or cells (regions).
4. This operation occurred twice, one for each side of the surface. This contributes to having the thrust surface in the most interior possible location within the vault mass. On the other hand, this algorithm has a planar clipping strategy for compatibility with the fabrication strategy which does not modify the top and bottom side of the raw material (Fig. 3-d).
5. Expanded Cork Agglomerate board, discovered in 1893 by accident (Wilson, 2013) and produced nowadays with the help of autoclaves, is a material mainly used for architecture in-sulation, but has seen other applications to external façade finishings, since Álvaro Siza ap-plied in it in Expo 2000 Hannover.

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# COMBINATION OF MASS CUSTOMISATION AND CONVENTIONAL CONSTRUCTION

*A case study of geodesic bamboo dome*

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**Abstract.** With the development of advance fabrication, several digital fabrication approaches have been developed. These approaches enable better form exploration than the conventional manufacturing process. But, the built examples mostly rely on advance machinery which was not familiar or available in developed country where construction workers are still abundant. Meanwhile, much knowledge gathers in the field practice. This research is aimed to explore an alternative construction workflow and method with the combination of mass customization and conventional construction method and to propose the structure system that emphasized this alternative workflow and method. Lattice structure was proposed. The conventional construction method was used in the struts production and mass customization method, laser cutting, and was used for connection production. The algorithmic process was used mainly for data mining, details design, and component production. The backtracking was needed to be predicted and addressed previously. Considerations that will be needed to be tested by further example are on the transition from the digital process to the manual process. Next research could be for analysing the other engineering aspect for this prototype and suggesting other structural system with more optimal combination of conventional construction and mass customization.

**Keywords.** Mass customisation; algorithmic design; digital fabrication; geodesic dome; lattice structure.

## 1. Introduction

In this modern and urban civilization, there are always need of unique space experience, especially in open, public or recreational space. It could be gen-

erated from a simple form or complex form of structure. Furthermore, what considered as complex form or structure always changes as the society moves and learns.

Moreover, in a complex urban city, construction of a building could be not just about creating unique physical building (Wood, 2007). Every built structure has its 'tectonics'. It is the characteristic of building that is explained through its structure, construction method, details, to its material. Built structure could not only be evaluated in terms of geometry, economy, or typology, but also social terms. Directly or not, who built a structure, could affect its 'tectonics' (Frampton, 1995).

With the development of advance fabrication machinery, several digital fabrication approaches have been developed. Some built examples of the approaches have been erected. The approaches have advantages in its mass customization ability; the ability to create different type of component in relatively efficient way. This ability enables better exploration of form than the conventional manufacturing process (Kolarevic, 2003).

Some of those built example mostly rely on advance machinery which are not familiar or available in developed country. In addition to that, most of those approaches require more special machinery and material. Meanwhile, in developing country, construction workers are still abundant.

The formalized knowledge of heavy machinery and/or digital fabrication tends to set the term of "modern" method of constructions. But, much knowledge actually gathers in the field practice. Those knowledge are those that gathered by the field workers, on-site supervisor, and other field practitioners. The field practitioner somehow has different thinking or workflow with that of digital fabrication. Especially in developing countries with a lot of traditional construction workers, this hidden skill might be valuable to be collected and used in modern construction method. As mentioned by Ellen and Harris (2000), however much systematic and technical knowledge is used, there is always a need for an interface from the knowledge to the real world problem, which is much depended on the individual knowledge of the workers.

Thus, an optimal combination of mass customization by machinery with the conventional construction method by workers should be proposed to enhance the exploration of form in the case of limited availability of technology and funding. This research is aimed to explore an alternative construction workflow and method with the combination of mass customization by advance machinery and with conventional construction method in developing country, especially Indonesia. This research also aimed to propose the structure system that emphasized this alternative workflow and method.

## 2. Conventional construction process

Conventionally, design of the building was seen as the consequences of building material manufacturing process. As the most building material will be cheaper as the increase in the quantity, as the concept of mass production, standard building component tend to be used, thus creating boundary in geometry (Dunn, 2012). But, this system offers simplicity which makes it simple to construct. Its simplicity and standardization makes it easier to assemble, to imagine, and to manage. Most of the available workers in Indonesia could easily understand the system.

Conventional construction process also has its consequence in design to construction workflow (Figure 1). The architect tends to take considerate component and material available. Structure system usually is taken as consideration in the design process. Since structure system is much bounded by component and material available, geometry also become restricted.

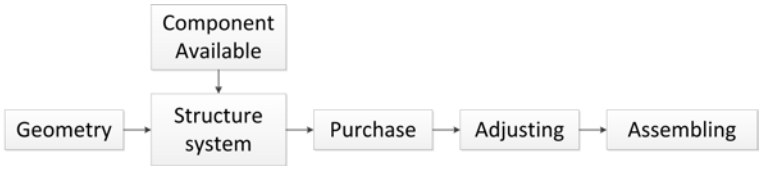



*Figure 1. Conventional construction process workflow*

## 3. Mass customization approach

As the technology of manufacturing advances, building design could be independent from standard material manufacturing. New machines have emerged with more compact size, relatively cheaper, and more flexible– compared to large scale factory machines. Digital fabrication tools, as a term of emerging manufacturing technology, is the key of mass customization.

While mass productions could create exactly same item cheaper in large scale, mass customization could produce large quantity of different item in same price as if producing same items (Dunn, 2012; Kolarevic, 2003; Lim et al, 2012). The capability of mass customization could not be separated from digital fabrication tool, designer workflow that using it, and digital computing that are hidden behind it.

As its term suggests, digital fabrication tools uses the means of digital language to comprehend process which are too complex to be handled conventionally. Its language enables digital fabrication tool to do precise, repetitive, fast movements; whether it is cutting, routing, milling, or forming (Dunn, 2012)

Algorithmic design is also important in the use of digital fabrication tools. Since it used to fabricate complex design, algorithmic design enables architect to tackle the emerging complexities (Jabi, 2013; Dunn, 2012). Complexities that are handled ranges from its geometry data, assembling data, to precise material handling. It creates better liberty for components geometry.

But, this automated method is not without backtracking (Agre, 1997). Compared to crafting methods, digital fabrication tools are still lacking in its flexibility and its response to errors. It is controlled by rigid rules that disable them to jump its process or to rewind its process. After production from digital fabrication tool, it may still need to be adjusted manually since not every variable of construction process is prepared. While conventional construction method may also include adjusting, it is still simpler because its component is more familiar for builder and workers.

These characteristics of mass customization are also affecting the workflow for designer (Figure 2). While the conventional construction makes designer considered available components in the market, mass customization makes designer considered how the component should be fabricated. From a preliminary geometry, designer goes deeper to design the detail of component, considering its production and assembling. It is almost like a designer takes part in production of components (Kolarevic, 2003).

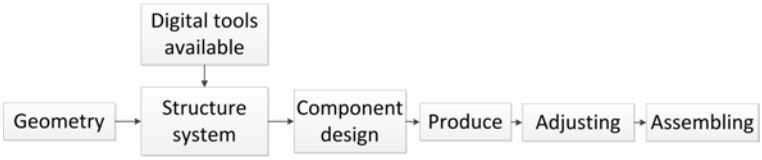



*Figure 2. Mass customization process workflow*

## 4. Combination of mass customization and conventional construction

As described in the previous chapter, there are several distinctive differences between mass customization processes with the conventional construction process in terms of designing complex structure (Table 1).

From the both workflow, it is also could be seen the differences between both system. In case of limited availability of digital fabrication tools, workflow for the combination of conventional construction and mass customization are proposed (Figure 3).

Table 1. Comparison of conventional construction and mass customization

| | Advantages | Disadvantages |
|---|---|---|
| Conventional Construction | - Easier to assemble and to manage<br>- Availability in market | - Expensive in low quantity<br>- Bounded geometry |
| Mass Customization | - Cheaper in low quantity<br>- Flexible design | - Limited in developing country<br>- Backtracking |

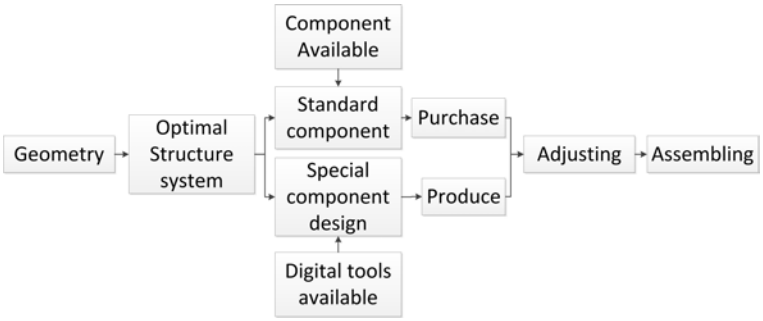



*Figure 3. Conventional Construction and Mass Customization Combination Workflow*

In terms of complex geometry, unique components are crucial. But creating all of the components by digital tool might be inefficient. So, a workflow that uses the advantages of each system efficiently was suggested. This workflow started by designing an optimal structure system that uses mass customization only in crucial component and uses standard component for the rest of the component. The structure system and its geometry should be optimized to achieve lower quantity of mass customized component and lower variation of standard component.

From its structure system design, the standard components and special component should be delivered separately. Standard components could be purchase from market, while the special component should be fabricated through digital fabrication tools. These components then assembled on site. What should be considered importantly in the design of the component is the easiness in assembling. Since it is more labour intensive than a pure mass customized construction, how much the worker could understand and execute the assembling process should be considered and prepared.

This process, as design process always did, will be in a form of iteration where many variations might be generated and the process might be move back to previous steps earlier. With more consideration included by the use of mass customization, iteration that is needed might be more complex. This iteration might be helped by the use of algorithmic process. It might be used

during optimization of the structure design to the detailed component generation.

## 5. Proposed structure: lattice structure

One of structure developed was a lattice structure with mass customized connections. The idea was using standard components for the struts and mass customized components for the connections.

### 5.1. GEOMETRY AND OPTIMIZED STRUCTURE

Geometry and the structure should be optimized to reach a lesser amount of variation and smoother result. Struts could be determined by meshing. Optimizing meshing or re-evaluate geometry should be done to achieve the optimum configuration. Several ways to done this in algorithmic design software are:

- Re-meshing component plugin to smooth the mesh generated.
- Divide surface to create grids based on NURBS curves.
- Geodesic configuration special for dome structure (Figure 4.).

Struts are the components that should be handled manually. The desired variety and length could be provided by manually adjusting the purchased components. By minimizing the number of variety, the lesser errors could be reached as the workers doing the simpler jobs.



*Figure 4. Geodesic configuration algorithm*

### 5.2. CONNECTION COMPONENTS

Connection component design was proposed. It is basically a multi-faces box with each faces' normal were parallel with the axis of struts. Number of faces depends on the grid of the structure; it will be a hexagon if triangle grid is used, it will be a box if square grid is used.

Algorithm for the connection could be described as following (Figure 5):

- Generate the mesh edges as the struts axis.
- Determine the end of the struts by evaluate 2 point near the end of each edges. Distance of each point with the nearest endpoint depends on the desired width of the connection.
- Create a plane with normal parallel with the edges at each end of the struts.
- Offset mesh points twice, inward and outward, the distance of each pair of outward and inward points depends on the desired height of connection.
- Create plane with normal parallel with the centre point of previously offset points and resultant vector from the normal of surrounding mesh surface.
- Create geometry from the bounding planes around each of mesh points.
- Create the silts.
- Remove one of the caps.

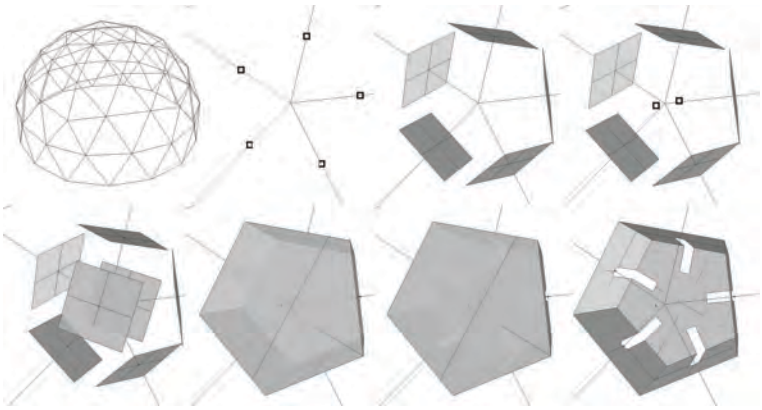


*Figure 5. Algorithm for connection design*

The connection component is the digitally fabricated component. There are several digital fabrication tools that could be used.

**Cutting.** The component could be made by fabricated the faces of each component and later assemble it by welding. The connection component model first needs to be unfolded. The digital fabrication principle that could be used is the cutting, where laser or waterjet cutter.

**Milling and routing.** Milling and routing tools could be the other tools that could be used to fabricate the faces of each component. It could be used for thicker plate. Milling tools could also be used to directly carved block of material into shape. This could simplify the production with cost compromise. Fabricating each face by milling tools was used in this case study.

**Forming.** Forming tools; moulding, and 3D printing, could be also used to fabricate the connection. The 3D printing could be used just as the rapid

prototyping tools for the base mould or directly using it to fabricate the component.

### 5.3. BUILT EXAMPLE

The built example of this structure was a bamboo geodesic dome with diameter of 10 meters built in World Bamboo Festival 2015 in South Korea (Figure 6). It tries to adopt as closed as possible the workflow and algorithm that has been proposed. Algorithmic design system was used. It serves mainly to generate rapidly the optimized structure model to be reviewed. It was also used for generating the geometry of the specialized connection to be mass customized.



*Figure 6. Built example: Bamboo geodesic dome*

At this project, geometry that assigned was a dome. To reach as small as possible number of member variation, a lattice structure in geodesic configuration was used. Number of member variation was consulted several times considering its geometry smoothness and the economy.

The struts of these geodesic were bamboo poles. Both ends of each bamboo were attached by T-joint that would be connected to the connection components. These components were purely assembled manually. The workers were traditional workers with special skills in bamboo construction. There were 3 variations with total of 165 strut components (Figure 7). The variation of the struts length was optimized by manual selection from sets of variation generated by algorithmic design software.

The connections were in shapes of bowl or truncated pyramid. There was slit in each faces to insert the threaded bar from the T-joints. The geometry considered its easiness of assembly, economy, and strength. There were 3 variations of connections with total of 61 components (Figure 7).

The connection faces were generated automatically from the configuration of the struts. The model of connection directly sent to the manufacturer

to be fabricated. Faces were fabricated by using the CNC milling, which then assembled and welded to form the truncated pyramid shapes. CNC milling was used by its availability. Each face was milled individually instead of milling the connection directly. It saved material cost and skilled welders were available. Here contributed both the use of mass customization and skilled manual assembling. All the components were prepared in Indonesia and assembled in South Korea (Figure 8).



*Figure 7. Struts (left) and connection component (right)*



*Figure 8. Assembling Process*

## 6. Conclusion and further research

As shown in the previous chapters, it is possible to combine mass customization and conventional construction. With material that has a lot of variety, like bamboo, it is needed to handle it manually. Even the production of connection still needed to be handled manually. With a simple labelling, welded was easily done.

Algorithmic design was used mainly to automate any complicated process. The algorithm that was used basically comprehended the workflow planned. Some backtracking still existed, such as connection detail process. At the built example, the detailed connection geometries were constructed and given to the CNC operators, which then manually translated it to script for the CNC. This process might be inefficient in much more complex ge-

ometry. An algorithm to translate the shape data into CNC script might be needed for next example.

Assembling was done easily since the connection was simple. The workers itself didn't understand the overall configurations, they just did the obvious details; welding and assembling the bolt.

Considerations that were needed to be tested by further example are on the transition from the digital process to the manual process such as, pre-welding assembling process, and on-site assembling. The former process included pairing each faces before welding and the welding process itself. Both were crucial since welding couldn't be undone. Pairing process might be difficult if the shape is more complex.

Next research could be for analysing the other engineering aspect for this prototype and suggesting other structural system with more optimal combination of conventional construction and mass customization. A more flexible method to calculate the mechanical properties of the connection might be needed.

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# LIGHTWEIGHT MATERIAL PROTOTYPES USING DENSE BUNDLED SYSTEMS TO EMULATE AN AMBIENT ENVIRONMENT

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**Abstract.** This paper describes and reflects upon a computational design and digital fabrication research project that was developed and implemented over 2014-2015, with subsequent development continuing for applications at present. The aim of the research was to develop methods of modelling, analysis, and fabrication that facilitate integrative approaches to architectural design and construction. In this context, the development of material prototypes, digital simulations, and parametric frameworks were pursued in parallel in order to inform and reform successive iterations throughout the process, leading to a refined workflow for engineering, production, and speculation upon future directions of the work.

**Keywords.** Digital fabrication; biomimicry; ambient environments; grasshopper; computational design.

## 1. Introduction

While the use of plastics in architecture is undoubtedly commonplace, applications overwhelmingly tend toward the utilitarian or emulation of natural materials (Brownell, 2015), in contrast to the consumer goods industry where the functional and aesthetic characteristics of polymers are used to their full advantage. One reason for this may be that many well-known fabrication methods with plastics typically require a high degree of skill (plastic welding, fiberglass moulding) or highly application-specific equipment

(blow-moulding, thermoforming) and are not suited to the one-off nature of building projects. Yet with the wide availability of many plastic products, specifically in sheet form, and the relative ease of processing with increasingly common equipment such as CNC routers, plastics can be seen as fertile ground for architectural experimentation.

The goal of this project from a research standpoint is to begin to bridge the aesthetic and structural properties of widely available polymer materials at an architectural scale and level of formal and structural complexity which is outside their normal functional domain. By employing generative and parametric design techniques, increasingly fabrication techniques, and assembly methods requiring little or no skill it is possible to effectively make use of the advantages of the unique material characteristics of plastics; its isometric structure, strength to density ratio, inherent flexibility, yet sidestep the aforementioned fabrication disadvantages, while also maintaining the ability to produce highly customised architectural artefacts.



*Figure 1. Arclight seen completed in situ, June 2015.*

## 2. Early development

Conceptually, Arclight is conceived from a biomimetic basis – namely, to emulate dense bundled systems of fibres or branching structures found in the natural environment e.g. the Mangrove or Strangler Fig tree, as a paradigm for structural and formal qualities. Like most fibrous systems in nature, the research investigated bundling at multiple scales in order to build up strength.

The project was initiated with students in an undergraduate research seminar at Bond University School of Architecture in September 2014. At this point the authors were in discussions with several external groups about the

possible installations for public events in Gold Coast and Sydney, Australia. Since these installations were not confirmed at the start of the seminar, the seminar was structured in a way that several different research projects could be developed and prototyped in parallel with the goal of at least one of the topics being more fully developed for a larger scale installation. This structure allowed the authors and their students to conduct a broad range of research while iteratively integrating new constraints and parameters related to the potential larger commissions into the research.

One of the initial research trajectories focused on the potential of using thin-sheet materials to construct volumetric structural elements. The research aims of this trajectory are as follows:

- Produce a strong, yet lightweight structural member fabricated from sheet materials.
- As several of the possible commissions were for light festivals, produce a translucent element that had the capacity to transmit LED light.
- Develop a fabrication workflow that takes advantage of the available digital fabrication tools at the Bond University School of Architecture while expanding the capacity of the equipment and the diversity of its output.
- Produce a parametric system composed of a singular component logic that can be differentiated to produce a range of effects and performances, and allows for continuity throughout the design process.

The authors and students pursued these research aims over the course of the semester through the iterative development of digital and physical prototypes. This process began with simple physical prototypes of box beams made from HDPE as these prototypes collapsed many of the aims into one testable framework. Each of these prototypes were tested for their structural capacity and stability, ability to transmit interior LED light, and various fabrication and assembly criteria such as ability to unroll the box beam's sides into flat patterns and the specific joint details connecting each side to its neighbour.

After several rounds of testing, an initial design direction was determined that rested on the use of a box-beam component with a semi-triangular cross-section. The faces of the beam were made from CNC-milled HDPE sheets that were then attached using standard aluminium pop-rivets. Across the length of the beam (or column if positioned vertically), the cross-section could change in size, position, and rotation. This transformation produced a global curvature to the beam that allowed bundles of them to form areas of loose or close aggregation. This variable aggregation allowed the bundle to both have widely spaced support points when loosely aggregated and increased stiffness when closely aggregated.

Furthermore, each strand's stiffness was increased through the curvature induced through the riveted connection. Although digitally modelled as an idealised triangular cross-section, each edge of the triangle was closer to an arc than a line due to the surface-to-surface contact made by the riveted connection. Thus, not only was the beam curving along its length, but along its cross-section. This curvature made each beam incredibly stiff in comparison with the relatively weak and thin HDPE material (Figure 2).



*Figure 2. Prototypes in the process.(Left to right) A beam failure due to buckling, testing light transmission; and finally, a successful aggregation of strands.*

## 3. Prototyping

*Arclight* underwent considerable prototyping over a short timeframe to resolve a number of issues concerning materiality, fabrication, assembly, and structural efficacy. As stated, a major goal in this research was the full integration of skin and structure, and as such at the prototyping stage this centred largely on the interaction of HDPE skin and the connection methods between elements.

Multiple options for connecting skin/structure elements though many these were dismissed as either not attractive (zip ties) requiring too much skill (plastic welding), too expensive (Chicago Screws), or unreliable (industrial staples and chemical bonding). Aluminium rivets, with washers to prevent tear-out, were eventually chosen as they fit all expected criteria, and integrated material fastening tabs with pre-drilled holes were developed to facilitate quick installation.

During this stage it was discovered that while very strong, HDPE is quite flexible and tends to bend not only in the longitudinal direction, but in order to allow the exterior tabs to be riveted together, it also bends transversely

causing material distortion and tends to create openings at vertical seams, exposing the LED lighting inside. This aspect made the distance between rivets critical in order to reduce unwanted openings. Due to the overall strength of the aluminium rivets the spacing had little overall structural effect on the installation the spacing, and thus total quantity, of rivets greatly increased assembly time, which was a real concern (Figure 3).



*Figure 3. A 'strand' cut with fastening tabs and pre-drilled rivet holes (left) and pieces joined with rivets (right)*

Further it was found that tab generation at an early stage in the computational process, ie. when the overall forms were being generated was too imprecise to be of value during fabrication as the tabs and rivet holes tended to not line up accurately and deform slightly while unrolling. It was discovered that generating the fastening tabs and pre-drilled rivet holes after unrolling surfaces was much more accurate and not only reduced the tolerance required for fabrication (+/- 1mm) but saved significant computation time while fine-tuning the parameters for the overall design. While 1mm tolerance is significant in terms of manufacturing precision – the equipment used is capable of +/- 0.05mm - as noted by Kolarevic, "'zero tolerance' is an oxymoron in the context of the building industry," - although digital fabrication would suggest such a goal is achievable – he continues that "tight tolerances (which should not be mistaken for no- or zero tolerances) are tied to the kinds of materials used. Good designers and engineers plan for precision and tolerance issues, allowing size variations and imperfections in interfaces."

## 4. Engineering workflow and optimisation

For the purposes of structural engineering, the Arclight structure is composed out of a bundle of 6 individual shaped triangular HDPE pipes. Different criteria have an influence on the final layout and geometry of the installation, including orientation, material thickness and behaviour, topology, fabrication processes, and external forces.

Those factors can be utilised as a design driver to change the overall geometry of each individual tree like structure. An integral workflow of shape making and structural behaviour was one part of the investigation that helped to understand the material behaviour to push the design to the material limits. The workflow can be described as a loop where the design was developed in the modelling environment Rhino / Grasshopper. The parametric logic allowed fluent changes of the shape and material thickness of each tree. Within Grasshopper a structural analyses with the plug-in KARAMBA was set out to gain real-time feedback of any change of the design.

The iterative analyses started to look at the smallest tree with a height of 2.6m and a simple extrusion body to understand the boundary conditions of the material, since HDPE is not a conventional building material that is used for structural purposes. The structural analyses had the following parameters as input: Wind speed of 80 km/h or 30.5 kg/sqm; Material properties of HDPE. The results show that the tree has a deflection of 9.6cm and is almost 70% utilised. The surface area of the tree is 13.24sqm.

The optimisation of the structure went through multiple steps and included twisting and tapering the individual branches of every single tree. The results of the manipulated geometry show that the deflection went up to approximately 10cm but the utilisation of the material could be reduced to 34%. The surface area are could be reduced to 10.5sqm (Figure 4).

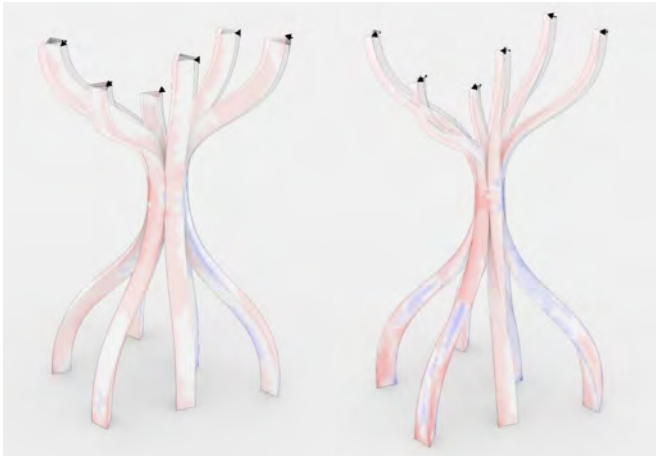


*Figure 4. Arrows indicate deformation. Colour mapping indicate utilisation (red compression/blue tension). Left: first simulation, Right: surface area reduced.*

The results for the tallest of the trees showed that the same optimisation approach was also effective. The deformation of the tree could be kept within a maximum of 40cm for an overall height of 6.8m. This is for the worst

case wind speed. Still the utilisation of the material was in the allowable range. The maximum utilisation of the material of the tall tree was only reaching 66.5%. As a result the optimisation could reduce the material usage but maintain a similar result for the deflection.

Since the structure could not be connected to a regular concrete foundation due to its temporary nature, 300mm high concrete footings were casted in the hollow cross section of the triangular branches of the tree. To ensure the sliding and overturning of each structure under horizontal wind loads, it was necessary to provide laminar footings e.g. plywood sheets as shown in the layout. The resulting forces for the support system were designed by a simple structural logic to divide the forces and to reach equilibrium with the least amount of additional structural elements (Figure 5).

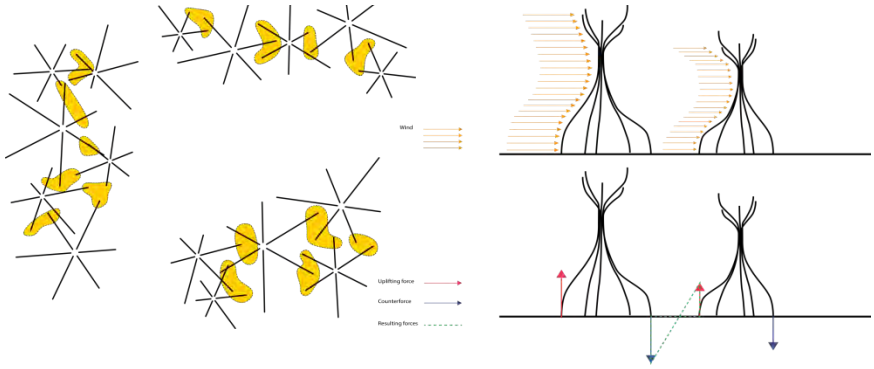



*Figure 5. Left: Arrangement of trees with shared footing system to reduce and counterbalance the overall system with the least amount of additional weight to ground the structure (Yellow area indicates position of ballast and connection). Right: Horizontal forces create an uplifting and a counter force. The forces are being balanced, reducing the overall ballast required.*

## 5. Fabrication and assembly

Though HDPE is relatively soft and can be cut rapidly on CNC equipment with good quality, the necessity of cutting approximately 1800 self-similar yet unique parts requires an efficient strategy for CNC cutting and part differentiation. A simple numbering system that systematically isolated a part location using an impromptu taxonomy, in this case Bundle-Strand-Length-Side, was developed and routed into each piece during fabrication to bypass human error.

While this had the disadvantage of increasing routing time significantly – it actually took longer to number the parts than to cut them out – small efficiencies were gained with minor adjustments such as rounding out inside corners, as routers tend to slow down during sharp direction changes, which

made up for a portion of the extra time. The parts were also nested in order so that assembly and fabrication could occur simultaneously and labourers were not waiting for parts to be cut.

The strands were manufactured from 3mm HDPE which was chosen for its translucence, high strength, isotropic composition, durability, recyclability, and value. In order to maximise material efficiency, it was necessary to dissect strands into multiple parts along their length and each strand was separated into its 3 constituent sides and further divided so that pieces fit neatly within the material bounds, which had the benefits of lowering material waste due to increased part nesting efficiency and increasing the number of lap joints to aid in load transfer and reduce the risk of buckling.

Assembly into subcomponents was carried out over a two week period with unskilled and mainly volunteer labour who were available at irregular intervals. For many projects this would be difficult or impossible to complete as the reliance on skilled labour is often critical to success. However, due to the simple logic designed into the structural and assembly strategies it was possible to train productive team members in only a few minutes and without the need for images or written instructions.

The entire project uses approximately 1.3 tons of sheet HDPE with a material efficiency yield of about 68%, approximately 12,000 aluminium pop rivets, and nearly 500m of LED lighting. The resultant strands vary in total length from 2.4m to 8.5m and are light enough to be carried and positioned comfortably by one person.

## 6. Installation

Logistics provide the biggest challenges for installing a project such as *Arclight* in the public domain. Additionally, the project site is more than 1000kms from the facility where the project is fabricated. Freight combined with remote assembly were both factored in as part of the strategy, resulting in branch segments of approximately 1200mm each – making parts both easy to handle and easy to pack into a shipping container. On site, parts can be easily laid out and prepared for joining; however this creates the need for an on-site compressor to run a rivet gun, as each section of the branches must be lapped and fixed before standing up into the tree clusters.

Due to the scale of the trees, mechanical assist in the form of a scissor lift is required to get up to a working height of ~3 to 4m above ground to make the attachment of each bundle. Attachment of individual strands to form a bundle is made simply with zip ties, which are concealed from view and allow rapid disassembly.

Additional logistical hurdles include fixing shallow 300mm star pickets to the ground surface in combination with the ballast. 800kg of ballast was required, which also needed to hired and delivered to site. While mundane and pragmatic, these issues are often overlooked in the context of digital fabrication projects, but they are an inherent reality for consideration. An on-site team of 2-3 skilled and knowledgeable team leaders run a construction site over 3 days, guiding a volunteer team of 6-8 people per day working 14 hour days to prepare all the trees and associated lighting (Figure 6).



*Figure 6. Site installation showing fully assembled elements and subcomponents.*

## 7. Conclusions

As with architectural projects that are contextually situated between pure research and built outcome for public use, Arclight was subject to the demands and rigour required from both extremes, which are at times opposed and at others compounding. Issues of budget, robustness both from climactic and human factors, transport and assembly/disassembly logistics, and maintenance and repair are typically addressed in the realm of built outcome. Conversely, issues of computational craft, geometric rationalisation, and design intent can be thought to reside chiefly on the research end of the spectrum, as the latter issues can be resolved with small scale prototypes and simulations.

As this work illustrates through successive iterations, managing complexity is fundamental to the task of architectural fabrication, and this can be managed effectively through key strategies. The projects here achieve this through the use of associative modelling strategies, reductions in material variety, separation of fabrication processes for employment of the appropriate tools, and assembly that relies upon awareness of tolerance and precision implications. The project presented here is ultimately limited – and optimized – for material properties. Through a feedback loop that runs from

conception to modelling to testing, and finally, to complete assembly, the prototyping feedback loop plays a central role in facilitating progress and efficacy in the work, resulting in the final piece which manifests an ambient environment of bundled light.

## Acknowledgements

The authors wish to acknowledge project collaborators from The University of New South Wales for their work on the interactive lighting aspects of the project, and Bollinger-Grohmann engineers for their support and oversight of the work in development and during installation. Numerous volunteers assisted in the development of the project, including key student help from Bond University Students Nicholas Palmer, Alvedin Hukicevic, Joel Hutchines, Rory Spence, Jarryd Pearson, Nicholas Allen, and Bond University Workshop Manager Nathan Freeman. Photography by Peter Bennetts.

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# AN ENVIRONMENTAL PERSPECTIVE ON DIGITAL FABRICATION IN ARCHITECTURE AND CONSTRUCTION

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**Abstract.** Digital fabrication processes and technologies are becoming an essential part of the modern product manufacturing. As the use of 3D printing grows, potential applications into large scale processes are emerging. The combined methods of computational design and robotic fabrication have demonstrated potential to expand architectural design. However, factors such as material use, energy demands, durability, GHG emissions and waste production must be recognized as the priorities over the entire life of any architectural project. Given the recent developments at architecture scale, this study aims to investigate the environmental consequences and opportunities of digital fabrication in construction. This paper presents two case studies of classic building elements digitally fabricated. In each case study, the projects were assessed according to the Life Cycle Assessment (LCA) framework and compared with conventional construction with similar function. The analysis highlighted the importance of material-efficient design to achieve high environmental benefits in digitally fabricated architecture. The knowledge established in this research should be directed to the development of guidelines that help designers to make more sustainable choices in the implementation of digital fabrication in architecture and construction.

**Keywords.** Digital fabrication; LCA; sustainability; environment.

## 1. Introduction

The construction sector is a highly active industry that employs more than 111 million construction workers worldwide and is responsible of high environmental impacts (Ortiz et al, 2009). Today's increasing concern about sustainability has induced the emergence of "green design" practices in order to decrease environmental impacts in construction. However, commitments to

sustainability remain weak and fragmented (Fry, 2008). Responding to the requirements of the current society, a new type of construction practice is needed. Specifically, innovative processes and technologies that recognize the importance of sustainable design and overcome the inefficiency and lack of interoperability present in the sector.

Digital fabrication processes are becoming an integral part of modern product development (Hague et al, 2003), and 3D printers are nowadays affordable for home use (Pearce et al, 2010). As interest in additive manufacturing grows, research into large-scale processes is beginning to reveal the potential applications in architecture and construction. Architectural design needs to extend beyond the form and function and engage with the management of complex systems (Fry, 2008). But their potential contribution to the improvement of sustainability in construction should be argued. The challenges of architectural scale additive fabrication are issues of size, material use, energy demands, durability, GHG emissions and waste production over the life cycle of a building and they must be recognized as priorities of any architectural project.

The aim of this study is to investigate the implications and opportunities of the development of digital fabrication to advance achievements in sustainable construction. The research focuses specifically on measuring the flow of materials, embodied energy and potential environmental impacts associated with digital fabrication processes. Comparative assessments with conventional construction processes are performed, with specific priority placed on new methods of additive fabrication and full-scale robotic construction in architectural processes. The final goal of this research is to develop guidelines that help designers to make better-informed and more sustainable choices in the implementation of digital fabrication.

## 2. Methodology

The Life Cycle Assessment (LCA) framework from the standards ISO 14040-44: 2006 (ISO, 2006) was selected for the assessment. LCA is well-established method, which application is increasing in the construction sector as it represents a comprehensive and systematic approach for environmental evaluation and optimization of construction processes (Cabeza et al, 2014). The objective of the evaluation was the comparison of digital fabrication and conventional construction projects. Therefore, the impact assessment was implemented in the software SimaPro 8 using the Ecoinvent v2.2 database (Hischier et al, 2010) and the method Recipe Midpoint (H) V1.06 (Goedkoop et al, 2009). But of course, to evaluate the environmental impact

of a digital project, we could also use existing tools that efficiently integrate LCA in Revit such as Tally.

After an extensive analysis and classification of digital fabrication processes and technologies, two case studies were selected. Two classic building elements (wall and roof) where computational design and robotic fabrication enable additional functions embedded in the structure. We observed that many digitally fabricated projects present additional functions such as thermal or acoustic performance integrated with the structural function that give an added value to the architecture (Moussavi et al, 2006). As a consequence, exists an evident arduousness on the environmental evaluation due to the difficulty on the performance of a LCA comparison with conventional construction. Specifically, the definition of the functional unit is critical due to the difficulty on finding a conventional system that concentrates the functions integrated in the digitally fabricated structure. Therefore, for each particular case study, a detailed study to tailor the functional unit it is needed.

## 3. Case study: Self-shading wall

The project selected for the assessment was a self-shading brick wall modelled by computational design and constructed by an in-situ robotic arm. The research in ceramic building systems through design robotics performed by S. Andreani and M. Bechthold (Harvard University) was taken as a reference. The study researches mass-customization methods for the creation of dynamic ornamental effects that reduce thermal gain on façades with brick cladding. Custom brick shapes are used to optimize assembly configuration, creating shades on the wall surface that contribute to the improved thermal performance of the façade (Andreani and Bechthold, 2014).

### 3.1. SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

The case study was assessed in accordance to a cradle-to-grave analysis, including raw material extraction, digital technologies and materials production, robotic assembly and operation of the wall. The self-shading project shows specifically the potential of digitally fabricated façades to reduce heat gain during operation, therefore, this phase was included in the assessment. Two functional units were compared: 1 $m^2$ of self-shading brick wall constructed with digital fabrication techniques and 1 $m^2$ of a wall system with a similar brick masonry aesthetic and the same structural and thermal performance.

## 3.2. DATA COLLECTION

The material composition of the self-shading wall were plain clay bricks assembled with cement mortar joints. Additionally, 10% of the mass of brick was added for the creation of the self-shading effect. In the conventional wall, the same type of brick was considered with 1.5 cm of EPS insulation in the interior to achieve the same thermal performance as the self-shading function during the use phase (Figure 1).

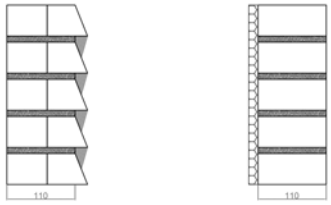


*Figure 1. Self-shading brick wall and conventional brick wall sections.*

For the calculation of the embodied energy, we collected production data from the "In-Situ Fabricator" robot (NCCR Digital Fabrication) and the laptop production process from Ecoinvent. In addition, the mass-customized bricks required a saw tool that attached to the robot cut them in the desired shape. The production process data of the diamond wire 500 mm saw was collected from literature (Ioannidou et al, 2014). Finally, we included the construction energy consumption of the robot and laptop computer (Deng et al, 2011).

The operation energy was calculated based on a residential cooling consumption system from the literature (Shah et al, 2008). The house reference was located in Texas (US) due to the high effectiveness of self-shading systems in hot climates. Initially, we considered 4240 kWh of cooling electricity consumption per year during 50 years of use. From the total energy demand, just a 20% corresponding to the walls heat gain was included (Department of State Development, 2015). Additionally, a reduction of the 16% of cooling energy demand was implemented due to the improved thermal effect (Andreani and Bechthold, 2014). Finally, the total operational energy considered was 559 MJ.

## 3.3. RESULTS

### *3.3.1. Environmental impact of digital fabrication process*

The environmental assessment of the self-shading wall was divided in four processes: brick production, cement mortar production, digital technologies

production, and electricity production. Figure 2 graphically depicts the relative contributions to the overall environmental impact of the construction of 1 $m^2$ of self-shading wall. The analysis reveals that the highest impact is attributed to the materials production. The energy consumption during construction remains relatively high in categories such as human toxicity, however, this factor varies depending on the electricity generation mix. Finally, the relative impact of the technologies production is negligible in most of the environmental indicators.

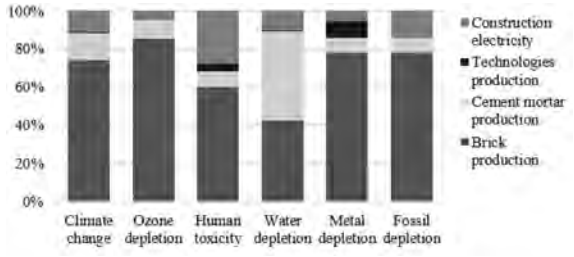



*Figure 2. Relative contributions to the environmental impacts of the self-shading wall production.*

### *3.3.2. Comparative LCA with conventional construction*

Subsequently, we compared the environmental impact of digital fabrication with conventional construction. Specifically, the comparison was focused on the production and operation of the two façade systems applied to a house situated in Texas (US). Figure 3a establishes that the self-shading façade has higher environmental impacts than the conventional façade with equal structural and thermal performance. In particular, the 10% of extra brick needed for the self-shading function is potentially the largest contribution to the difference in impacts. Similarly, after 50 years of operation, the difference between the relative impacts decreases but the self-shading façade has still higher contributions (see figure 3b). The results confirmed the high influence of the production phase in the global impact of a building element.

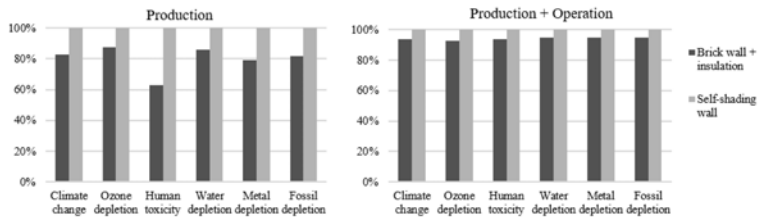



*Figure 3. (a) Comparison of environmental impacts of walls production. (b) Comparison of environmental impacts of walls production and operation.*

### 3.4. DISCUSSION

The previous results showed a clear environmental disadvantage in the use of digital fabrication processes for the production of brick façades. The reason may be attributed to the need for material optimization in the design. However, an important factor in the comparison was the additional thermal function represented by the self-shading effect and compared with the insulation in the conventional system. The environmental impact of the EPS is very small compared to the impact of the 10% extra brick used for the creation of a self-shading effect (calculations based on Ecoinvent database). Therefore, the integration of additional functions in digital fabrication did not provide environmental benefits because the equivalent function in the conventional wall had a low environmental impact.

## 4. Case study: "The Sequential Roof"

The second digital fabrication project selected was "The Sequential Roof" (Gramazio Kohler Research, ETH Zürich, 2010-2015). This wooden structure consists of 168 single trusses that compose a 2,308 square meter freeform roof design. The structure composed by 100-150 cm timber slats have been robotically assembled to create large-scale load bearing structures. The project demonstrates the potential of combining digital fabrication technology applied at full architectural scale with a local and natural building material. The mechanized assembly of the wood structures makes possible a reduction on the construction time from manual assembly and it has a potential interest with regard to the use of recycling waste wood (Gramazio Kohler Research, 2014).

### 4.1. SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

The case study was assessed in accordance to a cradle-to-gate analysis, from the extraction of raw material up to the construction site. The Sequential Roof integrates finishing and acoustic functions to the structural function, allowing the elimination of additional elements such as hanging ceilings. Therefore, the assessment was focused on the production phase. Two functional units with similar structural and functional factors were compared: 1 $m^2$ of computationally designed and robotically assembled wood roof and 1 $m^2$ of conventional wood roof structure with hanging ceiling.

### 4.2. DATA COLLECTION

The Sequential Roof is composed by 384 $m^3$ of C24 fir/spruce wood robotically assembled using in total 815,984 nails (see Figure 4). The digital man-

ufacturing process of the 168 trusses has been carried out by a special robot in the manufacturer factory. Due the lack of data from this robot, the embodied energy of two robotic arms and a desktop computer (Williams and Sasaki, 2003) were considered for the assessment. Finally, the energy consumption of both technologies during 12 hours of production.



*Figure 4. Section of "The Sequential Roof" (Architektur und Digitale Fabrikation, ETH Zürich).*

The conventional roof structure was formed by conventional Glulam spruce beams and joists. The joists were connected to the beams with galvanized steel hangers. The wood structure was covered by 19 mm of waterproof particle board attached with steel nails. In addition, a hanging ceiling finished the structure and protects acoustically. The ceiling was composed by laminated wood boards, 5 cm of rock wool acoustic insulation and a hanging structure of galvanized steel.

## 4.3. RESULTS

### *4.3.1. Environmental impact of digital fabrication process*

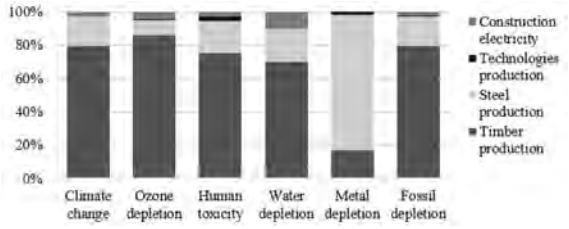



*Figure 5. Relative contributions to the environmental impacts of The Sequential Roof production.*

The results from the environmental assessment of the robotically fabricated roof were broken down into four processes: spruce timber production, low-alloyed steel production, digital technologies production and electricity production. Figure 5 indicates that more than 95% of environmental impacts re caused by materials production. Simultaneously, the graph shows that the construction energy impacts less than 10% in all the indicators. This fact is attributed to the production process in Switzerland, where the primary ener-

gy supply has small shares of natural gas and coal and a 22% of renewable sources (International Energy Agency, 2012). Similarly, the relative impact of the production of digital technologies is less than 2%. In conclusion, the analysis proved that the impacts of digital fabrication were negligible compared to the materials manufacturing processes.

*4.3.2. Comparative LCA with conventional construction*

Subsequently, we compared the life cycle of the digitally fabricated roof structure with the conventional system. Figure 6 graphically depicts the environmental benefits of The Sequential Roof production process. Specifically, the difference between the environmental impacts of both construction systems is between 30-40% in all categories. For example, in climate change the $CO_2$ emissions of The Sequential Roof are more than 40% lower than the conventional roof compared.

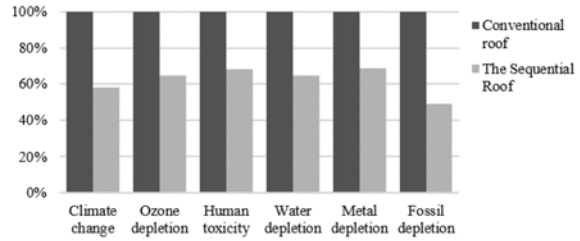



*Figure 6. Comparison of the environmental impacts of The Sequential Roof and the conventional roof structure.*

## 4.4. DISCUSSION

This case study showed clear environmental benefits in the use of digital fabrication processes during the production of wood structural elements. These benefits were mainly derived from the combination of different functions in a single element, which allowed a more efficient and material-reductive construction process. In order to prove this evidence, we carried out a study on the relative contributions to the environmental impacts of the conventional roof production (Figure 7). The analysis depicts that the hanging ceiling is responsible of approximately 40% of the impact. In conclusion, the integration of additional functions in a single digitally fabricated element provided environmental benefits because the element with equivalent functions in the conventional roof had high environmental impact.

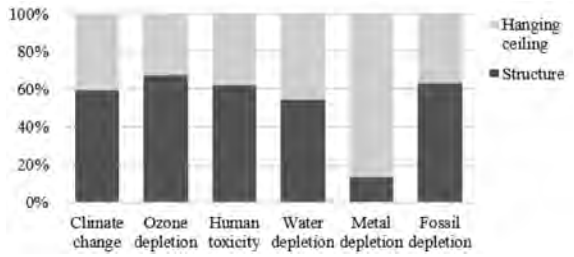



*Figure 7. Relative contributions to environmental impacts of the conventional brick façade production.*

## 5. Conclusion

Digital fabrication has fostered social and economic changes in manufacturing, but it still must mature to bring significant environmental benefits to the life cycle of buildings. This paper showed a preliminary step towards the formulation of guidelines that can help designers to make sustainable choices about implementing digital fabrication in architecture and construction. In each case study, the assessment was focused on the potential benefits that were enabled by computational design and robotic fabrication. The results of the evaluation evidenced that the largest environmental impacts depended primarily on materials production. Therefore, the most fundamental efficiency that might be brought to a project was found in material optimization during design. Nevertheless, robotic fabrication technologies and processes contributed minimally in terms of energy and environmental impacts.

Simultaneously, we observed that in many projects digital fabrication allows the integration of additional functions on the structure, such as thermal or acoustic performance that give added value to the architecture. These innovative digital construction process can contribute to achieve significant environmental benefits, elimination of waste and reduction of economic and labour costs associated with inefficient construction. However, additional functions can increase the requirement of material in the project, which might be disadvantageous from an environmental point of view. In the present study, we demonstrated that digital fabrication brought high environmental benefits when the integrated additional functions had high environmental impact. In conclusion, sustainable design in architecture through digital fabrication must focus on the functional and structural optimization oriented towards resource efficiency.

## Acknowledgements

This research was supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (project number 51NF40_141853).

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# USING THE SAMR MODEL TO TRANSFORM MOBILE LEARNING IN A HISTORY OF ART AND ARCHITECTURE CLASSROOM

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**Abstract.** This paper presents the progress of a pilot classroom, which uses mobile devices to enhance instructor-student classroom interactions and students' learning of the History of Art and Architecture. The main objective of this research was to find a way of improving classroom activities, for the coming year, by making the best possible use of technology to enable students to learn more successfully and improve their understanding of the lesson content. In this paper, classroom activities during 2014 and 2015 are analysed using the SAMR Model coupled with Bloom's revised taxonomy and the EdTech Quintet Model. In addition, a plan for the redesign and improvement of activities in 2016 is proposed, the effectiveness of the SAMR model at improving in class activities is discussed and a perspective on how to develop the classroom using the "SAMR ladder" is included. The results show that in 2015, 25% of the students in the class achieved an A grade, and less than 5% were graded F compared to 26% in 2012.

**Keywords.** Design education; mobile-based learning; History of Art and Architecture; SAMR model

## 1. Introduction

### 1.1. BACKGROUND

This paper presents the progress of a pilot classroom, which uses mobile devices to enhance instructor-student classroom interactions and students' learning of the History of Art and Architecture (Nakapan, 2014). This academic year (2015) is the third consecutive year that Rangsit University has implemented its policy of providing freshmen with tablets. Over the past three years, more than 24,000 tablets have been distributed to students. The

School of Architecture continues to use mobile devices/tablets to augment the learning process. Initially, in 2013, Mobile Learning (Koole, 2009) was used to characterise the pilot classroom. The model comprised of a three-circle Venn diagram, which represented the 'Learner aspect', the 'Social aspect', and the 'Device aspect'. These aspects distinguished the course from a traditional lecture-based one: the Learner aspect, where no lecture was given and no exam was taken; the Social aspect, where the class was activity-based and students worked in groups; and the Device aspect, where students used mobile devices and social media as part of the learning process.

## 1.2. PROBLEMS ENCOUNTERED, RESEARCH QUESTIONS, AND METHODOLOGY

The main problem encountered was cramming a lot of content, ranging from pre-historic to contemporary art and architecture, into 16 weeks. Instead of organising the material in the traditional way, i.e. by era (Pre-historic, Egyptian, Greek, Roman and Byzantine) the content was organised by theme: Ancient Civilizations, Great Artists, Great Designers, and 20$^{th}$ Century architects. Each week by focusing on a different theme, the students could expand their knowledge through a series of activities using mobile devices. The activities included searching for information, organising knowledge, preparing presentations and taking quizzes. As a result, mobile learning has greatly enhanced instructor-student classroom interaction and the students have readily accepted mobile learning in the classroom; however, some activities could be improved on. Therefore, the objective of this research is to find a way to improve on classroom activities for the coming year.

One question, which arose, was how to improve in class activities to get the most out of the technology so that students learn more successfully and improve their understanding of the lesson content?

The methodology employed was action research, where the researcher was also an actor. The method featured three existing models: the SAMR Model, the EdTech Quintet Model and Bloom's taxonomy, which were used to analyse classroom activities during 2014 and 2015 and redesign/improve those activities for 2016. The SAMR Model for integrating technology into teaching, developed by Dr. Ruben Puentedura in the late 1980's (Puentedura, 2009), was used to transform the classroom and help "kick it up a notch". The model represents four levels of activities that instructors can use to climb the "SAMR ladder": Substitution, Augmentation, Modification, and Redefinition.

### 1.3. MICRO-UTOPIA OF INFORMATION

In response to the conference theme, it is useful to consider an aspect of a complex system such as a classroom in terms of information. The history of art and architecture classroom is conceivable without a textbook or a single lecture because it is based on the premise that, currently, resources related to the course are readily available in the cloud. In this micro-utopia of information, an instructor who acquires knowledge then shares that knowledge with a class becomes obsolete because students can bypass the instructor to get information directly; they can also recheck the accuracy of the instructor's knowledge quickly. Wood (2007) stated, "designers should become the facilitators of flow, rather than the originators of maintainable 'things' such as discrete products or images". This means, within the context of the classroom, "Teachers should become the facilitators of the flow of information, rather than the originators of maintainable 'knowledge', such as discrete textbooks or lectures". It is necessary for students to develop skills that allow them to look for a specific piece of information, judge its reliability, know how to organise it and how to reuse it in an ethical way. With this new set of skills, learning can truly become sustainable.

## 2. Theoretical models for mobile learning

Several theoretical models have been developed within the context of mobile learning, i.e. Koole's Frame Model (Koole, 2009) and the TPACK (Technological Pedagogical Content Knowledge) Model (Mishra & Koehler, 2006). These models allow the instructor to understand and describe the kinds of knowledge needed for effective pedagogical practice in a technology enhanced instructional environment. The learning theory of Connectivism, which has been described as "a learning theory for the digital age" (Siemens, 2015) has also been used in the creation of instructional environments. However, one model, which was predominantly more interesting than the others, was the SAMR Model.

### 2.1. THE SAMR MODEL

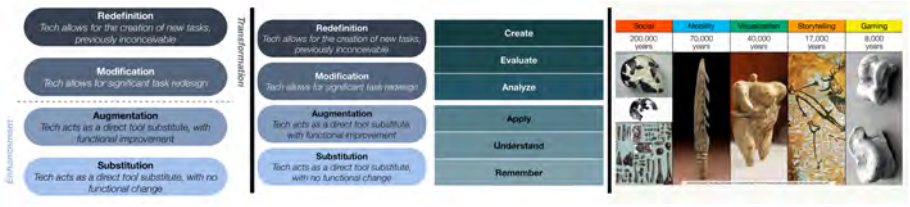



*Figure 1. The SAMR Model (left), the SAMR Model coupled with Bloom's taxonomy (middle),and the EdTech Quintet Model (right) - Images created by Dr. Ruben Puentedura, Ph.D.*

The SAMR Model is like a lens, which allows instructors to look at how they use technology in the classroom. The name of the model is derived from the initials of each of its four levels. Starting from the bottom (cf. Figure 1 –left (Puentedura, 2013)):

- **Substitution** is the direct replacement of existing tools or methods used in traditional classrooms, such as students using word processors instead of pens and paper to write reports,
- **Augmentation** is when substitution provides more functionality, such as when students who write on a word processor also annotate it or share the document with instructors on Google Docs,
- **Modification** is when parts of the tasks are redesigned, such as undertaking collaborative writing using Google Docs and using highlighting and chat functionality to give instant feedback to peers,
- **Redefinition** is the highest level, which allows students to do tasks that were previously inconceivable in traditional classrooms, such as recording videos to submit as homework and then posting them on social media to ask for feedback from the audience.

The first two levels are referred to as Enhancement, where technology assists in the accomplishment of traditional tasks. However, sometimes these levels may not be needed when looking at all the possibilities technology offers. The other two levels are referred to as Transformation, this is where the real metamorphosis of the classroom takes place and technology allows creative tasks, which are very different to those found in traditional classrooms.

The SAMR model offers instructors "a continual re-examination of practice to make the best possible use of technology" (Hogan, 2009). Four ways to integrate technology with learning are provided; it takes the technology into the students' world and instils lifelong learning habits (Harris, 2014).

## 2.2. SAMR MODEL AND BLOOM'S TAXONOMY

Dr. Benjamin Bloom first created Bloom's Taxonomy in 1956 to "promote higher forms of thinking in education, such as analysing and evaluation rather than remembering facts" (Bloom, 1956). In the context of mobile learning, a revised version of Bloom's taxonomy, the Padagagy Wheel (Carrington, 2013) is useful for lesson development because it incorporates numerous examples of online tools and apps that allow instructors to integrate each part of Bloom's taxonomy into the classroom. However, when the SAMR Model is coupled with Bloom's taxonomy, initially, instructors may feel daunted because, when the models are combined they appear more complex.

The goal for the instructor, when designing a classroom, is to construct a simple SAMR ladder that is coupled to Bloom's Revised Taxonomy (Anderson et al., 2001). As the task moves from the lower to the upper levels of the taxonomy, it also moves from the lower to the upper levels of the SAMR ladder. Figure 1 - middle illustrates the correlation between the two and it shows the steps required to integrate technology into the classroom (Puentedura, 2014).

## 2.3. THE EDTECH QUINTET MODEL

Apart from Bloom's Revised Taxonomy, when assigning tasks to students who use technology in the classroom, the SAMR Model is often coupled with the EdTech Quintet Model (Puentedura, 2012) to give another perspective.

The EdTech Quintet model proposes another way of looking at technology to get the most of out of it in an educational environment. This can be attained when we start thinking about which technologies relate most closely to what makes us profoundly human. The model depicts prehistoric artefacts (cf. figure 1 - right) that represent the concepts behind each category of technology. For example, the human skull discovered 200,000 years ago has modern features; it is from an era when human language expanded because, at that time, there was a complex society and the human race had become socialised. Therefore, it represents technology such as social media, the virtual world, and collaborative webs. Furthermore, the Lascaux cave painting tells the story of a Palaeolithic hero, which represents a storytelling technique that began around 17,000 years ago.

TABLE 1. Summary of technologies, associated practices, and examples

| Technology | Associated practice | Examples |
|---|---|---|
| **Social** | Communication, Collaboration, Sharing, | social media, discussion boards, the virtual world, file sharing, |
| **Mobility** | Anytime, Anyplace Learning and Creation, | mobile apps, cloud computing, tablet computing, |
| **Visualization** | Making Abstract Concepts Tangible, | augmented reality, visual data analysis, mind mapping apps, |
| **Storytelling** | Knowledge Integration and Transmission, | Storytelling: electronic books, video editors, video sharing websites, |
| **Gaming** | Feedback Loops and Formative Assessment. | Educational games, game-based learning such as quizzes and role-playing games. |

## 3. Analysis of activities

The following three activities were analysed using the SAMR Model coupled with the Bloom's Revised Taxonomy and the EdTech Quintet Model (Puentedura, 2012): (1) Great artists, (2) Great designers, and (3) The History of Art and Architecture Quiz. Table 2 summarises all three activities and provides an analysis of the three different patterns that were found.

- For 'Great artists', the activities during 2014 and 2015 stayed at the same SAMR level (Augmentation), using Mobility technology. However, assignments achieved a higher Bloom level (from Understanding/Analysis, Evaluation to Understanding/Analysis, Creation),
- For 'Great Designers', a higher SAMR level was achieved (from Augmentation to Modification) by changing from Mobility technology to Storytelling. The assignments also achieved a higher Bloom level (from Understanding/Analysis to Understanding/Analysis, Creation),
- For the 'History of Art and Architecture Quiz', a higher level of SAMR was achieved (from Augmentation to Redefinition) by changing from Social to Gaming. However, it stayed at the same level according to Bloom (Remember/Understand).

TABLE 2. An analysis of classroom activities using the SAMR Model coupled with the EdTech Quintet Model and Bloom's revised taxonomy

| **Lesson** | | **Activity in 2014** | **Activity in 2015** |
|---|---|---|---|
| **Great artists** | Description | Students use apps (like PowerPoint or Keynote) to create presentations on iPads. They gather information about a famous artist of their choice, their peers can vote on the quality of the presentation. | Students use apps to create presentations on iPads. They gather information about a famous artist of their choice then create artwork inspired by that artist. Their peers can vote on the quality of the presentation. |
| | SAMR | Augmentation | Augmentation |
| | EdTech Quintet | Mobility | Mobility |
| | Bloom's | Understanding/Analysis, Evaluation | Understanding/Analysis, Creation |
| **Great designers** | Description | Students use apps to create presentations on iPads. They gather information about designers and artists of their choice. | Students create a video about a famous designer of their choice using iMovie. |
| | SAMR | Augmentation | Modification |

| | | | |
|---|---|---|---|
| | EdTech Quintet | Mobility | Digital Storytelling |
| | Bloom | Understanding/Analysis | Understanding/Analysis, Creativity |
| **History of Art and Architecture Quiz** | Description | Students participate in a quiz related to the architectural styles of a building on a Google Spreadsheet by searching for answers or asking their peers. | Students participate in an online quiz (Kahoot), to test their knowledge of the history of art and architecture while competing with their peers. The scoring system incorporates self-evaluation and real-time feedback. |
| | SAMR | Augmentation | Redefinition |
| | EdTech Quintet | Social | Gaming |
| | Bloom | Remember/Understand | Remember/Understand |

## 4. Transforming the classroom

### 4.1 THE SAMR LADDER

For each of the activities the SAMR model was used to discover how the classroom could be transformed. The following SAMR ladder exercise (Table 3) was created to find ways of integrating technology into the classroom.

Table 3: SAMR ladder exercise

| **Lesson** | **SAMR ladder** | **Description** |
|---|---|---|
| **Great artists: Students work in groups to present a famous artist of their choice** | Substitution | Students use apps (like PowerPoint or Keynote) to create presentations on iPads. They gather information about a famous artist of their choice. |
| | Augmentation | Students use apps to create presentations on iPads. They gather information about famous artists of their choice then create art inspired by that artist. Their peers can vote on the quality of presentation. |
| | Modification | Students use apps to create presentations. They gather information about a famous artist of their choice then they create artwork together using a collaborative online whiteboard. |
| | Redefinition | Students use apps to create presentations by gathering information about a famous artist of their choice then they create artwork using new visualisation technology i.e. augmented reality (Layar), |

| | | |
|---|---|---|
| **Great designers: Students work in groups to present a famous designer of their choice** | Substitution | Students use apps to create presentations by gathering information about an artist of their choice |
| | Augmentation | Students use apps to create presentations by gathering information about an artist of their choice. They also incorporate Interactive media such as audio, video, and hyperlinks, |
| | Modification | Students create a video about a famous designer of their choice using a video editing app (iMovie). |
| | Redefinition | Students create a video about a famous designer of their choice using a video editing app (iMovie), then share the video on social media and ask for feedback from the community. |
| **History of art and architecture quiz: Students take a quiz** | Substitution | Students take a quiz related to the history of art and architecture on an electronic document or a web form. |
| | Augmentation | Students answer questions related to the history of art and architecture on a Google Spreadsheet by searching for answers using iPads or asking their peers. |
| | Modification | Students answer questions related to the history of art and architecture on a Google Spreadsheet by searching for answers using iPads or asking their peers. The spreadsheet is improved with an add-on (i.e. Doctopus) that allows automatic assessment and emails the results to the students. |
| | Redefinition | Students play an online quiz game (Kahoot) to test their knowledge of the history of art and architecture while competing with their peers. The system provides instant feedback, ranking, and a summary of the results. |

## 4.2. PROPOSAL TO IMPROVE THE CLASSROOM

Next year, the following improvements to classroom activities are proposed:

- For ‘Great artists’, to achieve the Modification level, let the students create artwork together using a collaborative online whiteboard. For the Redefinition level, let the students create artwork using new visualisation technology such as augmented reality (i.e., Layar).
- For ‘Great designers’, to move from the Modification to the Redefinition level, let the students share video on social media and ask for feedback from the community.
- For the ‘History of Art and Architecture Quiz’, the game represents the SAMR Redefinition level since it allows students to compete with each other in real time and provides instant feedback of the students’ ranking.

Even though the original assignments from the lessons ‘Great artists’ and ‘Great designers’ were the same (students working in groups to present fa-

mous artists and designers of their choice), the activities were different; one incorporated a voting system, while the other let the students create artwork. This is where the SAMR Model is most useful because it allows the instructor to analyse the classroom and ensures that they get the most out of it.

## 5. Conclusions and discussion

The SAMR Model was found to be an effective tool for instructors who design classrooms in a technology enhanced instructional environment. It provided four ways to integrate technology into the classroom that had a significant impact on the students' learning outcome. As a result, in 2015, 25% of the students in the class achieved an A grade, and less than 5% were graded F compared to 26% in 2012. However, the model is more effective when coupled with Bloom's revised taxonomy and the EdTech Quintet model because this combination gives a clearer picture of what is happening in the learning environment in terms of technology use and cognitive learning. Guidelines were framed to improve classroom activities, which resulted in a higher level being accomplished according to Bloom's taxonomy.

For the quiz game, even though the Redefinition level was achieved using SAMR, the cognitive level stayed the same (remember/understand). However, the quiz was found to be a very useful way of improving students' general knowledge of history and geography. The key was letting the students take the same quiz twice so that they could reinforce their knowledge. Moreover, it was found that the quiz was the most effective way of engaging the students in the classroom. Apart from the three activities that were held in the classroom for the last two consecutive years, a new activity, the "Ancient civilization war game" was designed in 2015. In the game, students work in groups representing civilizations to ask questions in defensive mode while trying to answer questions about another civilization, which is in attack mode. Since they search for answers on the internet using mobile devices this activity is considered as Modification under the SAMR model, Gaming under the EdTech Quintet model, and Remember/Understand under Bloom's revised taxonomy. This activity could be developed into an app for collaborative gaming. Therefore, future work will focus on further integrating gaming technology into the history of art and architecture classroom.

However, the classroom has still not been completely transformed according to the SAMR model because some activities remain at the Enhancement level while others are already at the Transformation level. This is as expected because instructors take time to become familiar with using technology in the classroom. They need to be at ease with using technology at the Substitution and Augmentation levels (Enhancement) before they pro-

gress to the Modification and Redefinition levels (Transformation). It is important not to assume that Redefinition must be achieved for all of the activities. For example, it may be impractical to assign first year students to complete artwork using augmented reality within a week. The most significant role of the SAMR model was to raise instructor awareness when technology was incorporated into the classroom.

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# DISRUPTIONS: IMPACT OF DIGITAL DESIGN TECHNOLOGIES ON CONTINUITY IN ESTABLISHED DESIGN PROCESS PARADIGMS

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**Abstract.** This paper aims to provide a critical understanding of the discipline of architectural education, exploring how digital technology forms part of two Australian architecture schools. Generally accepted as the unbroken and consistent existence or operation of something over a period of time, continuity represents stability without interruption. In the context of architectural design education, continuity aligns almost symbiotically with the design process; a system that facilitates a continuous loop of input, output and feedback for the designer—from defining the brief, collecting information, synthesising and presenting a design proposal. Preliminary findings of a larger research study that investigates the role of technology in architecture education, suggest that cultural patterns of technology adoption and valuation exist, valorising particular tools and establishing a framework for design teaching and practice that might disrupt the continuity of students' design process. Moreover, the study shows evidence of a disruption of continuity in design school narratives, emphasising the need to rethink design pedagogy and the place of technology herein. Reflecting on these observations, this paper explores the question: when the tools of digital technology challenge the established design process paradigm of an architectural school, how do educators respond to such a disruption in continuity?

**Keywords.** Digital design technology: student learning; course delivery; perception; phenomenology.

## 1. Introduction

The notion of continuity embodies a diverse definition; applicable to almost any function that determines movement from one point to another. Generally accepted as the unbroken and consistent existence or operation of something

over a period of time, continuity represents stability without interruption. In the context of architectural design education, continuity aligns almost symbiotically with the design process; a system that facilitates a continuous loop of input, output and feedback for the designer—from defining the brief, collecting information, synthesising and presenting a design proposal. However, when the tools of digital technology challenge the established design process paradigm of an architectural school, how do educators and students respond to such a disruption in continuity? Through an exploration of qualitative data collected at two architectural schools in NSW, this paper aims to shed light on this question. We will briefly explore the evolutionary design paradigm that underpins contemporary architectural education debate, outline the research design in brief, and explore the question of how continuity and disruption form part of how educators embrace design technology. By exploring the nexus between institutional archetypes, and educational practice, we aim to initiate debate about the role of individual preference, institutional framing, continuity and disruption. The paper pursues a holistic understanding of the impact that digital design has on continuity in the design process and the place of distinct technologies in design school's historic practice.

## 2. Evolutionary design paradigm

The fields of design education and research are inherently dynamic, yet, currently, a sense of stasis often characterise distinct architectural institutions through definitions of particular directions and schools. Coupled with a perpetual influx of technological innovation and the associated *evolutionary design* paradigm, traditional design methods and theory are being questioned. The challenge of emergent digital design tools and ideology has positioned design educators and researchers to respond to the driving forces behind this technological shift (Boulton-Lewis et al. 2006; Milne 2007; Brill & Park 2008). Influencing the prevalence of emerging digital technology is the exploration of new educational, which support the movement towards an evolutionary design education.

With the continuous expansion of digital design tools into the educational sphere, educators and students are presented with an increasing amount of opportunity and diversity. Changes within professional practice are placing novel questions on design educators and institutions on how to incorporate expanded technological fields with core architectural techniques in the curriculum (Yanik & Hewett 2000; Savage 2005). Pressures from professional practice and governing bodies on creating 'work-ready' students force consideration of what skills architecture graduates must possess: specific technological skills or life-long learning skills that develop technical resolutions?

(Oxman 1999, 2006a,b,c). In its shadow, educational institutions, educators and students must negotiate the question of whether to embrace the emerging technologies within their curriculum and pedagogy or remain loyal to the traditional methods characteristic of the school's approach to design. This question is at the heart of this paper, which looks at how adoption of new technology is paralleled by continuity of practice due to the presence of strong archetypes that guide student and staff adoption of novel approaches.

## 3. Research design

The study on which this paper is based, explores the tension between traditional and emerging design technology within two distinct architectural schools. In contrast to conventional research on the topic—which generally use traditional quantitative research methods and case study based exercises—the study of which this paper forms part adopts a phenomenological approach and a qualitative research design. Adopting the research techniques of participant observation and semi-structured interviews, the project attains a detailed focus on moments of learning and creativity, as they materialise. As such, it aims to develop a novel understanding and provide a rich foundation from which to better understand how technology can, and should, form part of architectural pedagogy, specifically.

The research was designed as a comparative qualitative study. Data was collected from two distinct field sites, which both have an accredited undergraduate architecture program. The two universities were chosen following an Internet-base preliminary analysis of the architectural curriculums of Australian tertiary institutions. This analysis found that Australian architectural education institutions can be categorised into two general groups, distinguished by their approach to technology in design education. Group A contains schools or faculties that are more technically aligned with the use of digital technology or with a specific focus on digital design. Group B contains schools or faculties that follow design process largely informed by analogue design methods, and where computers are predominantly used for documentation and presentation purposes. The two schools chosen for Group A and B present particular characteristics— *Postdigitalism* and *Critical Regionalism*, respectively—which, we argue, have implications for the established pedagogical systems and, subsequently, the students' experience of continuity and disruption in the design process. These two paradigms and the notion of continuity will be explored next.

## 4. School A: postdigitalism and the digital complexity fetish

### 4.1. FRAMING POSTDIGITALISM

The data collected during the course of fieldwork at School A is indicative of a *Postdigital* archetype of teaching, suggesting a perception of digital technology amongst the study participants that has become increasingly transparent, primarily due to its popularisation. Negroponte (1998, p.1) defines the postdigital age as the time when:

> [t]he technology, is already beginning to be taken for granted, and its connotation will become tomorrow's commercial and cultural compost for new ideas. Like air and drinking water, being digital will be noticed only by its absence, not its presence.

Adding to the establishment of the Postdigital epithet, Pepperell and Punt (2001, p.2) suggest that tools and techniques of the digital are no longer novel, prompting a new approach to conceptual models:

> [i]ntended to acknowledge the current state of technology whilst rejecting the implied conceptual shift of the digital revolution…to describe the continuity between art, computing philosophy and science that avoid binarism, determinism or reductionism.

In the digital arts discourse, the term Postdigital can be understood more generally as the constantly changing relationship and attitude towards digital technology; an attitude focused on humanisation, rather than digitalisation of a subject. The essence of this humanistic view in the Post-digital environment is summarised in the words of self-confessed 'Postdigital operative', Mark Burry (2005, p.49), who explains how he has 'no particular interest in the digital per se', just as he has 'no interest in the traditional per se'. Conversely, he explains:

> I have a lot of interest in their fusion. And I think that the people who I admire most and work best with are the people who rather than polarising one way or the other are able to form some kind of fusion between the digital and the analogue, without getting too strung out about the difference between the two modes of practice.

This comment, which could be taken as a simple clarification, captures the essence of the Postdigital attitude indicated by the data pertaining to School A: the staff participants from this school demonstrate similar attitudes as Burry, in which past emphasis on the digital is muted by a fusion of the digital and analogue. Subsequently, the school has moved away from its digital focus to a post-digital archetype within which the student's design practice and learning take place.

Both educators and students at School A express an understanding of digital technologies as essential to the design process and a fundamental asset to both producing and representing architecture. The established teaching style at School A has manifested from the opportunities afforded by the digital medium, exploring the extent of innovation in architectural design at both a conceptual and developed level. One of the staff participants, Matt, suggests that past academics involved in the conception of the school's curriculum and agenda approached 'the digital wave' with a philosophical understanding, integrating digital thinking into the program through an abstract understanding of the theory behind the movement.[1] This was largely informed by key teachings of Greg Lynn (Paperless Studio 1994) and Ben van Berkel (UNStudio 1998), who had been seen to be successful in intellectualising digitals role in the design process.

At the time of data collection, the established teaching methodology at School A has been through a period of dynamic change, with an increasingly holistic view that expands the previous emphasis on the digital and, subsequently, moves it towards a Postdigital educational setting. Described as a 'reverse shift' (Mark), this cultural transference in thinking and design with digital media are illustrated in staff accounts about how the school had once been almost entirely focused on the digital process. As Mark explained, 'for a long time it was very much the digital uni, it had a very strong focus on computation', whereas now, it has 'a more nuanced understanding of what digital environments are capable of, in a design sense'.

Nonetheless, within the Postdigital philosophy present at School A, the analysis of the data set reveals a trend towards digital technology being perceived as a tool and technique of reverence and respect; a type of fetish, which we describe as a *digital complexity fetish*, exist. This fetish is identified as a disruption in the established design curriculum, in which the continued, yet subdued, emphasis on the digital restricts students' individuality and, subsequently, restricts individual agency and continuity.

## 4.2. DISRUPTIONS: THE DIGITAL COMPLEXITY FETISH

The perceived devotion to digital practices can be attributed to the popularisation of digital technology over the past decade, with students now expected to be familiar with the plethora of digital tools that currently exist, in some cases even before they begin their training. Matt articulated this in our conversation: 'digital means have been popularised, and this corner of the world has access to both sophisticated software and means of production that are digital'. A familiarity and knowledge of technology is expected; as Matt explained, '[students] use [technology] as they use a pen to draw'.

The concept of a digital complexity fetish was initially revealed through discussions with staff participants Matt and Mark. Matt's observation on the role of digital technologies in the design process, particularly in relation to expectations of students to be 'familiar with those tools and use it in a non-fetishist way', initially provoked our investigation into digital technology as a potentially fetishist device. Matt argued that the school's past emphasis on digital design technology delivered via technique-based instruction has left a legacy in which digital design technologies maintain a particular cultural capital, which bestows a notion of preference that might guide students' design choices. Whilst, as Mark explains, this is today contrasted by a devaluation of digital tools, which are rendered as 'one dimensional' in their application to the design process; 'a tool to generate complexity rather than an actual design method', the digital complexity fetish leads to an emphasis on the design tools rather than the process in itself. This observation suggests that if students develop a convention and corresponding design behaviour that is exclusively devoted to the digital medium, they risk 'exclusivity that narrows [the students] capabilities in terms of design thinking' (Mark). Mark suggests that when digital environments are fetishised and exclusively used by students in the design process, 'they actually structure the way that [students] think at a very fundamental level'. This can lead to a risk of predictable and banal design outcomes, despite the use of complex design tools.

To further rationalise the concept of the digital complexity fetish, it is imperative to define the underlying notion of *complexity* in this definition. For example, a student designing in a digital environment could develop an expectation that their design outcome would have inherent intricacies due to its conception in otherwise complex digital realm. However, if the design outcome was not perceived through feedback as a rigorous solution to the brief—a design lacking in complexity—this may present frustrations for the student. Subsequently, we argue, in order to progress and avoid the traps of this perceived digital fetishism, the discipline must further develop pedagogical strategies that incorporate a wide range of working methods: 'to try and understand that digital tools enrich the process rather than fundamentally revolutionise it' (Mark). This is not only the understanding of digital media as a tool to stimulate seemingly inconceivable design outcomes, but more so as an obsession of computationally driven design in an attempt to achieve the complex.

## 5. School B: critical regionalism and the digital stigma

### 5.1. FRAMING CRITICAL REGIONALISM

The data collected at School B show evidence of a teaching culture that emphasise an awareness of geographical context in design, the importance of topography, light, climate, and a tectonic sentience of form. Central to this teaching philosophy is the local traditions of the environment in which architecture is placed, which should be honoured and maintained. The school reflects a teaching ethos that bears similar physiognomies to the architectural movement of C*ritical Regionalism*, an established approach to architecture associated with architect Kenneth Frampton (1983, 1989, 1992) and architectural theorists Alexander Tzonis and Liane Lefaivre (1981).

When applying this movement as a tool to understand the philosophy of this school, it is first necessary to deconstruct Critical Regionalism to question its values and suitability as a tool for characterisation. Philosopher Paul Ricoeur (1961) frames the beginning of the regionalist developments through an examination of the universalisation of a modern civilization and its predominately negative impacts on traditional culture. He states that 'every culture cannot sustain and absorb the shock of modern civilisation' (Ricoeur 1961, p.277). It was, however, not until the two proponents of the movement, Tzonis and Lefaivre, coined the term Critical Regionalism, that it was defined in general terms. In line with Tzonis and Lefaivre, Critical Regionalism has become known as an architectural approach that 'upholds the individual and local architectonic features against more universal and abstract ones' (Tzonis & Lefaivre 1981, p.170). Frampton has expanded this philosophy, emphasising regionalist attachment to culture not as 'something given and relatively immutable but rather as something which has, at least today, to be self-consciously cultivated' (Frampton 1992, p.315).

Critical Regionalism has been celebrated for humanising modernity. At the same time, however, the advocacy of 'back-to-the-roots' have led to a criticism of conservativism. A major failing of the movement was evident in its reaction to the populist movement; the dangers associated with an agenda narrowly focused on stemming the gradual post-industrialisation of our technocentric culture, as obseved by Tzonis and Lefaivre:

> [t]he upheaval of the populist movement – a more developed form of regionalism – has brought to light these weak points. No new architecture can emerge without a new kind of relation between designer and user, without new kinds of programs (Tzonis & Lefaivre 1981, p.170)

Due to this movement's roots in deep contextual attachment, some forms of Critical Regionalist architecture tend to display a conservative undertone,

deriving architectural forms from an erroneous use of vernacular, ultimately severed from its historical context. In relation to the design studio and communication subjects within School B, the established traditional methodology reinforces similar sentiments of the Critical Regionalist ideology, with the collected data suggesting a high level of importance placed on learning and developing the skills of hand drawing, sketching and model making; techniques synonymous with the conventional core values of architectural representation. As identified previously, the Critical Regionalist manifesto suggests that the styles of both modern and post-modern architecture are 'deeply problematic', prompting a resistance of the movements of universalisation in architecture at the time. While the school does not appear to advocate this notion in its entirety, it does present evidence concerning a rejection of *modern* tools. This observed aversion to digital technology as a modern proponent to design thinking and process, is identified in this ongoing research as *the digital stigma*, and will now be discussed as the by-product of digital design technologies impact on the established teaching archetype.

### 5.2. DISRUPTION: THE DIGITAL STIGMA

In the scope of this research paper one of the key phenomena identified, which characterises this identified rejection, is defined in this paper as the *digital stigma*. The collected data suggests that this attitude existed in the culture of School B during the late 90s, triggered by the transition towards a digital method of architectural production in the degree. The collected data identifies distaste amongst educators and students towards CAD generated drawings, particularly due to the lack of human touch; a quality revered in Critical Regionalist thinking. The current use of digital technology as a tool in the design process has become more accepted in the school, but data suggests that there is still division in the design faculty regarding its use, characterised by an uncertainty of the value of the digital in the design process. The notion of *cultural resistance*, highlighting a 'threat by crowding out critical thinking' (Denzer & Hedges 2008, p.3), has been identified as a running theme in the data. This theme is closely associated with the development of the inherent digital stigma existing in the school, a consequence that can be perceived as territorial in nature.

Building on this perceived cultural resistance, the staff participants of School B cited digital media as 'a weasel word' (Harry), 'the enemy' (Andy), 'lazy tool' (Ryan), 'a dirty word' (Cindy), and 'frowned upon' (Anna). This attitude is suggested to have been cultivated by past and current academics within the school, who possess a conservative viewpoint towards digital technologies application in design education. Ryan explained how the

most senior members of academic staff ‘see it purely as a tool, and they preach heavily on getting to the stage where your eye and hand can work together on a piece of paper’. Harry further describes digital technologies perception in School B as a potential ‘hangover’ from ‘the old days’ when digital design tools became more mainstream. During the course of this research there have been many recorded instances in the student data group that uncover this rejection of digital technology by academic staff, largely perceived as a negative impact on the student learning experience. More than 75% of the student participants reported encountering barriers pertaining to issues surrounding the acceptance of digitally produced work. These barriers ranged from fear of being marked poorly due to their choice of medium—‘if you use any sort of CAD you're shunned and they almost look down on your work’ (Dean, School B Student)—to trying to masquerade their computer generated image to please tutors and critique panels—‘we all create our presentation models using ArchiCAD but then we print it off, then we trace it using pen and paper...because that's what the lecturers like’ (Joanna, School B Student). This data suggests a trend that characterises the current attitude towards digital technology in this learning environment, in which the student’s design choices, the individuality of and continuity in the design process and learning process are impacted by a cultural stigma against particular types of technologies.

## 6. Conclusion

The process of characterising each of the two selected field sites has established a framework to analyse the data set, facilitating an interpretation of the identified phenomena within the aligned pedagogical agenda. This framework presents an exploration of digital technology from a cultural perspective, reflective of an individual design process and differentiation of the institutions surveyed.

This paper is underpinned by the observation that there exists a disruption in continuity through a shift in design education and practice. We maintain our position that the established pedagogical systems are deeply affected by the evolution of digital methods and media. However, our on-going analysis indicates that there is no distinct divide amongst digital and analogue practices; suggesting that a more integrated use of various tools can enhance experiences of continuity in the design process and promote learning.

Our future research aims to incorporate these results to provide a more inclusive description of the phenomena discussed here. We now seek to explore the student participants' own experience of the digital design paradigm within the defined cultural group, rather than prove these extrinsic ideas and

categories. This paper will contribute to the larger study by enhancing the understanding for academics and researchers of the student perspective in architectural design, allowing for more informed conclusions to be reached regarding the implementation of digital design technologies in today's higher education institutions.

## Endnotes

1. Synonyms are used throughout this paper. UON HREC Approval H-2013-0401.

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# 'I'M A VISUAL THINKER.'

*Rethinking algorithmic education for architectural design*

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**Abstract.** The representational and visual aspects of architectural design education cause certain pedagogical stresses in student's capacities to learn how to code, and this paper will serve as a critique of the current state of algorithmic pedagogy in architectural education. The paper will suggest that algorithmic curriculum should not frame code as 'a design tool', but as something to be designed in its own right; the writing of the code is the 'design brief' itself and not something additional to an architectural design brief. The paper will argue for an architecture-less educational environment that focuses on computational competencies such as logic, loops and lists along with building a strong analytical basis for students' understanding of programming and digital geometries.

**Keywords.** Pedagogy; algorithmic; programming; education.

## 1. Introduction

This paper will argue for a new mode of algorithmic education within the discipline of architecture in order to deal with new modes of architectural thinking. The rise of complexity theory and emergence has changed the way we frame and talk about architectural design in relationship between design outcomes and algorithmic processes[1]. Ideas such as 'top-down design' and 'bottom-up processes' have entered the way we frame and understand code within design processes. Although the introduction of these sorts of ideas into design is by no means new, it is becoming clearer that architecture lacks the educational frameworks in order to increase student literacy within the family of algorithms that embody these complex and emergent properties that seem to simulate the natural world.

The problem for architecture is two fold. Firstly, one would expect to see an increase in the complexity and sophistication of algorithms within architecture over time; however, this is not occurring. Instead there is an increase in the complexity and sophistication in understanding direct applications of the algorithm. Secondly, as algorithmic problems in architecture become more complex and dynamic, and thus the code required becomes more complex, new modes of algorithmic andragogy are required to bring students into a position where they can not only engage with these algorithms, but also innovate them. Further to this, as these problems become more complex, it is very likely that we require more algorithmic-literate architects to engage in these new modes of practice and problem solving in order for architecture to deal with complex and 'big data' problems.

This paper therefore positions itself as a critique on current algorithmic educational frameworks and attempts to question, understand and propose a solution to some of the deficiencies in current educational frameworks.

## 2. The nature of algorithmic education

Programming is undoubtedly difficult. Computer Science courses have one of the highest dropout rates of any course at a university level (Ljungkvist and Mozelius, 2012, p. 285) and many students have trouble learning even within introductory subjects (Lahtinen et al, 2005, p. 14). These subjects are not difficult because they are necessarily ill-structured or the tutelage is weak, but because the fundamental content is both theoretically and practically challenging to students, especially in fields in which students have no formal background (Eckerdal, 2009, p. 12; Robins et al, 2003, p. 138). Fundamental computer science ideas such as classes, functions, arrays, matrices, loops and gates are taught implicitly alongside their mathematical basis of number theory, set theory and logic.

Programming for architectural purposes adds the additional requirements of computational geometry, vector algebra and topology. To further conflate the problem, programming is often taught after a core competency with basic CAD, for example Rhino3D, is met. Students are therefore familiarized with user-friendly graphical user interfaces and thus programming within an integrated development environment is extremely alienating (Muller and Kidd, 2014, p. 176). Although Muller and Kidd (2014) are referring directly to teaching programming in a geography andragogy, they quite rightly argue that reintroducing mathematics, statistics and computer programming subjects at a later stage in student education can lead to anxiety, and architecture is no exception to this. This alienation and anxiety requires particular engagement from the educator in order to help students learning. Further to

this, material aimed at assisting students learning to code are generally ill-conceived and poorly designed. The Grasshopper Primer (ModeLab, 2015), is a particularly poignant example; its 242 pages rush through mathematical basics, logic and list structures at an alarming rate. Further, at no point does it attempt to meaningfully challenge the reader to engage with their learning, by coding something from scratch. Finally, to make the issue of programming andragogy worse, the educators within the field tend to have no formal computer science or mathematical education themselves. They are often self-taught making the process of framing core computer-science concepts difficult.

In short, a general algorithmic-design course in architecture is far more difficult than a programming fundamentals course. This is because more is taught faster and students in architecture have no fundamental understanding of computational geometry. For example, although students comfortable with any given CAD package can draw a B-Spline, very few know what it is or how it works. Although within the majority of architectural production, the technicalities of how geometry is computationally constructed is irrelevant, in the instance of programming understanding a geometric object's underlying construction is fundamental in framing how to build it from first principles and debugging potential problems that rise from this construction. This is not to say that we should change the way we teach CAD, as some students have no interest in programming, but that students lack the ability to understand the deficiencies in their knowledge (Kruger and Dunning, 1999, p. 30).

Further, this paper's second author has produced a series of interviews with computer science researchers revealing a general belief within the discipline that students require two to three programming courses in order to become sufficiently skilled (Nassir, 2015). It is important to note that in this instance 'skilled' does not refer to students capacity to know a 'programming language' but an understanding of programming fundamentals and logic (B. Faqeh, 2015). This begs the question: what has lead to the current curriculum expectation in architecture, that students with no deep knowledge of logic, programming or computational geometry can pick up algorithmic design and produce a 'good project' within twelve to fifteen weeks?

## 3. Unpicking the visual thinker

Architecture predominantly represents itself through visual communication, for example images, drawings and models. As such it is no surprise that many students, architects and academics consider themselves 'visual thinkers'. It is because of this visual nature of the discipline that architecture has

gravitated to more visual modes of programming, such as Processing and Grasshopper, in which designers are given visual feedback to help understand what a piece of code does.

However, visual programming has its limitations; it doesn't alleviate the lack of understanding about more non-visual fundamentals of programming and mathematics, for example, 4-dimensional transforms. Further to this, visual programming allows users to employ geometry without any understanding of its mathematical basis (Ozcan, Akarum, 2001, p. 27). Although at first glance this seems like an ideal situation in the andragogy of algorithmic design for architecture, it does make algorithms that are inherently object oriented, such as agent-based systems, far less obtainable to students learning to program. This is not to say that students would not be able to use an agent-based system, but that they would be far less likely to both understand it fully and write it from scratch.

Visual programming itself is not a problem as the majority of programming done within architecture is inherently visual. The issue is that most algorithmic design curricula within architecture rarely extend themselves outside the visual aspects of programming and reinforce these visual aspects through lesson and assessment design[2]. Most curricula direct students to create 'architecture' or at least something architectural as the goal of the course, rather than directly grade students on their capacity to program. Further to this issue, the fundamentals of programming are usually compressed into a smaller portion at the beginning of semester to make more room for design. This therefore transmutes the problem of 'learning to code' into a more comfortable 'architectural design problem'. This generally leads to a low percentage, somewhere between 5 to 15 percent, of students leaving an algorithmic design course knowing how to program at a basic level.

It is important to mention that architectural design andragogy is not merely problem solving but a creative endeavour in its own right, in which the outcome is judged by the merits of how the problem is solved and not just on the fact that it solves the problem (Harfield, 2007, p. 164). Further, this architectural design favours 'creative', 'novel' and/or 'good' outcomes not only from the perspective of the student themselves but also the tutor and coordinator. Although the relationship between outcome and process may be causal (i.e. a 'good' process implies a 'good' outcome), the process is generally only graded on its capacity to produce 'good' outcomes. Student focus therefore moves from learning the fundamentals of programming to 'designing through code'. Ironically, 'designing through code' is difficult, problematic and foolhardy without knowing the fundamentals of programming as students will know in a general sense what kind of outcome they want, however they lack the skills in order to produce it. This can likely lead to stu-

dents not using programming techniques and reverting back to methods of design they are personally comfortable with.

## 4. The Dunning-Kruger effect and algorithmic education

The Dunning-Kruger effect is a psychological phenomenon of cognitive bias where a relatively unskilled individual overestimates their abilities and their very lack of skills also robs them of the ability to realize they have over- estimated it (Kruger and Dunning, 1999, p. 30). For example, in the context of an architectural design studio, a failing or passing student may personally expect a grade of a credit, distinction or high distinction. This should come as no surprise to the reader. However, evidence suggests that the converse is also true, namely, that skilled individuals will underestimate their abilities (Kruger and Dunning, 1999, p. 33, p. 42-43). Using again the example of an architectural design studio a high distinction student may expect a grade of a distinction or a credit (while of course secretly hoping for an 'HD').

The Dunning-Kruger effect has been well studied and applied to understanding and grading student self-assessment within universities (Karatjas and Web, 2015, p. 30). What has not occurred, however, is a critique of curriculum design through this lens. Kruger and Dunning (1999, p. 43) argue that individuals that are skilled in a task, and thus find it easy, assume that other people would be equally skilled. This implies that individuals that easily learnt programming in architecture, which are the individuals most likely to be teaching programming in architecture, assume that other people will find it equally easy. This begs the question: Do algorithmic design curricula in architecture assume that students will retain fundamental programming concepts and logics beyond what is reasonable to expect? Considering the rate in which algorithmic design is taught, the amount of time that is spent within those curriculum on programming fundamentals in comparison to computer science courses, and the findings from Muller and Kidd (2014), it would not be foolhardy to suggest the answer to that question is *yes*.

It would, however, be foolhardy to suggest the solution to the problem is simply to go slower over a longer period of time. The problem, with algorithmic design in architecture, is that a lot of the simplest and most canonical algorithms (for example, voxelisation, recursive subdivision, packing, swarms, diffusion-limited aggregation, dynamic relaxation, cellular automata, etc.) require fairly well-established and fundamental knowledge of loops, logic gates, arrays, functions and classes in order for students to understand them, read them and write them. In other words the issue with algorithmic andragogy within architecture is that quite advanced programming concepts are required to produce quite basic visual outputs. This issue, along with the

Dunning-Kruger effect, therefore calls for a radical shift in the way that programming is taught within architecture schools.

## 5. The death of the tutorial

From the student's perspective, electives are a rare commodity. From the perspective of academia, core subjects are of equally rare value. Architecture requires knowledge of design, history, theory, construction, etc. Space in architectural studies is limited, and programming, in the scheme of a wider architectural education is a specialisation. Students are likely to only be interested in using one elective on programming, rather than the two to three subjects suggested by Nassir (2015).

The next problem is that it is likely that after completing an algorithmic design course, students will not program again. This may be because of subject focuses and tutor positions outside of the students' control, or a general dislike of programming. On this note, Bjork (2013, p. 2) states that the goal of instruction is to "equip the learner with the type of knowledge or skills that are durable and flexible". It is clear that current algorithmic andragogy in architecture struggles to retain 'durable' and 'flexible' knowledge within the majority of students. Nevertheless, if algorithmic design courses wish to educate more architecture students with base programming competencies, curricula need to be designed in a manner that focuses on the retention of programming fundamentals as its core goal.

Leonard (2015) quite aptly states that:

> Researchers have shown that, in laboratory tests, people quite consistently have "illusions" of competence. That is, they over-estimate their ability to solve future problems when they've been given a lot of help during lessons. When shown answers to questions, experiment subjects are likely to think they could have produced them ("Oh, sure, I knew that!") And the more familiar the material seems to them, the worse the students do in actually using it. Familiarity breeds complacency.

Leonard's statement implies a reasonable explanation for why students can understand programming concepts in particular contexts and not others. Showing students how to use abstract programming fundamentals in one context does not give 'flexibility' to the knowledge, and further it is only in hindsight that students see the solution to simple programming problems. Further, it allows the student to confuse performance, "…which is what can be observed and measured during instruction…" (Bjork, 2013, p. 2) with learning, that which is exhibited after instruction. This confusion between performance and learning suggests that the lab tutorial itself is a non-

productive mode of learning and should instead be replaced with, for lack of a better phrase, the lab problem. If we, for example, momentarily consider the famous turtle algorithm from LOGO in which users learn to move a turtle around a screen. Over time users would get better at moving a turtle around a screen and not better at programming algorithms as the problem is solved for them. Asking students to write code constitutes learning in a way that is relevant to them being able to solve different problems in the future.

Therefore algorithmic education should focus on setting students up to practice solving problems rather than following through a problem. In following through a problem students tend to copy the code without any understanding of its meaning. For example, students don't understand that they may have forgotten a '(' or a ':' in an IDE, or not add a number to a 'division component' in Grasshopper because there appears to be nothing to copy. If students regularly problem-solve while slowly understanding the abstract ideas of fundamental programming concepts, these ideas will remain abstract, flexible and more durable then standard tutorial methods. This mode of andragogy already exists within core architectural subjects; core design, construction and communication subjects already focus on practicing problem solving rather than following through problems. Further, it could be argued that this is intrinsic to architectural education. This is not to say that existing algorithmic design curricula do not practice problem solving, but that they practice solving architectural problems rather than solving programming problems.

What this suggests is that algorithmic design should be taught in a manner in which students are required to grapple with abstract programming fundamentals in a variety of different ways (Ekerdal, 2009, p. 11) in order to maximise learning at the cost of other significant architectural ideals such as 'good', 'novel' and 'creative' outcomes.

## 6. The architecture-less environment

At this point, it should be clear to the reader that the writing of an effective algorithmic design curriculum within architecture is a wicked problem. There is no clear solution, and any solution will have to sacrifice particular pieces of knowledge and trust students to develop those pieces of knowledge independently. This is under the assumption that the students understand why they should independently develop this knowledge and that they are engaged enough with their education to do so.

The authors propose that architecture itself should be thrown out of algorithmic design curricula, in order to shift the focus away from outcomes to a fundamental understanding of algorithmic processes. This is not to say that a

curriculum would remove students understanding of architectural applications of a said algorithm, but that it should not be directly assessed within the design of a curriculum. In other words, what if rather than grading the architectural potentials generated from an algorithm, the students understanding of the algorithm itself is graded? For example, the architectural potentials of cellular automata are ignored, and instead the focus is on the students writing Conway's Game of Life. The architectural applications and lack thereof of many canonical algorithms in architecture are already well known and can be set as a reading task at the beginning of a curriculum. Now students no longer focus on designing a 'good' outcome with cellular automata; students are free to research, program, and most likely struggle through, Conway's Game of Life, thus giving far more focus and understanding to core programming competencies, namely in this example, arrays, functions, loops, logic gates and classes. In short, the focus shifts from designing with code to designing code.

In context, a curriculum asking students to research and program a piece of code has several advantages over traditional modes of teaching algorithmic design in architecture. Firstly, the problem is not wicked like a design problem and as such it is very clear to the student what constitutes a 'good' outcome (i.e. a working piece of code) rather than a student's first foray into algorithmic architecture, in which both the outcomes and processes appear quite abstract. Secondly, the process of learning to program is stretched over a whole curriculum, and students are not disadvantaged for struggling to learn core skills quickly. Often algorithmic design curricula in architecture attempt to push towards 'good' design outcomes as quickly as possible, even though it is clear from Muller and Kidd (2014 p. 176), Eckerdal (2009), Robins et al (2003), Ljungkvist and Mozelius (2012, p. 285), and Nassir (2015) that not only some students will struggle with the content, thus being disadvantaged, but it is very likely that the majority of students will! And thirdly, it requires students to develop core-programming competencies along with analytic problem-solving skills. In other words, the goal of the curriculum's design is to give students the skills in order to program, which assumedly, is the reason that students would have enrolled in it. On this note, in this paper's first author's experiences, students can solve programming problems very easily if computers are not involved. For example, when students are given three hours to translate a given board game into pseudo code consisting of while loops, for loops and logic gates, the vast majority of students easily complete the task in the time limit. However, when students are asked to write a small piece of python script that draws a line between two points without assistance, many struggle and many simply give up. The point here is not that programming is difficult, but that this shift in curriculum fo-

cus doesn't give students the capacity to get through a curriculum via their architectural expertise, aesthetic sensibilities and visual-thinking skills, but pushes students to slowly solve logical-programming problems over the course of a curriculum rigorously and in detail.

This method of algorithmic andragogy falls short on other vital characteristics of a perfect algorithmic design course. It does not completely solve issues of student anxiety (Muller and Kidd, 2014 p. 176) and it doesn't solve the problem that students require additional subjects to complete their education on the topic. On a side note, it would appear wise that this method of algorithmic andragogy be considered a pre-requisite for algorithmic-design studio streams within core university subjects.

## 7. Conclusion

This paper's findings are in no way complete as to make any clear judgment about the success and failures of new modes of andragogy requires a substantial amount of research. However, this initial attempt highlights the issues with current modes of algorithmic andragogy within architectural education.

In conclusion, programming is undoubtedly difficult. Our current modes of algorithmic andragogy are severely limited by time, student capacity and curriculum design, and as such are unsatisfactory for successfully educating the majority of students. If architecture wants to deal with complex algorithms, emergence and 'big data', algorithmic architects need to move past visual programming and engage in core programming fundamentals. Albeit not perfect, the architecture-less environment offers several advantages over traditional modes of education and appears to have the capacity to produce a stronger programmer in conjunction with support from the core curriculum.

## Endnotes

1. Although not all algorithmic processes are necessarily *digital*, in the sense that they use a computer, instances where students are required to write, read and understand code will be the focus of this paper.
2. This statement is made from the perspective of the authors. Having taught at several universities and seeing a wide range of differing algorithmic design core subjects and electives between the years 2009-2015 the general design of curriculum prioritising visuality has been a consistent theme.

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# THE PEDAGOGICAL MEANINGS OF AN EXPERIMENTAL FULL-SIZE MOCK-UP OF COMPUTATIONAL DESIGN

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**Abstract.** Skill in the use of digital media tools is growing more important in architectural education. However parametric objects in computational geometry or digital fabrication as an assist for project-based learning are not in themselves sufficient to extract the potential of computational design. When we consider the performance of a design, or the fundamental purpose of parametric design toolsets in the contemporary context, education must act as a connecter to the ambition of global sustainability. With regards to the advantage of computational methodologies, students benefit by developing a holistic vision of non-standardized assembly technology. This is particularly useful in overcoming problems of mass production, and with the creation of interactive technology that is incrementally adaptable in the process of answering to unpredictable change. In this context, a comprehensive understanding of digital tools as part of a holistic and ecological architectural design mindset is crucial for future designers. Exploring effective ways to guide students in the development of this capability is therefore important. This paper documents a recent effort in this direction through examples of education within a digital design studio. As a conclusion the paper discusses important factors in the encouragement of students as they develop a comprehensive understanding of the use of digital design culture.

**Keywords.** Digital design studio; full-size mock-up; comprehensive capability; practical performance; project-based learning.

## 1. Introduction

With the ongoing progress of digital communication media in architecture and urbanism, programmable 3D data has become a comprehensive tool for sharing ideas. Consequently, it has begun to affect the form and function of objects, as well as the construction and utilization of living spaces. 3D data is used in many ways, including the visualization of complex topology and geometry, the simulation of environmental factors, and the materialization of unique shapes and tectonics through digital fabrication. It is used to navigate the vast design space that results from algorithmic processes, in the adaptation to dynamic environments, and in responding to human behavior through digital sensing technology. As these uses become more common, the skilled use of digital media is growing more important in the education of architectural designers.

The use of parametric objects in computational geometry have become common as design tools, while digital fabrication is becoming less expensive and more popular. However computational processes are often viewed as a limited part of the architectural design process. In a more negative light, computational design is criticized for killing creativity by its focus on technical issues and unjustifiable novelty. Without answering those critiques directly, it is possible that a more comprehensive theory of computational design is needed in order for designers to completely take advantage of the tools and to grasp their full potential. The criticism provokes a look beyond the technical advantages and improvements in functionality, towards the more fundamental question about the ultimate purpose of design with regards to the use of these emerging tool-sets.

One answer to that question is the sustainability of human living systems. It is a logical fit as all of the tools when taken together offer the power to engage with complex dynamic systems. In that case the development of a comprehensive understanding of the digital tool-sets is an essential capability for future designers. If this is the case then it is important to explore effective ways to guide students as they build those capabilities through their work.

With this in mind, looking back at the last five years of our design coursework one of our ambitions was to encourage students to develop a comprehensive understanding of computational design as they developed their digital literacy. The organization of courses, and studio courses especially has changed as we learned better how to achieve that aim. This paper documents our efforts in this regard and introduces ongoing efforts to develop teaching methodologies that allow students to develop both technically and philosophically in the process of their education as architectural designers.

## 2. “Porus Torus” - installation work for research exhibition 2010

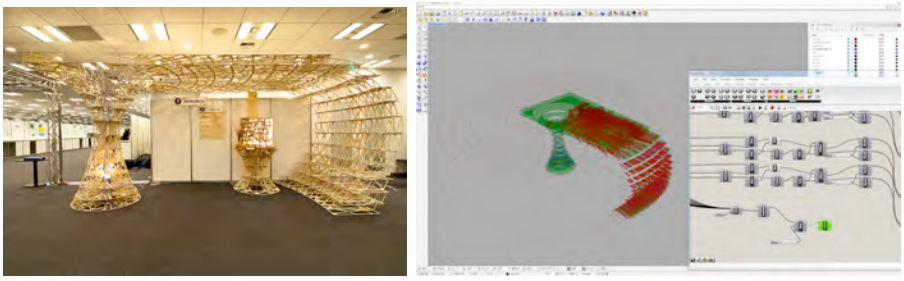


*Figure 1. Porus Torus (left) and the generation of geometry and parts (right).*

This pavilion-like installation work was our first attempt to ask student teams to combine multiple features of computational design. Since it was a public demonstration about the potential of computational tools in architectural design, we tried to include and visualize especially unique aspects from the point of view of novices to the field. For example, we chose the radial geometry of a torus as a starting point for design because it naturally produces unique forms that are obviously distinct from shapes that might be derived from the use of standardized parts. Non-standard fabrication is a unique feature of laser cutting. Algorithmic tessellation can be used to generate a series of no standard parts that are nonetheless similar enough to be manageable in terms of complexity and buildability. We called this approach non-standard homogeneity as it enabled the construction of an irregular form with relatively simple parts.With regards to project-based learning with full size mock ups, when we made this project we already had several years of experience with research-led pavilions and had developed a systematic methodology around the topic of portable architecture. In this case the size and uniqueness of the project had a significant effect on student motivation and helped them to also develop management skills in a collaborative team setting. In the process of developing the project we noticed that even though it was a small pavilion the structure required the solution of many technical issues to make it buildable, including the development of joints, assembly methods, ways to move it and to lift up parts. From a pedagogical viewpoint it is ideal because these are most basic topics of architectural technology, all useful in projects of much larger scales.

Simultaneous to the physical design of the pavilion we also started research on how to apply computational methods to the tasks of plan optimization and the generation of different forms through mathematical algorithms. However, this latter aspect seemed to be an unapproachable topic for most of the students who did not have mathematical sensibility or an interest in com-

puter science. When we attempt to extend these topics to all students taking a design studio at school some means must be put in place to encourage students to take on the challenge. In part that was the original motivation for the scope, size, and approach of this project, however we found some unexpected effects. In our observation students are conscious of the use of these digital tools in order to improve the practical performance of their design. For example, for technical reasons related to the location of the exhibition of the pavilion we needed to punch out holes in each panel part in order to reduce the total amount of combustible materials. Eventually one of the students proposed an algorithm that would generate the pattern of holes covering more than 70 percent of the surface, while avoiding any impact on the connections. In the practice of design pragmatic intentions overcame reluctance to use mathematical solutions. We took this as a key lesson of the project.

## 3. "Emergency Light Wooden Structure" – 4-day international workshop, 2011

While we were planning the next step in our program of computational design studios Japan was suddenly struck by a terrible earthquake in 2011, leaving more than 25,000 people dead or missing.

Although damage in Tokyo was light, our school was forced to postpone the start of the school semester, and most events were likewise cancelled. This event gave us both time and a need to rethink the ethics and social meaning of design and architecture. Initially we felt our computational methodologies had almost no power against unpredictable natural disasters, but this was turned around and we looked for ways to use the technology I closer alignment with the goals of resiliency and the sustainability of our society. We organized a workshop to build "the fish arch" with children from an elementary school in the disaster-struck area during the O-Bon festival (a mid-summer Buddhist festival to honor the spirits of one's ancestors) 6 months after the Tsunami hit the area. We wished to ease and encourage the local children's mental state. Having survived the disaster they were living amidst the wreckage of their homes and so we felt it could help them to better imagine a future if they had the chance to build something new with their own hands and in a symbolic way begin the reconstruction together. After some struggle we developed a small and simple application of the technology that showed the potential to include a noble attitude in the design mindset.

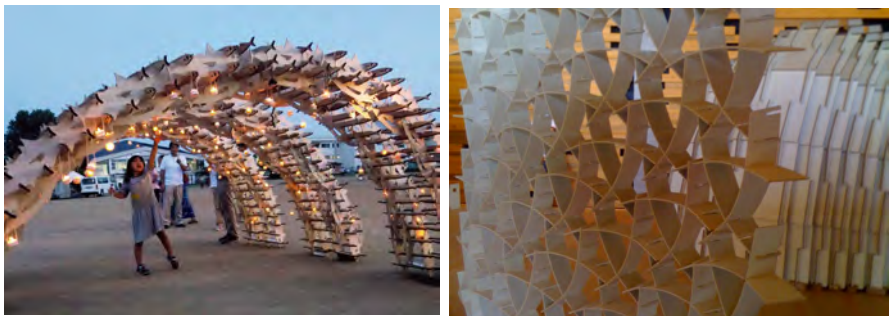


*Figure 2. The Fish Arch (left) and the Emergency Light Wooden Structure (right).*

It is an unforgettable lesson, and as a result we decided to restart a workshop that had been suspended because of the disaster, this time focusing on the creation of works that learned from the unexpected experience.

The workshop theme asked participants to consider feasible environmental designs that respected both modern lifestyles and traditional values, using computational geometry with wood as the main material. Digital fabrication tools enable designers to use this material in innovative and sustainable ways. Participants were required to realize a form of "*rapid architecture*" that could be compacted and then quickly deployed into emergency areas to cope with a variety of needs: housing, shelter, aggregation points, camp hospitals, privacy in shared public spaces etc. After 3 weeks of online software training we held a 7 day workshop in Tokyo to make a full-scale mock-up. The workshop was brought successfully to completion on September 10th with 4 international teams and 24 participants. The whole process of the workshop and symposia proved to be surprisingly sustainable, as the resulting models have been reused 3 times in 3 different occasions and therefore fulfilled the requirement of compactness, transportability, ease of assembling/dismantling and reusability that were set at the beginning. Through this process we have gained some important insight into the validity of computational design in the face of challenging social issues. The use of these tools in the education of young designers wishing to take on the serious challenge of sustainability also began to take shape.

## 4. "Digital Eco-City Landscape" - advanced design studio course work, 2012

Following on this project we set the next studio class for senior students in a new direction. Setting aside the construction of full-scale mock-ups we looked instead to the topic of dynamic sustainable system design as enabled

by information technologies, including computational modeling of complexity. We asked students to proceed according to the following steps:

1. Chose a typical area recognizing the working systems of human activity, with environmental elements such as food, energy, transportation, economy, culture etc.
2. Consider a model of the system to explain existing mechanisms in order to create its characteristic appearance, including environmental elements, and transfer it to a computational simulation.
3. Find controllable parameters in the simulation in order to understand a range of design space and to get idea for the potential to maintain its structure in the face of contemporary change issues.
4. Propose an urban system to work continuously for at least the next 30 years based on the simulation study.



*Figure 3. Digital Eco-City Landscape (left) and Computational Bamboo Structure (right).*

It was too difficult for a single student to solve all 4 steps. The work itself was used to analyze and predict the changing townscape in one of the most expensive residential areas of Tokyo. Reviewing the currently typical mechanism for property lot subdivision in the city the model indicated that green space in the city would entirely disappear in the next 50 years. In response to this future scenario a system to create micro-scaled semi-public spaces between houses was proposed as a kind of system protocol amongst neighbors. A simulation showed both space diversity and improvement of green coverage effects would result from the applied system. Though we tried to motivate students to learn system oriented algorithmic modelling in order to adapt to a changing environment, the domain was still relatively unapproachable even though they possessed a strong motivation to respond to social issues and especially issues around sustainability. Modelling of environmental mechanisms are very difficult to imagine without an insight in the workings of natural systems.

### 5. "Computational Bamboo Structure in a remote island" - summer workshop project, 2014

This project was unfortunately suspended because of a volcanic eruption in the middle of its construction in 2014. We were in the final process of building a full size structural bamboo hut for use as a sustainable solar shower in our summer camp at a remote volcanic island in southern Japan. The bountiful self-supporting island community has only 120 residents and no shops or manufacturing. Our challenge was to build for our own needs with as few imported materials as possible, and using in-situ material and energy by application of computational methods. After long discussion and research, we decided to use a combination of local bamboo and 3D-printed joints. To build the structure required adapting to uncertain conditions of the natural materials, and so a flexible geometry was prepared and the final joint confirmed after measuring the bending strength or diameter of bamboo on the site. The approach meant that even if we dismantled the structure after 2 week use, the system could be used every year and rebuilt using renewable natural materials. In the end this idea became a good example for how to create a fresh solution for contemporary issues of local sustainability in a global community. The life of a remote island was in part viewed as an inconvenient location for our study because of the remoteness and shortage of industrial products, however when viewed from a different perspective it was more properly a location with abundant natural resources waiting for innovation. Mass production is arguably wasteful and places low value on local character in our contemporary lifestyle.

In this way, this project became a significant case-study for understanding how computational design and digital fabrication could be used to not only create a value in the personalization of things but also in the localization of technologies, in the process overcoming current issues of sustainability in a society built on industrial mass production. Through this experience we established a common concept of sustainable technology as part of an adaptable system that should work over a long time. Design is always the discovery and development of solutions that bridge human activity and technology. Therefore, every student of design should be sensitive to the potential and limiting factors in materials and construction, including the physical, chemical, and visual, etc. These would ideally be considered in light of human activities corresponding to the demands of space quality. One essential vision we would like to teach students is that design is shifting from the discovery of form towards the creation of systems through the use of information technology.

## 6. “Portable Personal Popup House” - advanced design studio, 2015

Looking at all the observations and feedback from students, we have come to see the production of an experimental full-size mock-up as a very effective means to cultivate designers who possess a comprehensive understanding of digital media and technologies. This is mainly because the process forces students to make use of several fundamental tools of computational design.

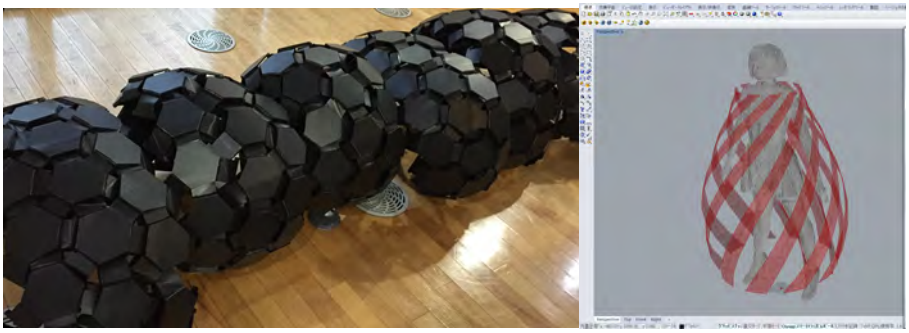


*Figure 4. PPP House by H. Okawa (left) and PPP House by S. Ohta (right).*

As a result we have set the structure of the new design studio according to feedbacks from students and our observations of results in previous studio works. The objective of the studio is firstly to realize the practical potential of computational design. Secondly it is to build a concrete skill set through a hands-on working method. Returning to our original ambition, our aim is to allow students to learn to use parametric geometry or digital fabrication through the development of a full sized experimental mockup of their architectural design. However, we asked student to undertake intensive research about a specific topic related to the subject of their expected works with a focus on natural phenomenon and the natural forms that can be found in nature. From these we hope they will find a solid basis for design inspiration. The quick hands-on iterative design process gives students substantial feedback from both tools and materials. Though digital Fabrication tools can be a perfect assist for project-based learning, the skill set used to perform quick and precise manufacturing is not sufficient to extract the real potential of computational design. It is important to recognize the ability to develop and use non-standardized assembly technology or incremental processed to answer unpredictable and continuous changes in the systems we work with. Intuitively, natural systems will always offer the best reference when pursuing this idea in practice.

## 7. Conclusion

As a result we gradually became to aim at education of a designer who is capable of using computational techniques in a creative and robust way. Then looking back previous attempt we have found 5 categories of subjects.

These ideas are considered with regards to the projects described in the Table 1. The latest project purposefully brings them all together with the aim of producing better designers who are not only capable of using the tools at their disposal but also understand their role in the broader context of society. Because our hope is to create an educational program that produces students who will be able to adapt to the most difficult challenges that we will face in the next decades, from sustainable design to social and demographic crisis.

FABRICABLE GEOMETRY: To understand the possibility of the combination of complex geometry and digital fabrication.

ALGORITHMIC ADAPTABILITY: To understand the idea of a dynamically adaptable model that exists according to a massively repeating algorithmic process.

PRACTICAL PERFORMANCE: To look for critical performance of proposed digital systems and their evaluation according to real practical conditions.

SYSTEM CONTINUITY: To create continuous working system that operates in response to human interaction.

BIOLOGICAL INSPIRATION: To investigate and refer to a simulation of natural forms, such as biological systems.

TABLE 1. 5 factors in capability model of comprehensive designer and its application.

| Educational Factor / Theme of program | Fabricable Geometry | Algorithmic Adaptability | Practical Performance | System Continuity | Biological Inspiration |
|---|---|---|---|---|---|
| Porus Torus | ○ | ○ | ○ | | |
| Emergency light wooden structure | ○ | | ○ | | |
| Digital Eco-city Landscape | | ○ | | ○ | |
| Bamboo structure in a remote island | ○ | | ○ | ○ | |
| Portable Personal Popup House | ○ | ○ | ○ | ○ | ○ |

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# WHY IS MAKING IMPORTANT FOR THE CULTURE OF DESIGN?

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**Abstract.** A select review of making in design in an epistemological framework presents two dominant approaches and a less practiced third approach. Whereas the first two value the control and accuracy in the processing of information, the third values the uncertainties in the processing of materials. Whereas the first two rely on final product and prior knowledge, the third relies on the processes of formation and flows of matter, and thus is key to a dynamic and sustainable model for design.

**Keywords.** Making; representation; hylomorphism; design culture.

## 1. Introduction

The ontological views of the material world, namely the Cartesian metaphysics that separate the mind and the body, and the Aristotelian *hylomorphic* model of creation seem to dominate our understanding of design today. Maintaining the physical matter, or the product, as a static and passive outcome of predetermined human thought, and making as the imposition of form upon the physical matter with a *design in mind*, these views frame design as an immaterial, fully intellectual activity. Ironically, the products of design are often material. There is therefore a great discontinuity in practice between the conception and the execution of a design idea, and in return, a disconnect with the environment, as both the resource and the habitat that receives. Perhaps due to skills gained in training, designers often do not design through matter but instead seek the right materials and techniques on the market to materialize their design ideas. The lack of interest in matter prevails in post-production: the behaviours of the materials over time are often not taken into consideration.

In this paper, I explore the alternative framework where design and making, form and its matter, as well as minds and things, are not only causally linked, but strictly interdependent. Recent findings in cognitive science research on embodied and situated cognition as well as in anthropological studies of creativity shed light on what it means to make things. Ideally, form of a thing emerges from the making process itself, established through the active engagement of the maker "with materials that have their own inclinations and vitality" (Ingold, 2013, p.26). In return, the things we make "mediate, actively shape, and constitute our ways of being in the world and of making sense of the world" (Malafouris, 2013, p.44).

Pérez-Gomez (2012) states that tools are never neutral as they underlie the whole process of generation of form. As design tools change over time, it is not only the design and its manufacture that undergoes change but also profoundly the thinking of design, its concepts and its language (Thomsen and Tamke, 2009). With the advent of digital fabrication tools and technologies, material practices commonly reappear at the centre of design activity. Is the long existing *hylomorphic* doctrine in design finally being challenged? If making remains solely "the hierarchical assembly of [digitally] preformed [material] parts into larger wholes" (Ingold, 2013, p. 26), I argue that it cannot yet be considered an integral part of the design activity. Digital fabrication protocols have compulsory predetermined instructions before materialization, and so require precise control over the process.

Only when the material process is favoured as a creative endeavour and over the outcome, we may then begin expecting to encounter with the uncertain. Brancusi observes that subject and form both come from "within matter" and not "forced upon from without" (as cited in Bach et al, 1995, p. 23). In DeLanda's words, this is "teasing out a form from the material", rather than "imposing a shape", where the makers act "more as triggers for spontaneous behaviour and as facilitators of spontaneous processes than as commanders imposing their desires from above" (2002, p. 135). From this perspective, a high-tech making process is deemed ideal when digital fabrication tools are used, not to materialize predefined forms with accuracy but are rather intermediary aids during form finding processes. As such, a process is a *making for* process (Gürsoy and Özkar, 2015) where materiality, with all the sense experience it comprises of, becomes a design drive. This way tools are constantly changing, adapting to unique situations, and an open community develops to share them. I claim that this inclusive and pluralist view can be the key to establish a dynamic and continuing culture of design that relies on the processes of formation and flows of matter instead of being driven by final products fulfilling templates of prior convictions of experts and authorities.

In the following section, I elaborate the existing views: how the Cartesian opposition between the mind and the matter, and the representational view of mind emerging thereafter, together with the *hylomorphic* ontology, result in an immaterial conception of design.

## 2. The backdrop to design as an immaterial activity: symbolic representation and *hylomorphism*

The way we relate with the material world significantly affects how we position ourselves within the world of material things. Western thought, now in the Anthropocene, seems to have been long nourished from ontological and epistemological views grounded on dichotomies separating the immaterial and the material, such as mind and body, minds and things, subject and object, as well as form and matter. Eventually how we shape the world around us has been deeply affected by the way we shape ourselves as the dysfunctional relation of an inner mental entity (the mind) and a material external entity (the body).

Symbolic representation, a consequence of the Cartesian division of the mind and the body, is considered as an intermediary process that feeds the mind with information from the external world and that defines how the mental contents are externalized and materialized by way of various sorts of behavioural output into the world. The mind, in this representational framework, is a "storehouse of passive internal representational structures and procedures" (Malafouris, 2013, p. 25). It is located *inside the brain*. This *intracranial mind* relates with the material world through symbolic externalizations of preconceived mental images. In design, this corresponds to representational drawings and models. According to this representational view, what is outside of the brain is outside of the mind, and the cognitive processing occurs in the brain between perception and action. The representational framework, to a large extent, remains the dominant paradigm in present-day cognitive science that conceptualizes the human mind primarily through representation and information processing. Together with the *hylomorphic* doctrine, they shape the understanding of design as an immaterial, cognitive activity.

*Hylomorphism*, initially credited to Aristotle, is the ontological view that all substances are constituted of form (*morphe*) and matter (*hyle*). Form gives the substance its very essence and identity and actualizes matter, thus, form is substantial whereas matter is not. Form precedes matter; matter does not inform form. This distinction of form and matter consequently evokes a separation between minds and things, and mental and physical actions.

These dichotomies are institutionalized in many domains within the modern society. However there are instances where these distinctions become problematic, as in the case of design. Design is directly related with the material world as its outcomes usually depict material things in various forms. However, relying on the *hylomorphic* view where the form precedes the matter and is conceived in advance in the mind, design remains within the domain of the mind and of the immaterial.

### 3. Design as an immaterial activity

The concept of design as we use today originates in the Renaissance from the Italian word *disegno*, meaning drawing, suggesting both the drawing of lines on paper and drawing forth of an idea from the mind into physical reality, thus implying a direct link between an idea and a thing (Hill, 2005).

The distinction of design and making originating in the Renaissance is derivative of the *hylomorphic* doctrine. In Leon Batista Alberti's architectural writings from the mid-fifteenth century, design is a "product of thought" requiring "the mind and the power of reason" (Alberti, [1452] 1998, pp. 5-7). Similarly, Vasari ([1568] 1998) elevates the intellectual labour in design by claiming that "the greatest geniuses sometimes accomplish more when they work less, since they are searching for inventions in their minds, and forming those perfect ideas which their hands then express and reproduce from what they previously conceived with their intellect" (p.290).

The superiority of the intellectual labour over the manual labour in design became ever more apparent as drawing became essential to design practice as a mode of representation in the Renaissance. This shifted the role of the designers from master craftsmen to *masterminds*, where, as Ingold (2000, p. 295) puts forth, in one field "excellence is attributed to expertise"; in the other it is "attributed to genius". Craftsmanship, once a main skill of the master craftsmen requiring the ability to handle the uncertainties and intense manual labour, became irrelevant to the profession of the designers. The new role of the designers as the *masterminds* required mastering new representational skills. The designers do not work "with the object of their thought" anymore, as they work at it "through some intervening medium"(Evans, 1997, p. 156). This complies with the representational view of the mind elaborated in the previous section. The mind, confined within the boundaries of the brain, is now detached from the material world. The communication is possible through symbolic externalizations.

These views and the modes of designing are still dominant today. Tim Ingold frequently highlights and criticizes the dominant *hylomorphic* approach to creation. Ingold (2010, p.92) claims that *hylomorphism* became

"ever more deeply embedded in Western thought" influencing how making is conceived. Form is considered as the particular design in mind, matter as the static and passive outcome of predetermined form, and making as the imposition of form on matter "from without, rather than unveiled from within" (Ingold, 2000, p. 339). In what Ingold calls "the standard view" of making to refer to the *hylomorphic* model of creation, "the form pre-exists in the maker's mind, and is simply impressed upon the material" (ibid, p.342). It is predefined through abstract representations – either through internal representations in one's mind or through external representations such as drawings. Thinking and judgment precedes making.

## 4. Making and the approach of the extended mind

I explore a new understanding of design that is neither bounded within the representational framework, nor *hylomorphism*, but is closer to Ingold's (2010) new approach -- the "textility of making". Ingold places emphasis on the movements and cooperation between the material and human action in the generation of form. Referring to the work of Deleuze and Guattari, he suggests replacing the *hylomorphic* ontology with "an ontology that assigns primacy to the processes of formation as against their final products, and to the flows and transformations of materials as against states of matter" (Ingold 2010, p.92), therefore thinking through and with the matter. In this alternative approach, the maker effects an ontological transformation in the material, "not through the application of exterior force to inert substance, but through intervening in a play of forces and relations both internal and external to the things under production" (Ingold and Hallam, 2014, p. 4). We call such process in design a *making for* process where uncertainty in the processing of the matter is valued over the control and accuracy in the processing of information (Gürsoy and Özkar, 2015). Conceptualization does not necessarily precede materialization, but instead evolves through the interactions with the materials. The design processes, as well as its tools, are open to constant change, adapting to unique situations. Design and making, form and matter, as well as minds and things are interdependent. This transformation in the material is the outcome of an experience-based connection of the maker-designer, which can be a non-expert as well, to the material at hand.

*Making for* processes are neither dependent on scale nor determined by the tools and technologies employed. Hence a traditional hands-on craft process such as pottery and basket weaving and a high-tech making process can both be *making for* if the focus is on discovering the uncertainties in making instead of materializing predefined forms with accuracy. The physical mod-

el-making processes of Antoni Gaudi and Frei Otto, for instance, can be considered as *making for* processes as the models not only represent their design ideas, but also guide their three-dimensional form generation. Gaudi and Frei Otto, instead of imposing preconceived forms on matter, explored “materiality both as genesis and fabrication of [architectural] form” (Voyatzaki, 2015: p. 14).

Over the last decade, there has been an increasing tendency to implement digital fabrication tools to design practice. With the ease provided by these technologies, material practices are once again in the design scene and among the responsibilities of the designers. Digital fabrication protocols, however, require precise instructions and control over the process. Designers have to shape their design representations according to the constraints imposed by the machinery, since machine precision tolerates no mistakes. Drawings once offered the designers a higher status in the Renaissance. Now with the solid interfaces of the digital fabrication tools, the drawing shifts from a measured representation read by the manufacturer, to a direct instruction to the machine. It becomes the "direct handling of the tool, the pressing of the drill or the pointing of the saw" (Thomsen and Tamke, 2009). It is at this critical point that the problematic aspect of the contemporary making arises: attention is directed to how closely the materialized work resembles its digital master rather than how the ideation process is shaped through the materialization of the digital. I argue that in the first case, making cannot yet be considered an integral part of the design activity as design still remains within the immaterial domain.

In Figure 1 and Figure 2, I present a selection of examples, which comply with the *making for* framework, thus challenge the *hylomorphic* doctrine and the representational view of mind. The scales of the examples range from the scale of a vase to that of a weekend house. This highlights the insignificance of established professional boundaries when making is at the core of design activity. A material experiment or knowledge can be translated across different settings and scales. In the examples presented in Figure 1, sheet materials gain variable flexibility by regularly arranged cuts. In all of the examples, the material aspects are open to exploration once the slits are cut. The effects of the cuts on the material affordances and constraints are usually unpredictable in advance. The physical interventions yield to emerging shapes and three dimensional form configurations, thus become design drives. In the three examples presented in Figure 2, final forms emerge through the “flows and transformations” of plaster, porcelain and concrete. In all three cases “processes of formation” are essential and constitutively determine the outcome instead of being predetermined by static moulds. As such, design is a material activity and making is an integral part of design.

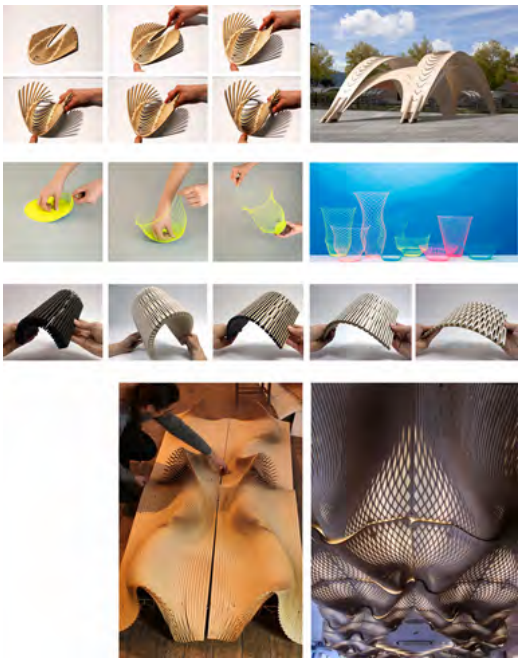


*Figure 1. First row: EmTech (AA) + ETH Pavilion, conceptual model and the full-scale pavilion. Second row: Air Vase by Torafu Architects. Third row: Dukta. Fourth row: The Wooden Waves by Mamou-Mani, prototype and design.*



*Figure 2. Top row: P Wall by Matsys. Bottom row left: Sponge Vase by Marcel Wanders, and right: Trufa by Anton Garcia Abril.*

Recent findings in cognitive science provide further support for the *making for* framework. Against the representational view of mind, a number of theoretical frameworks have been established in cognitive science over the years. These include extended cognition (Clark, 1997), embodied cognition (Lakoff, 1999), distributed cognition (Hutchins, 1995), enactive cognition (Varela et al, 1991; Noë, 2004), and situated cognition (Clancey, 1997), with a common point that the material world is a constitutive part of the cognition, challenging the mind/brain association and mind-body dichotomy.

In the embodied cognition framework, the body no longer passively contains the mind, but actively shapes it. The hand in particular, is not a tool to implement what the mind dictates; it effects how the world is perceived. As put forth by Lakoff (1987), "the very structures on which reason is based emerge from bodily sensorimotor experiences" (p.368).

In distributed cognition, besides the primacy of bodily experience in the structuring of human conceptual processes, the boundaries of the mind extend beyond the limits of the body to accommodate "the constraints and affordances of the material reality with which it is constitutively intertwined" (Malafouris, 2013, p.66). Material world is not only the passive background of the embodied activities but becomes "a cognitive artefact". Similarly, external representations are not simply physical records of the inner mental states, but are extensions of those states. How we externalize our mental contents onto material things actively shapes us. This suggests an on going dialectic of creating things which in turn creates us, where "cognition and action arise together, dialectically forming each other" (ibid, p. 74). These frameworks reverse the *hylomorphic* model: it is not the mind that imposes its forms on material objects, but rather the latter that give shape to the forms of thought (Gosden, 2005).

## 5. Conclusion: tools, technologies and the culture of making in design

According to Bergson ([1911] 1944) the "constant characteristic of man and of intelligence" is *Homo faber* and not *Homo sapiens*, thus "the faculty of manufacturing artificial objects, especially tools to make tools, and of indefinitely varying the manufacture" (p.153). Similarly Malafouris (2013) argues that the tools are "enactive cognitive prostheses" with which we define and shape ourselves (p.154). In the context of design, as Pérez-Gomez (2012) states, tools underlie the whole process of generation of form. Every tool leaves its trace on the material surface with which it gets into contact. This holds true for digital fabrication tools too. However perfect the digital master is, its materialized outcome will always bear *imperfections* and traces of the fabrication tool. There is still neither a 3d printer that prints surfaces on

which the trajectories of its nozzle cannot be traced, nor a CNC milling machine that does not leave the traces of its drill. By way of treating these imperfections as emerging design features, or discoveries the process can become one of *making for* and break from the "rather tantamount withdrawal of the producer, in person, from the centre to the periphery of the productive process" (Ingold, 2000, p.289).

Knowledge acquired through material engagement and making have long been deemed essential in various pedagogical frameworks, including constructivism (Dewey, 1938; Piaget, 1953) and constructionism (Papert, 1980); and more recently in critical making (Ratto, 2011). Yet a making-centred culture of design is still uncommon in the profession and education despite the well-known historical examples such as Bauhaus, Vkhutemas, and Ulm School of Design. It is through the developments in the digital fabrication tools and technologies in the last decade that we have started to discuss making alongside design, in an embodied and enactive model that extends the mental processes into the world of material things. The technological and social developments also instigated an open design and maker culture that educated designers start to acknowledge as the scope of design knowledge expands in range and to a broader community. This, however, is only the beginning. As we have illustrated above, a culture of making in design emerges only when the material process is continually the drive of the creative endeavour over the outcome.

Multiple examples in our review are testimony for an emerging potential of an inclusive and pluralist culture of design. These examples can be expanded to non-expert designs and makings, too. The approach of *making for* narrows the gap between the conception and the execution of a design idea, and in return helps preserve the natural and social resources as well as give back to the habitat. A dynamic and sustainable culture of design that relies on the processes of formation and flows of matter can relocate designers at the centre of the materialization processes.

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# HOW VERIDICAL ARE DIFFERENT MODALITIES OF DIGITAL REPRESENTATION?

*The effect of presentation modality on physiological response*

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**Abstract.** This paper presents the methodology and results of a pilot study comparing the eye movements of architecture students when looking at different modalities of digital spatial representation. The two participant groups consisted of third and fourth year undergraduate architecture students from the University of North Carolina at Charlotte, USA and from Harbin Institute of Technology, Harbin, China. The two modalities studied were a computer-generated line drawn perspective and a digitized photograph of the same architectural space. The results of this study show that student designers' physiological response varies with different representation modalities.

**Keywords.** Eye movement: spatial representation; modalities of spatial representation; designers' physiological response.

## 1. Introduction

Architects design with varying modalities of representation; these include sketches, drawings, physical models, and digital models to assist in the development of design concepts. Visual representations during the design process assist designers with their concept development (Schön, 1992). With the increasing application of computers in architectural design, the effect of digital representations on designers during the design process is not understood. With this pilot project we aim to produce evidence-based results about de-

signers' physiological responses as they are exposed to different modalities of spatial representation. This study is part of the project which aims to relate designers' responses in the embodied experience of the built space with the responses evoked when looking at digital models.

This pilot study utilized eye tracking to collect physiological data, comparing responses to different spatial representations. Building on the research paradigm of Scene Perception (Rensink, 2000), researchers have been interested in how designers look at scenes. Experiments typically present the scene on a computer screen, allowing for a high level of control over variables of the scene. All modalities of spatial representation are abstractions of physical space and are therefore subject to interpretation. From the analysis of the relationship between designers' eye tracking data and different modalities of representation, designers' responses to spatial representation will be presented and compared.

The remainder of the paper presents a brief background to computer representation, spatial perception and eye tracking. This is followed by the research aim, significance and research design. From an analysis of the eye-tracking data, results are presented and discussed.

## 2. Background

### 2.1. DIGITAL REPRESENTATION

Design representation is a core issue in most design domains including product design, architecture and engineering. With the development of computational modelling, digital design representation becomes possible during the design process, which assists designers in both off-loading cognition and providing the possibility to interact with their external representations (Schön and Wiggins, 1992). For example, BIM technology enables 3D (model check, design view, enhanced reality) and 4D visualization (plus time) (Eastman, 2008). Virtual reality (VR) can provide realistic virtual environment which enable designers navigation possibilities (Wang and Dunston, 2013); augmented reality (AR) can enhance the user's perception by complementing the real world with 3D virtual objects in the same space (Morrison et al., 2011). These digital representation tools allow designers to more readily explore design ideas and assist with the concept development of their designs. However, there is a lack of understanding of the physiological effect of digital representations on designers.

## 2.2. SPATIAL PERCEPTION

Oliva et al (2011) studied the representation of the shape of visual space. In their study they critique the isovist theory of spatial perception for leaving out other characteristics of space such as texture, material and colour that contribute to the human perception of space. They also propose a model called the 'spatial-envelope representation', which describes qualitatively the character and mood of a physical or pictorial space, represented by its boundaries (e.g., walls, floor, ceiling, and lighting) stripped of movable elements (e.g., objects and furnishing). Then they proposed a formal, computational approach to the capture of the shape of space as it would be perceived from an observer's vantage point (Oliva and Torralba, 2001; Oliva and Torralba, 2006; Oliva et al, 2011). The collection of properties describing a space in view is referred to as the spatial-envelope representation. This distinction in the characteristics that contribute to the human perception of space pertains to our research into representations of space that include or exclude some of those characteristics.

## 2.3. EYE TRACKING

Early research on eye movement can be traced back to Buswell (1935) who focused on the aesthetic impact of photographs of artwork, patterns and sculpture, particularly the layout patterns of advertisements. Kaufman and Richard (1969) measured eye fixation times in several pre-defined parts of figures, the results show that the center of gravity is an attractor as are the edges and corners. Gould and Peeples (1970) suggest that a subject's interpretation of a figure does not affect eye movements, which means that only "physical attributes" have influence on the eye movements. Torralba et al (2006) proposed visual attentional guidance through an experimental search task. Results of their study suggest that the context information plays an important role in object detection and observation. They also suggest some parts of the scene attract more attention than others.

While the relationship between eye movement and perception of artworks has been investigated, there has been very little study on the role of eye movement in the perception of three-dimensional architectural space. One of the few studies on this topic was conducted by Weber, Choi, and Stark (2002) in which they collected eye tracking data as participants were asked to look at three-dimensional models, or photographs of models, of architectural space. These models were constructed to collect data on the perception of the following architectural issues: empty space; symmetry vs. asymmetry; left and right reversed; obliquely-oriented elements; vista; and foreground. The research focused on comparing different arrangements of objects within

a space, rather than different methods of representing the same spatial configuration. Their results showed that, with no priori model in a figure, the attention would fixate at the center; while the foreground was common for initial fixations, the eye did not typically scan the edges of interior space or rectilinearly-oriented contours; the objects on the left attract more attentions than the ones on the right. This confirmed the results by Arnheim (1985). The study also concluded that fixations did not vary significantly when viewing the three-dimensional model compared with a photograph of the model, with the exception of the foreground, which attracted greater attention in the 3D model.

## 3. Aim

In the present study, we studied the eye movements of architecture students in the US and China in different modalities of digital spatial representation. The aim of this research is to explore the physical responses (eye movement) to spatial representation of architecture students when they view spatial scenes. To determine whether computer-aided representation of a set of spaces is veridical with a digitized photograph representation of the same set of spaces, measurements of physiological response – eye movement is reported here – to both a computer generated 3D model and a digitized photograph of the same set of spaces are undertaken.

Through the collection of eye tracking data, our aim was to test the preliminary hypothesis that physiological responses vary with representational modality.

## 4. Significance

As a starting point, our preliminary investigation focuses on the relationship between the perceptions of space in different representational modalities for subjects trained in architectural design. A future larger-scale study aims to identify the modalities of representation that most closely correlate with the embodied architectural experience to predict how spaces will affect the occupant's physiological state. The potential to predict physiological responses to a constructed space before that space exists would be an invaluable design tool. This could be achieved by collecting and analysing data for the anticipated user group's physiological responses to the most veridical representations of that space.

## 5. Research design

To achieve the preliminary hypothesis we measure physiological response to representations, in particular, eye movement. In this experiment, 22 third and

fourth year architecture students at UNC-Charlotte (UNCC) and 30 third and fourth year architecture students at Harbin Institute of Technology (HIT) in China participated in this pilot study.

During the experiment participants were asked to complete demographic questions regarding their gender, age and first language. They were required to look at two images shown on a screen (Fig.1): the first (R1) is a computer generated perspective drawing, the second (R0) is a digitized photograph of the same space when built. When they looked at the images, their eye-tracking data were recorded by an eye-tracking system (Gazepoint in USA and Tobii studio in China). Each of the images was shown for 20 seconds with a few seconds for recalibration in between them. Half of participants were first shown R1 then R0. The other half was first shown R0 then R1. After each image session there was a questionnaire session. Data collected included eye fixations and saccades.

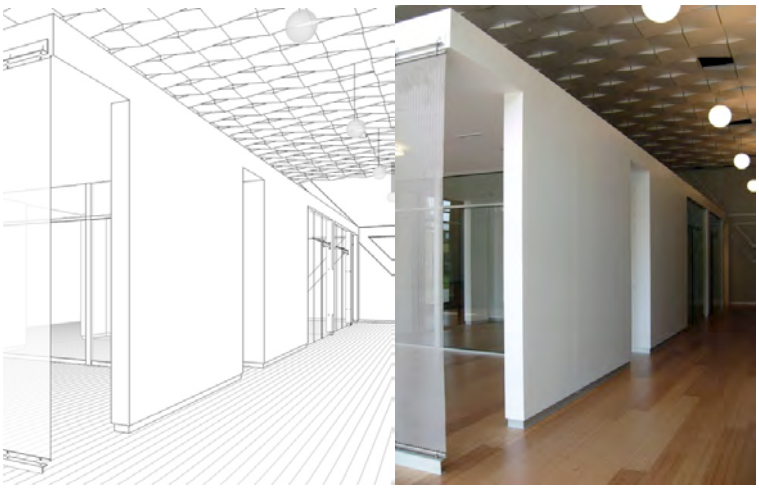


*Figure 1. Left: Computer generated perspective drawing (labelled R1 in the experiment). Right: Digitized photograph of the same space (labelled R0)*

We identified 7 Areas of Interest (AOIs) in the visual scene presented (Fig. 2). Each AOI defines an area that we wanted to gather data about. AOIs defined the three doorways, the two wall surfaces between them, the terminus of the corridor and the ceiling.

## 6. Results

Four metrics of eye movement data were captured during the experiment: Time to First View (secs), Time Viewed (%), Fixations and Average Revisits. Time to First View measures how long it takes before a test participant

fixates on an active AOI for the first time. Time Viewed (%) is the percentage of time viewed within an active AOI of the total viewing time – 20 seconds in this experiment. Fixations measure the number of times the participant fixates on an AOI. The Average Revisits measures the number of visits within an active AOI. A visit is defined as the time interval between the first fixation on the active AOI and the end of the last fixation within the same active AOI where there have been no fixations outside the AOI.

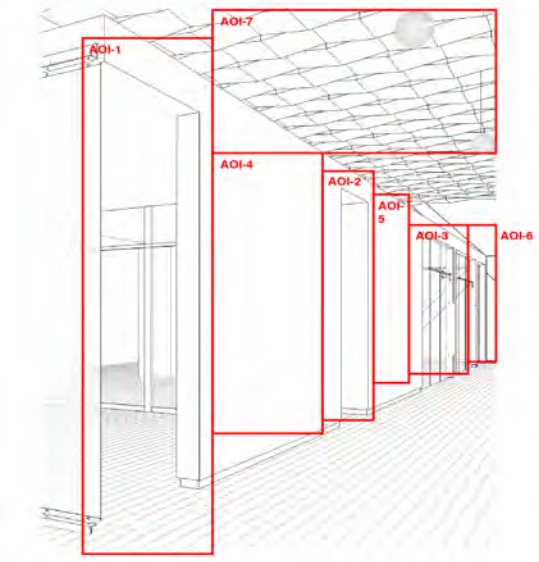



*Figure 2. 7 Areas of Interest labelled AOI 1 through AOI 7 in R1, they occupy the same positions in R0.*

There were no significant differences in the results based on the order of viewing of the images.

Table 1 shows the averages of the four metrics for the data of the 7 AOIs in Image R1. Table 2 shows the average for each of the four metrics of eye movement data of the 7 AOIs in Image R0.

We next determine whether there are statistically significant differences between these two representation modalities. Table 3 presents the t-test results of comparing Image R1 to Image R0.

TABLE 1. The average of eye-tracking data of 7 AOIs in Image R1.

| **AOI** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
|---|---|---|---|---|---|---|---|
| **UNCC students** | | | | | | | |
| Time to First View (secs) | 2.84 | 4.39 | 2.04 | 3.50 | 2.98 | 3.70 | 1.14 |
| Time Viewed (%) | 14.68 | 3.61 | 9.90 | 4.07 | 2.66 | 3.56 | 12.74 |
| Fixations | 12.58 | 5.18 | 10.18 | 6.09 | 5.55 | 4.64 | 13.60 |
| Average Revisits | 6.00 | 4.30 | 7.73 | 5.20 | 5.30 | 4.80 | 7.30 |
| **HIT students** | | | | | | | |
| Time to First View (secs) | 1.16 | 3.18 | 0.95 | 1.44 | 2.79 | 5.93 | 2.50 |
| Time Viewed (%) | 24.06 | 7.05 | 21.43 | 6.04 | 2.10 | 6.62 | 12.10 |
| Fixations | 19.61 | 5.87 | 11.83 | 6.30 | 1.83 | 4.97 | 9.70 |
| Average Revisits | 6.78 | 4.03 | 7.10 | 4.40 | 1.63 | 2.97 | 4.30 |

TABLE 2. The average of eye-tracking data of 7 AOIs in Image R0.

| **AOI** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
|---|---|---|---|---|---|---|---|
| **UNCC students** | | | | | | | |
| Time to First View (secs) | 0.86 | 3.24 | 2.31 | 1.71 | 4.13 | 7.83 | 2.16 |
| Time Viewed (%) | 22.16 | 3.00 | 10.12 | 4.06 | 2.79 | 4.51 | 8.49 |
| Fixations | 19.71 | 4.78 | 9.52 | 5.52 | 5.13 | 4.70 | 8.48 |
| Revisits | 8.13 | 4.10 | 6.70 | 3.95 | 4.95 | 4.00 | 4.46 |
| **HIT students** | | | | | | | **i** |
| Time to First View (secs) | 0.53 | 4.63 | 2.34 | 0.76 | 3.70 | 7.27 | 4.86 |
| Time Viewed (%) | 28.51 | 5.82 | 14.48 | 6.58 | 3.08 | 4.21 | 8.99 |
| Fixations | 28.70 | 5.93 | 12.17 | 8.47 | 3.83 | 3.97 | 8.77 |
| Revisits | 8.73 | 3.80 | 6.77 | 5.27 | 3.30 | 2.83 | 3.93 |

Table 3. t-test of Image R1 compared with Image R0.

| | **p values** | | | | | | |
|---|---|---|---|---|---|---|---|
| **AOI** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| **UNCC Students** | | | | | | | |
| Time to First View (secs) | 0.001* | 0.558 | 0.661 | 0.188 | 0.412 | 0.049* | 0.224 |
| Time Viewed (%) | 0.031* | 0.635 | 0.760 | 0.888 | 0.803 | 0.388 | 0.234 |
| Fixations | 0.042* | 0.861 | 0.895 | 0.814 | 0.900 | 0.799 | 0.123 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Revisits | 0.062 | 1.000 | 0.621 | 0.393 | 0.832 | 0.478 | 0.165 |
| **HIT Students** | | | | | | | |
| Time to First View (secs) | 0.001* | 0.204 | 0.030* | 0.633 | 0.400 | 0.353 | 0.029* |
| Time Viewed (%) | 0.028* | 0.267 | 0.009* | 0.633 | 0.154 | 0.067 | 0.026* |
| Fixations | 0.003* | 0.960 | 0.873 | 0.633 | 0.015* | 0.359 | 0.631 |
| Revisits | 0.002* | 0.751 | 0.667 | 0.633 | 0.007* | 0.820 | 0.591 |

*$p<0.05$

## 7. Discussion and conclusions

The results of eye-tracking measurements are discussed initially in terms of the architecture students' behavior when viewing each image. This is followed by a discussion comparing the results of the eye-tracking measurements for both images to determine whether different modalities of digital representation produce different physiological behavior in the viewer.

The results in Tables 1 and 2 show how students allocated their cognitive effort. For example, from Table 1, we can see that the participants from both UNCC and HIT have the longest time viewed in AOI 1, largest average revisits in AOI 3 and the most fixations on AOI 7, AOI 1 and AOI 3. The least cognitive effort is allocated in AOI 2, AOI 5 and AOI 6.

There are two possible reasons for the long time viewed and fixation in AOI 1. Firstly, participants were attracted by the relatively more complex spaces in a spatial figure - AOI 1 is an open door through which they could see a glass wall inside the room, as well as some spaces behind the glass wall. When a designer is trying to understand the space, he/she will be attracted by this kind of complexity. Secondly, AOI 1 is located on the left hand side of the image, and according to study of Weber et al. (2002) and Arnheim (1985) the left side of a composition attracts more attention than the right. AOI 7 is the ceiling, which contains some complex structure, therefore it attracts the attention of the participants. The most revisited is AOI 3. This may be because compared to AOI 1 it is relatively small and distant so that participants need to revisit to try to understand the space. The least attention is directed at AOIs 2, 5, and 6 possibly because they are relatively simple areas.

The results in Table 3 indicate differences in three of the four eye movement measurements. Time to first view, time viewed and fixations were all statistically significantly different when viewing the computer-generated line drawing perspective compared to viewing the digital colour photograph for Area of Interest 1, which is the first AOI to be viewed in the digital photo-

graph but is only the third AOI to be viewed in the line drawing perspective. Interestingly, AOI-1 had the highest percentage of time viewed for both modalities, whilst there was a lack of congruence for the other three measures.

The results from this study additionally imply the following:

- Architectural students put more cognitive effort on the relative complex spatial representation areas, as well as the structural complex parts.
  The complex spatial representation areas such as AOI 1 naturally attracts more attention probably because it needs more exploration to understand the space. Certain features are more likely to attract eye focus, for example, in a face figure the eye focus is usually on "eye" and "mouth" (Gould and Peeples, 1970). In architecture, past research suggest that architects pay more attention to the spatial arrangement of various architectural elements (Weber et al., 2002). The more complex spatial area such as AOI 1 contain multiple architectural elements: the extensive rooms behind the opening and the glass door. Also the complex structural parts in the ceiling attracted more attention.
- The left-hand side parts in an image are likely to attract more attention.
- Research on eye movement of static images has shown that the left-hand side parts attract more attention than the right (Arnheim, 1985; Weber et al., 2002). The present research confirms this claim that human eyes tend to "rest" at the left hand side. The possible reason may due to the visual pattern recognition and memory system of the brain. Further exploration of this phenomenon in spatial representations is needed.
- The edges of the interior space were not frequently scanned.
- The most fixated areas are the complex spatial areas, rather than the edges or corners of the interior space. This result agrees with Weber et al. (2002)'s research on eye-tracking of interior space. However, in Kaufman and Richard (1969)'s study, they state that icons such as corners and edges are more likely to attract attention, while the current study does not confirm this claim.
- The center of gravity is not always the focus of eye movement.
- In the early eye tracking research, researchers found that the eye fixation is always focused on the center of gravity of a figure (Kaufman and Richard, 1969), however in the current study, the center of the image is not the focus on eye fixation, instead it is the relatively complex space. This indicates that the semantics of the image plays a role.

This paper has presented the results of a pilot study comparing the physiological response of eye movement of architecture students when looking at different digital modalities of spatial representation. Results from the analysis of eye-tracking data suggest that designers' physiological responses vary with the changes of digital representation. In order to make a more comprehensive conclusion, a larger experiment is needed in a future study. Future

studies would include a broader demographic (comparing trained designers with non-designers) and a wider range of representational modalities.

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# IS CONVENTIONAL KNOWLEDGE ENOUGH?

*Playing the devil's advocate in the adoption of digital fabrication technology*

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**Abstract.** Building on the research on the industrial potential of digital fabrication technologies commenced by the late University of Melbourne academic, Professor Bharat Dave, this paper explores actual patterns of technological adoption within communities of practice bound together in a few selected projects. Its main aim is three-fold: 1) highlight the distribution of knowledge required for the actual take-up of digital technologies; 2) look for the presence of possible gaps in such work landscapes; and 3) discuss the transformations that may occur in practice as a result of the conflation of innovative technologies and established professional cultures. The research being reported in this paper examines the socio-technical environment of the projects selected and the challenges intrinsic to the introduction of innovative digital technologies. Its findings suggest that the inherent complexity of building production needs to be considered in a far more nuanced and substantive manner than generally assumed by mainstream technological positivism.

**Keywords.** Innovation; digital technologies; digital fabrication.

## 1. Introduction

This paper relates to research exploring patterns of adoption of innovative digital fabrication technologies by Australian architecture practices. Specifically, the research aimed to develop better understanding of (1) emerging opportunities for design and construction of non-serial architecture using digital fabrication technologies, (2) possible gaps in work landscapes and (3) cascading transformations in established norms of design practice that follow adoption of such fabrication technologies.

The gradual shift to production of built environment using fabrication technologies extends earlier passages from craft-based, manual processes to mechanised and standardised industrial techniques. The increasing informatisation of design and construction processes is accompanied by opportunities and costs. Whereas most published literature offers descriptive accounts of designs as constructed, a few detailed studies describe procedual trade-offs and transformations that professional practices undergo once they embrace innovative digital technologies (Schodek, 2005; Pfammatter, 2008). This research provides an understanding about the transformations that occur when innovative technologies and established professional cultures come together, investigating the interaction between communities of practice. It relates to the idea that what is still developing is not only how one designs buildings, but also how one manufactures and constructs them (Callicott, 2000; Kolarevic, 2003; Schodek, 2005). Therefore, digital technology (adequacy of software, translation of information, material fabrication, etc.) and project sociology (patterns of communication) need to be investigated together.

## 2. Background

The use of digital fabrication technologies in architecture is most visible in the works of Frank Gehry, whose practice has experimented with and skilfully integrated use of digital technologies for representation, fabrication and assembly. (Shelden, 2006; Boland, 2007).

With the subsequent development of computer graphics and computer-aided design systems beginning in the 60's, Computer Numerical Control (CNC) systems were developed to aid efficient production of machine parts directly from digital data in the automotive and aeronautical industries (Callicott, 2000). These developments are currently embraced in the architecture and construction community in the form of digitally fabricated design projects (Kolarevic, 2003; 2015). From integrated digital tools to design through fabrication and assembly, a different paradigm of file-to-factory informatisation has emerged which allows a shift of emphasis from design projects comprising repetitive, mass produced elements and which feature low complexity to one of mass customisation or buildings comprising non-repetitive elements often featuring high complexity (Kieran, 2004). This transformation to non-serial architecture hinges upon use of integrated design, fabrication and construction processes underpinned by digital tools and technologies (Schodek, 2005). A robust theoretical account of innovations in design practices is offered by Boland (2007). Based on the multi-project and multi-year study of the firm of Gehry, the notion of "wakes of innovation" is intro-

duced that propagate among heterogeneous communities of practice but deviate from established norms, occurring at different rates and times in different professions, and diffuse through at the permeable zones between communities of practice bound together in a project.

The focus of this research is just on these lines of demarcation: how and in what ways digital fabrication technologies are adopted and how they reconstitute knowledge boundaries in contemporary design practices. For their very own nature, these questions cannot be addressed adequately by studying technology alone or patterns of communication among or organisational structures of project teams in isolation, but need to be investigated together.

## 3. Methodology

A case study approach has been adopted with material presented in this paper arising from open-ended interviews undertaken with key members of project delivery teams. The research agenda is organised around three Australian design projects, each representing a distinct scale, function and character and each illustrating the use of a distinct palette of materials, fabrication technologies and project organisational structures: Webb Bridge, Burst House and Southern Cross Station.

Webb Bridge (2002) grew out of a winning competition project by a collaborative team of DCM Architects and mixed media artist, Robert Owen, in Melbourne. The bridge is a serpentine construction consisting of steel hoops that vary in width and height. Each hoop is an ellipse of a different size, centred differently across the span of the bridge. The steel straps that span between hoops also vary in width and height of the coil to accommodate the levels of the bridge. The design evolved from the artist sketches and physical models into a parametric 3D digital model.

Burst House 003 (2005), located in a mid-north coastal NSW town, is an experimental prototype of a laser-cut plywood house designed by SYSTEMarchitects to serve as a "weekender" for its owners. Working from New York, the firm utilised software that took as a starting point space requirements, site and climatic data, from which were generated spatial configurations. The project, evolved into a second iteration via the participation by the architects in the 2008 MoMA exhibition *Home Delivery: Fabricating the Modern Dwelling.*

Southern Cross Station (2006) is a major infrastructure project being the refurbishment and extension to an existing public transportation hub in Melbourne. The project was delivered as a Public-Private Partnership, with Leighton Contractors engaged to deliver the works, with architects Grimshaw in collaboration with local practice Jackson Architecture. Its iconic

wave-form roof of naturally ventilating “moguls”, together with skewed geometry of the tracks from the street edge, results in steel members and components that look alike but are in fact unique in terms of their geometry and dimensions.

## 4. Scale, context and challenges

The three case studies demonstrate that the uptake of digital design technologies are not necessarily contingent on the specific project or its scale or context, yet project specific challenges remain influential to its implementation.

The concept of Burst House 2005 evolved out of a digital technology determinism geared towards the possibility to provide an alternative to mass-produced housing, seeking parametric conditioning accounting for site, context and environmental responsiveness. Utilising *Maya* software to generate a 3D model, a large number of design iterations could be generated quickly, which could evaluate environmental performance and prefabrication production methods, which could be optimised through nested software to limit wastage in its plywood structure (Architect: 2015 personal communication). The idea of optimisation of prefabricated ribs – which ideally lowers project costs, as well as wastage on the building site – reflects how new digital processes may enable considerations of resource minimisation embedded into design conception and construction.

Despite these aspirations, the project had to proceed under a self-build construction procurement regime due to difficulties in obtaining a head contractor within budget. The formal complexity of the building system placed time and labour demands in positioning and assembly of the numerous frame components. This necessitated the engagement of a site architect to operate as a mediator between the digital information and site personnel assembling the building componentry. Significant on-site adjustment led to cost implications that eroded the objective of cost-effective, ease and speed of construction. Factoring for the inherent difficulties encountered, the 2005 Burst House in many ways represents a precursor of a new way to interpret the customisation of prefabricated building systems, as demonstrated by later examples, such as Alastair Parvin’s 2011 *Wikihouse*.

The Southern Cross Station demonstrates that project specific challenges may support an interest in digital design uptake, in this case, by facilitating rapid design optioning, modelling and testing for the roof system in dealing with the discharge of diesel fumes via natural ventilation systems. It is the capacity of the digital domain in its application to the supply chain where the close integration between architecture, structural engineering, shop-drawing

production, and fabrication came to the fore in meeting site, program and cost constraints. This resonance of Charles Eastman's (1975) postulation of the potential of computer-based building representation, its parametric design opportunities and linkage to production suggests that the Southern Cross project cannot be considered innovative in engaging with a Building Information Modelling (BIM) process, but in its manipulation of the process in meeting project specific requirements and revealing how digital technologies can be conditioned by the supply chain context in proceeding through different disciplinary territories of architecture, engineering, fabrication and construction. The roof structure comprises of approximately 8,000 tubular steel members with 3,500 connection nodes. The tube lengths vary in size due to the variability of the roof geometry. The decision to engage only one steel shop drawer, responsible for the whole project, and introducing this entity upstream into the project process allowed for the generation of one 3D digital model. (Project Manager: 2012 personal communication). From this the quality, accuracy, form of information output and its dispersion, despite the fragmentation of production across different suppliers could be controlled to ensure the exact coincidence of information and program scheduling.

**5. The uptake of digital technology is not exclusively a technical decision**

Initial uptake of digital technology may not derive from technical capacity building, BIM leverage or supply chain production management. In all three cases these followed cultural inclinations motivated by formal decisions independent from production. The Webb Bridge project arose from funding sources related to urban art patronage and developed via the interaction between artist and architect. The scheme was viewed as a development from previous urban design project interests and practical compliance issues related to pedestrian gradient considerations. The realisation of the difficulty in the refinement of the formal aspects of the design using traditional representational systems led to the adoption of 3D digital modelling techniques. The further development of this model for fabrication occurred via the engagement of the same shop drawing production agency that would be utilised for Southern Cross Station.

Southern Cross Station presents a digital uptake profile similar to Webb Bridge, in the early realisation that arose from working through various digital representational tools in dealing with the configurations of design elements. The continued development of digital technology for use along the supply chain, then responded to conditions specific to those actors within the context of the overall project, such as engineering constraints or fabrication,

supply and assembly efficiencies. Although sophisticated digital modelling was undertaken, the initial uptake did not arise from purely technical considerations in digital adoption.

The Burst project arose as a prototype for an interest in demonstrating what fabricated housing can achieve by mining the possibilities of the computer. This approach accords with notions of "critical design" speculation as articulated by such proponents as Dunne (2013). The use of heuristic algorithms, responding to environmental and space planning inputs whilst accounting for its structural use of plywood components as a flat pack assembly system was presented as a prescient response to a more general condition of residential construction design and production innovation. Here the challenges are largely cultural, and the Burst project demonstrates that these cultural challenges exist beyond just customer or client support but also within industrial context and communities of practice.

## 6. Communities of practice, construction procurement, industrial capacity in adopting digital technologies

The adoption of digital technologies relies on the actors of the community of practice, in their capacity to drive, enable, follow or hinder an innovative process, having coincidence of means, motives and opportunities. It demands the adoption of integrated information and therefore a deep collaborative design strategy which may determine the success or the failure of the process, as much as in the role of drivers, enablers, user, and reactionaries. In the Burst House the architects, the only driver along the supply chain, assumed responsibility to facilitate the fabrication and assembly process, having the view that the risk involved arising from the complexity of the project could not be contained well enough to convince contractors that risk was limited. (Architect: 2015 personal communication). The owner/builder construction procurement approach for this bespoke residential house facilitated an experimental process of digital design speculation, underpinned by the argument that the digital design method and the mode of fabrication production afforded ease and speed of construction, within budgetary limits. Despite these intentions the project was plagued with budget and time over run. The second iteration of the Burst project at the MoMA, used different materials and fabrication processes, a different contracting regime and less budgetary conditions. The building process took 10 weeks, 4 off-site and 6 on-site, demonstrating the iterative nature affiliated with prototyping new technologies and systems.

In Southern Cross Station, resistance to digital uptake and BIM innovation lay with a fabrication industry embedded to tooling and production

methods which reflected prior modes of operational practice. The response was to identify specialists with the capacity to provide the services to push the adoption of innovation along the supply chain. The ability to innovate in the construction industry is limited by its fragmented structure as a project based industry with a low volume output characterized by ever different products, assembly plants, and strategic coalitions. The procurement system and scale of the station and in part the bridge provided the framework for push-pull dynamics of innovation to be implemented. Critical path items could be modelled and reviewed, such as, various iterations of 3D steel component profiles accounting for requirements such as minimum head clearances and high-tide water levels. Developed as a Public-Private Partnership model, the Southern Cross Station mandated cooperation between the actors: architects, consultants, contractor and sub-contractors. The central shop drawing coordination agent was identified as being a key player, who picked up the fabrication component of digital design production. This coordinating agent evolved as a central driver for digital uptake taking a determining role by assuming responsibility for the digital information and the coordination of the other actors involved. The involvement of the shop drawer from an early stage can be considered an endemic consequence of this kind of procurement, but the introduction of a 3D model, entirely managed by a single coordinator, was considered to be one of the meaningful reasons of the success of this project. Given that the same fabrication information agent had worked on the earlier Webb Bridge the flow on of expertise developed in the complex geometry of the steel framed bridge is noteworthy in the role these types of projects play in knowledge transfer and as innovation incubators.

A defining condition that individual actors have as their starting position is often set within the framework of the industrial capacity and the operative characteristics in which they must engage. While every building imbues decisions affecting its various aspects, every building also implies a different combination of those decisions, produced on the basis of established priorities and existing operative conditioning. The Burst House concept seeks to apply a new ideal of mass customisation to the residential construction sector arising from an attempt to reconcile singularity with customisation whilst negating a corresponding increase in costs. But this project, with its bespoke nature, in attempting to pull the industrial status quo forward, in demonstrating pathways for digital supply chain networks and connectivity, faced an industry that had not reached maturity in its adoption of digital technologies both in its social context and market setting. Webb Bridge and Southern Cross Station operate within different frameworks having a different order of complexity in terms of the number of components and number of parties in-

volved in the whole processes. The use of parametric modelling for generating and fabricating variations within a geometric schema, in the bridge represents how constraints of fabrication and assembly become integral to design development from the earliest stages of design.

Component sourcing from state, national and international sources, require discussion to occur on the relative interfaces across boundaries. The diversity of components involved requires significant attention to interfaces between different geometries, materials and sequence in which they are assembled together. Specifically, it illustrates how careful attention to geometry and tolerances becomes a fundamental necessity not only during design and fabrication but also during intermediate and final construction stages in the project.

All three projects demonstrate that technological take-up is not contingent on *developed knowledge* or on existing industrial capacity. However, such innovations need to address both these conditions and are factors in the success of the outcomes of project realisation.

## 7. Discussion and conclusion

It can be argued that our understanding and exploration of digital technologies requires more than knowledge of the technology involved. It demands a deep awareness of its connection to existing practices of design, fabricating and building. The availability and adoption of integrated information processes acts not only as a change enabler but also as a change agent.

The implicit motivations behind this paper and, more in general, the funded research on which it is based, had to do with the validation (or, by extension, the dismissal) of a doubt about the determinants of technological adoption in the design and construction process, particularly when it came to digital fabrication techniques. Irrespective of the emphasis placed by IT pundits on the inevitable onslaught of numerically controlled machinery into building, should construction scholars let others worry about hardware, and rather concern themselves with the social software of the industry – its people, its work protocols, its established relationships, its culture? Are these the real determinants of – or barriers to – change, even in digital matters?

The socio-technical analysis of the three projects, succinctly described in the previous sections, seems to suggest that not only is there significant import to this proposition, but also that any agenda truly concerned with the introductory efficacy of digital techniques in building cannot afford to overlook some of the components that came out of the parallel examination of the procurement histories of the case studies undertaken: a small beach house, a bridge folly, and a train station. Firstly, the study of how each pro-

ject unfolded clarifies that the uptake of digital technology was never exclusively a technical decision. Although the introduction of digital fabrication methods differed depending on the scale of each project, the context of each project and the manufacturing challenges specific to each project, the decision to follow the path chosen against possible alternatives in each case seemed to be determined more by cultural inclinations (and, at least in one case, by ideological positions) than incontrovertible production advantages in terms of supply chain management. In many ways, the initial take-up was motivated by formal decisions in each of the projects analysed. Such decisions may not have made the procurement of the building "easier" (and therefore "economic" in every sense) but did indeed make the contribution of digital manufacturing processes vital to the viability of the ideas underlying the aesthetics of each building in practice. The "pull-in" from construction, in other words, could be considered necessary only post-facto – in terms of "bounded rationality", that is – once other decisions, originally independent from production, were taken.

This finding introduces the critical role played by specific actors – literally, members in the community of practice of each project with the ability to act and to influence the behaviour of others or to follow directions that may not have been technologically driven or informed. Both adoption and application of digital manufacturing technologies, in other words, relied on the existence of driving champions and/or technical followers. Yet, caution should be exercised when placing excessive emphasis on individual actors' drive. Although certainly critical to the eventual success of the enterprise, the study shows that the "existing" industrial capacity of the community of practice in which the project is embedded cannot be sufficiently highlighted. On the one hand, it is the level of related maturity of the industry involved in the project that enables both the adoption of particular techniques and the adaptation of existing work conventions to them. On the other hand, it is the morphology of building procurement – i.e., when and how, certain actors are expected/allowed to undertake certain tasks – that makes it possible for the community of practice to interact as necessary, either by following established procedures or by defying them. In the case studies examined, this second element produced some significant divergences, with the design and technology teams in the small beach house and bridge folly scattered across unconventional and informal landscapes of contributions, whereas work on the train station identified specialists with the capacity to provide the services needed in the position expected along the supply chain. This does not mean that technological take-up always took place under conditions of "developed knowledge" – in fact quite the contrary. In each one of the projects examined, uncertainty and specific inexperience were the markers of the

process. Thus, while actual knowledge gaps existed, these did not deter the decision to go ahead with the plan. Yet the fact that the three projects were eventually built (and received several accolades) should not underestimate the impact of "imperfect (technological) knowledge" on their design and construction performances. When looked at in detail, the physical results of the process undergone warn against the dangers of placing the digital manufacturing cart ahead of the industry's ox, particularly when the pathway has not yet been cleared of longstanding hurdles. Even though each one of these projects may appear as a glistening example of digital manufacturing from a distance, it invariably owed its actual implementation to non-digital elements – either social or trade-based. By contrast, it is in their never-resolved (and opaque) problematic aspects that the study of technological innovation and its non-technological repercussions should dwell.

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# ARTIFICIAL IMAGINATION OF ARCHITECTURE WITH DEEP CONVOLUTIONAL NEURAL NETWORK

*"Laissez-faire": loss of control in the esquisse phase*

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**Abstract.** This paper attempts to determine if an Artificial Intelligence system using deep convolutional neural network (ConvNet) will be able to "imagine" architecture. Imagining architecture by means of algorithms can be affiliated to the research field of generative architecture. ConvNet makes it possible to avoid that difficulty by automatically extracting and classifying these rules as features from large example data. Moreover, image-base rendering algorithms can manipulate those abstract rules encoded in the ConvNet. From these rules and without constructing a prior 3D model, these algorithms can generate perspective of an architectural image. To conclude, establishing shape grammar with this automated system opens prospects for generative architecture with image-base rendering algorithms.

**Keywords.** Machine learning; convolutional neural network; generative design; image-based rendering.

## 1. Introduction

What does it take to make an architectural representation believable? By just putting a 1/50 figurine on a model or a mere shape, we envision it on a human scale and start to imagine it as life-size architecture. Hollow, residual volumes are imagined as spaces where we might go once a project has been built. By doing so, our imagination fills in the gaps and ignores the lack of details that are usually present in realistic representations.

This way we use our imagination is based on our experiences. We've seen thousands of buildings of various shapes and we can envision that what

we have in front of us, a mere shape is more than what we see. All the types of windows, doors, roofs we have seen are registered in our memory. They are elements that we articulate with non-formalised grammar while we perceive and create. Therefore, chief characteristic of an artificial imagination system that mirrors human ability is a shape grammar (Stiny, 1980), which formalise various types of architectural styles, materials and structural systems. Developing this system presents worthy outcomes for the design process studies and it is obvious how appealing it would be to automatise the formalisation of such system of rules.

Recently, progress in ConvNet shows that it is possible to use existing architecture building pictures to extract rules and then recombine these rules into a new architecture building image. Indeed, rules of classification are implicitly embedded in the images' compositions, and a system such as ConvNet extracts them. From a series of training pictures, the "back propagation" algorithm progressively sets weights and biases on branches and nodes of the network in a bottom-up way (Nielsen, 2015). The strength of this process is autodetermination, letting the system figure out by itself how to select criteria in order to perform the correct classification. This contrasts with the top-down way experts use to formalise such grammar.

Similar to our imagination process, this system needs something to trigger and orient its "imagination". As front-end interfaces, the user can orient and influence the generated image through pictures that serve as hints about what he expects from the generative system. What raises interest for design research is that non-human logic offers designers a new point of view on their object. By envisioning the Algorithmic architecture definition of Kostas Terzidis (2006), this ability could improve the control loop feedback by providing a new way to interact with computers. The paper will focus on the way we could build this system and more specifically about the interface to control it while keeping its ability to surprise us.

The paper presents experiments with ConvNet that explore what kind of ConvNet architecture, training data sets and, rendering algorithms can generate perspective view of the architectural scene. The first part is focused on the explanation of the process that ponders the weight of the neural network. Through the use of Deep Dream (Mordvintsev et al, 2015) algorithms, the importance of the learning material will be emphasised. Then, in the second part will be pointed out the default of current pre-trained deep neural networks when they are used for architecture image generation purpose. This observation will guide us in the need for a better understanding of inner workings of ConvNet in the third part. This part will develop on how features are extracted and how they can be crafted and used to orient the generation of more coherent pictures. As conclusion, regarding what existing

image-based rendering (Fitzgibbon, 2003) algorithms can produce, guidelines to build architecture image generation system and its control interface will be proposed. The generative system presented in this paper is limited to 2D perspective representation of architecture. This is mainly due to the input data format: pictures of architecture buildings. We authors understand that a solely using one picture to represent a building or a room is a very truncated expression of architectural projects.

## 2. First experiment: generate architecture with deep dream and an architecture image

### 2.1 REVEAL THE SUBCONSCIOUS OF THE NETWORK

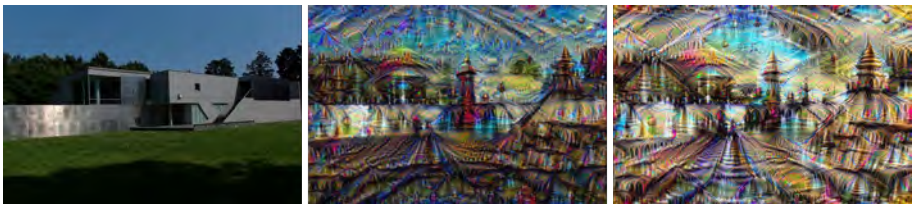


*Figure 1. Details appear gradually at each step. They are based on shapes of the input image.*

The central component of this system is the neural network. It concentrates and encodes all the information implicitly embedded in pictures. The network is composed of various hidden layers of computational neurons. Each performs an abstract classification task. In order to visualise what is being detected in each layer, the “Deep Dreaming” algorithm has been created by Google researchers. When Deep Dream, exploits a ConvNet it performs “gradient ascent process that tries to maximise the L2 norm”(Mordvintsev et al, 2015). In simpler terms, it modifies the input image in a way so that the detection score with the features encoded in the ConvNet is higher. Then, the output image with features exacerbated is again processed in the ConvNet with the same process. On each pass in the loop, the likeness with the ConvNet encoded features get higher. It’s important to understand that features are abstract representation; they are not image components.

As we can see, it provides unclear psychedelic images that are difficult to recognize. Nonetheless, we still feel some architectural tectonic underneath. A noticeable aspect of these images is the part of the meaning is derived from what is projected by the observer. In the stance of the Rorschach test, it may reveal the viewer's mind. These dreamed images are halfway from our imagination and the “imagination” of the ConvNet. The vision of this odd dream awake us from the “world created by smart advertisers …” (Wood, 2007) since the original is close to the unimaginable.

## 2.2 THE DATASET



*Figure 2. Left: image produced with GoogleLeNet; Right: with MIT Places (Zhou 2014).*

A downside of the Deep Dream algorithm is its obsession in making us see animals in everything. By default, the program uses the GoogleLeNet trained on ImageNet Dataset. This Dataset contains a large amount of animal pictures and it explains this strange obsession. For architecture design purposes, it's more suited to use models train on MIT Places Dataset. By using it, there is a strong tendency to reveal more "architecture expressive" friendly forms.

We clearly see more biological tendencies with GoogleLeNet. This author can see a chimera of Scorpion and insects on figure 2 left. Instead of that, the Places205 ConvNet changes trees into Pagodas, and generate fractal straight roads with vanishing point wherever possible. Further experimentations of deep dream based on Places ConvNet show that that kind of dream is not so specific to the building input image used in the figure 1.

The usual explanation for this behaviour is the different types of pictures in the dataset are unbalanced and the ground truth categories in which they are classified are oriented for a specific detection task. If large parts of the pictures in the dataset contain eyes and if this visual detail is an asset to recognise in which category the image should be classified, this leads to create a tendency of popping eyes when Deep Dream is used with this ConvNet. If we look closely the M.I.T. Places dataset, we can find lots of images with humans on it. These images are poor in architectural or environmental detail but they still inform us on the plausible place.



*Figure 3. Samples of the Places Data set: labels for each row starting to the top, fitting room, floral shop indoor, arch. The last row could be used in a more architecture oriented Dataset.*

Since places are partially defined by human activity, the data set contains lots of pictures with humans inside. But a humanoid shape doesn't pop when Deep Dream because to classify images in the demanded category, it seems that the network discovers more valuable abstract features than the one present in eyes. In short, what links these images for us can be the human behaviour factor but, for the trained ConvNet, it's something else, such as maybe a few values of colour pixels in a specific pattern.

## 2.3 CRITICS OF DREAMING

As said before, Deep Dream has been created to envision what is encoded inside the ConvNet. The purest expression of what is encoded is done by using an RGB noise as the input image (see Figure 4). It reveals the tendency of the ConvNet. Whatever we use Place ConvNet or GoogleLeNet ConvNet, the tendencies are different but we can notice familial likeness in their dream: Images tend to have a "rainbow" texture that prevents generated architectural pictures the ability to express materiality. Secondly, elements are unrelated and are floating next to each other without structure.

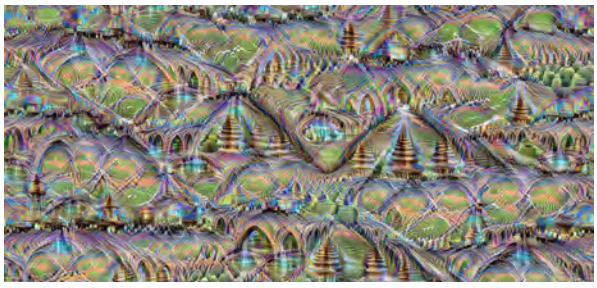


*Figure 4. "Natural expression" of the ConvNet trained with places. From an RGB noise image the algorithm is more prone to generate this kind of shape.*

Often, pictures of architectures present a background that fills the pictures' space more than an iconic element that stands in the middle. From our experimentation, actual Deep Dream is more suited to help us invent a new chimera than an unseen architecture environment. Last, the elements don't fit into any layout context: the upper part is filled with elements similar to the one on the lower part: Context of the canvas is not taken in consideration.

Unlike with this noise input image, the generation can be structured in a particular context as shown in Figure 1. It doesn't state clearly a design intention, but that's the designer's responsibility to transform it in a reachable "micro-utopia" (Wood, 2007). What does it take to produce more realistic images of an architectural environment? Firstly, there is a lack of scale hier-

archy between elements. In the element itself, relations of proportion are respected, but through the space of the picture, a pagoda can be the size of a mountain. This can be due to a lack of relation to the human scale and rules of perspective that aren't encoded in some ways in the network. This will be the theme of further research.

Moreover, pictures of the data set are framed to show something specific: It doesn't try to detect something in the background. This technical limitation creates an implicit connection between pictures: mainly centred on the one central element it should learn to detect, and then discarding the background. This is not a problem for their initial goal, but to hijack the model to generate architecture image, the lack of features encoding the context is a pitfall.

Besides changing the dataset, improving such system can be done by changing the architecture of the ConvNet. For instance, if it includes SpatialPyramid module like in the work of Clement Farabert (2013), we can expect that dreamed images will loose the tendency to imagine people in the sky or other incongruous elements. Indeed, the Spatial Pyramid module duplicates the trained image in various resolutions and process them in parallel and share the weight of neurone layer at different scales. By doing so, low-resolution images processed will detect more general and composition related features while higher resolution ones will detects components itself.

## 3. Second experiment: generate architecture image with 2 inputs images and neural style algorithm




*Figure 5. The algorithm is far more than a Photoshop filter; it identifies how things are represented in the artist's style.*

The design cognitive process could be a model to change the network architecture. If the algorithm generates architecture in a similar fashion as architects design, generated architecture could be more realistic. Moreover, it could test the cognitive process used as a model for the algorithm. Neuroscientists (Gatys et al, 2015) create a neural network to show the process involved in the creation and perception of artistic imagery. The algorithm they created is a model of artistic process that supposes a dichotomy between style and content. Basically, the algorithm takes a content input photo and

one or more style input images like a painting and applies the style on the content − i.e.: the content is drawn with the style provided.

This theory of cognitive processes can be applied to architecture, too. Same as in the painting field, there are historic architectural style and personal architectural style. But the transposition can't be so naively done: architects don't only represent reality with their style; they create it. The sole representation time is during the project rendering phase and the sketching phase. Even if they use an architectural sketch as style, this notion of content can't fit in the architecture cognitive design process theory: architects don't apply their style on content. The content can't be another architect's building since this one already has a style embedded into all the details. The closest notion that can replace content could be the program. The architect applies his or her style on the way to execute the program.




*Figure 6. If the pictures are wisely chosen, it's possible to use this algorithm with architect style on content.*

Like in figure 6, if we try to apply the neural style algorithm on architecture to generate an architectural hybridisation, it doesn't apply a style. Instead, patterns and materials are applied. To illustrate this, we mixed naively, the style of the architect Kengo Kuma with the "content" of Louis Khan library. Nevertheless, understand that this algorithm could be useful to improve generative architectural images. As we see, output images are cleaner and more realistic even if their novelty factor is less wild.

After experimenting with the code on some content and art pairings, it reveals that the inner mechanics can be popularised as: an understanding of the style as a summary of the textures used by the artist. Hitherto, it's appropriate for impressionist art but less efficient on textureless art. It matches content with ways to represent it in the original art.

Again, for this to work, it is based on a trained neural network. This one provides abstract categories in which style and content features match. Changing the ConvNet will influence the process by creating different features matching categories.

As has been explained before, upon building a ConvNet specifically for architecture, it will be interesting to see if the matching is more precise. Another way to use Neural Style for generative purpose is to hack the inner log-

ic of the algorithm in order to apply it to architecture. The example in figure 7 shows how the style factor can be replaced by a material set. The algorithm will apply them geometrically in almost a rational fashion. Right now, we are here in-between fulfilled expectation and surprise.




*Figure 7. The Bunker shape as content, an abstract style image composed with desired material give a wooden bunker.*

Neural style was intended to support the theory of "understanding of style" through the algorithmic process. In the case of architectural design, the alteration of the image in figure 7 doesn't show an understanding of the construction materials used in design. To explore that point and more about the cognitive process of architect, a specific algorithm to model the architect creation and perception of pictures of architectures should be established. Supposing that architectural design is the interaction of structural solutions, materiality and tectonics. The model that is able to test this theoretical division and how they can interact in the creative phase should stimulate the extraction of the relevant information for recomposition from input images.

Mere generation for serendipitous purpose is a less ambitious goal. If we exclude that the algorithm should fit the model of a plausible cognitive process. We could focus on merely being more genuine in following the rules of perception, rather than architectural design ones, in order to get more visually satisfying images. For further research, dropping the cognitive process likeness seems more realistic.

To conclude this part, the extracting and matching ability of this algorithm open the perspective of using multiple image input of various types in order to drive the image generation. We can imagine image equations that can be processed through an algorithm similar to Neural Style.

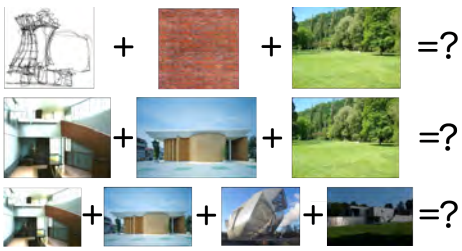



*Figure 8. Various types of input equation that can be used to drive the image generation*

We could imagine that the first equation is in a similar fashion to Neural Style algorithm, matching material and sketch and inlay the image in the site. The second equation will extract relations between site and architecture, elements position (like windows) and tectonics and then generate pictures of architecture within a site picture. Or, just hope that the network find a “weird logic” of abstract features associations and succeed in designing a building and the site background by taking inspiration of the 4 inputs presented in the third equation.

## 4. Conclusion



*Figure 9. In this dataset sample we can notice the iconic and stand alone aspect of the chosen architecture building*

As we see in this paper, deep neural network succeeded in grasping a few notions of architecture and managed to manipulate them in unexpected ways. Despite the fact that these notions are encoded within the black box of the ConvNet in a format we can not operate with, we still can control the building input material and parameter of the ConvNet. In future works, we aim at generating a more coherent architectural space and it seems that more notions need to be taught to the network. In order to achieve that, we will keep using the open-sourced code cited here while refining the ConvNet. In this case, ConvNet can be tuned through two parameters: curation of pictures of the training dataset and the design of ConvNet architecture.

Currently, ConvNet architectures have been designed for a detection and identification purpose. In future works, we would like to set up a network architecture for the sole purpose of generating. Then, instead of feeding it with the usual dataset focused on daily life objects or domestic animals, we would like to create an architecture specific dataset.

Since architecture has a wide range of expressions and points of view, we will segment the task into various datasets. Indeed, inside space cannot be fully grasped through one picture. It seems wiser to start simple and make the first test dataset with the front view of various individual buildings standing in a open surrounding. With this test dataset, we aim to produce images of iconic buildings in an understated context, like in the Figure 9. If we want

to work with more architecturally inner space, pictures such as the ones in Figure 10 would be used.

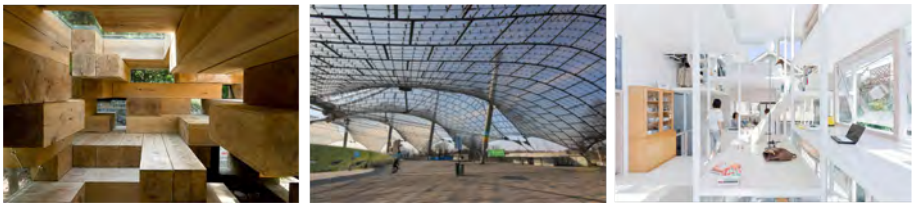


*Figure 10. Unlike the previous figure, the background is more significant than the foreground*

Beside the appropriate data set, other obstacles need to be overcome: conceptual notions of a pictures' construction need to be embedded in the network. We can imagine that notions of hierarchy of scale and perspectives need to be encoded in someway into the system. One solution could be to provide RGB+D pictures of architecture space or a set of two close views of each scene. Once such a base is set, we can start to experiment on a combination of ConvNet architecture, type of image feeding datasets and image-based rendering methods. When the combination of these three elements are settled, it will be very intuitive for designers to express an orientation of design through operations between only a few reference images.

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